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Internet of Things-Based Landslide Threshold Detection and Monitoring System on Ambon Island, Maluku Province, Indonesia

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ABSTRACT

Landslides frequently occur on Ambon Island, causing extensive damage each year, including debris avalanches and slope failures. Landslide mass movements are unpredictable, and investigations are usually only conducted after they occur. Therefore, direct landslide investigations that can be continuously monitored, anytime and anywhere, are crucial for establishing an early warning system. This study aims to detect and monitor slope landslide thresholds using IoT technology integration through cloud communication, as well as determine the maximum speed and total time of landslide runoff until deposition.. This research method is an innovation in the development of smart IoT devices by involving smart sensors (GesIC), and also a landslide physics approach. The research results obtained are smart IoT device products that detect and monitor landslides in real time so that slope landslides can be detected at a critical threshold angle of 32.5□ on September 29, 2025 at 13:11:55 EIT, with a soil temperature of 30.8 □C, soil moisture of 23.2%, soil conductivity of 29.0 □S/cm, and rainfall of 215 mm. Then, a subsequent landslide occurred on October 7, 2025, with a threshold angle of 32.5□ at 12:43:00 EIT, and a soil temperature of 26.8 □C, soil moisture of 21.0%, soil conductivity of 17.0 mS/cm, and rainfall of 203 mm. The estimated maximum speed of the landslide run was 20.4 m/s with a maximum landslide range of 2.24 seconds at a slope angle of 85.0□. Meanwhile, for a slope angle of 41.2□, the maximum landslide speed is 7.3 m/s with a maximum landslide reach time of 17.9 seconds. These findings reveal that climate change can intensify landslide disasters during the rainy season. Therefore, a strategy is needed to design an adaptive landslide monitoring system, including increasing communication network capacity and optimizing an IoT-based EWS to be developed in the Maluku Islands region.

Keywords: landslide, slope failures, thresholds, IoT, cloud communications

INTRODUCTION

The Ambon Island region is frequently hit by landslides on slopes, hills, and roads experiencing subsidence/collapse, because when it rains, water causes the soil load to increase and the slope's covering soil becomes saturated. Landslides that occur on Ambon Island cause very severe damage every year, including rock falls, debris flows, rotational slides, slide translations, jars, and falls (Souisa et al., 2015; Souisa et al., 2016; Souisa, 2018; Souisa et al., 2018; Souisa et al., 2019; Souisa et al., 2020; Souisa et al., 2023). Areas frequently experiencing landslides during the rainy season include Sirimau District, Nusaniwe District, and Teluk Ambon District (Souisa, 2018 and Souisa et al., 2023). The occurrence of slope landslides usually occurs naturally, and no one knows when it will occur (Souisa, 2018; Souisa et al., 2018; Souisa et al., 2019); therefore, in this study, a more controlled direct approach was carried out to observe the mechanism of landslide disasters so that mitigation efforts can be carried out.Landslide disasters can be avoided if the public is aware of the signs of landslides and receives early warning of their occurrence. Consequently, early detection tools for landslides that can be monitored in real time are needed to save lives and property (Wu et al., 2020 and Bhardwaj, 2021). Current landslide monitoring methods and techniques still have many limitations and are not yet appropriate (Zohari et al., 2024). Therefore, various landslide early warning system (LEWS) designs need to be built and distributed throughout areas prone to landslides (Teuku, 2015), as a direct implementation of the SGDs program. According to Gamperl et al. (2021), LEWS is an effective measure to reduce disaster risks quickly and to long-term disaster risk mitigation measures. The LEWS designed by researchers uses a Geo-sensor Interfacing Circuit (GsIC) network and ESP32, which will transmit data through a cloud communication network (Gubbi et al., 2013; Dhobi et al., 2017; Farikha et al., 2020; Elavarasi and Nandhini, 2021; Idris et al., 2022; Thirugnanam et al., 2022). ESP32 is a microcontroller that has the advantages of high resolution, smaller size, and lower price (Maier et al., 2017; Pratama and Kiswantoro, 2023). With the help of cloud computing and other similar technologies, IoT devices can communicate collaboratively to perform specific tasks either through human interaction or independently by their own machines (Sharma and Wang, 2017; Puspitawati et al., 2021). The use of IoT technology is expanding across various sectors such as the construction sector, energy, industry, transportation, health, security, technology and networks, smart homes, smart cities, and so on (Susanto et al., 2022; Khanna and Sharma, 2019; Stolojescu-Crisan et al., 2021).

Determining the level of slope landslide disasters is currently still not fast and accurate, so technology is needed to support intelligent decision-making. To synergize research with industry, LEWS innovation is needed, namely through the development of IoT integration with cloud communications. This device lies in the integration of IoT GsIC installed on the surface of landslide-prone and former landslide areas using local calibration (such as landslide history), a connectivity implementation strategy for island conditions using orbit and solar energy, and an operational workflow that connects community-level warnings and automated decision rules for rapid disaster mitigation. When the slope cover begins to collapse at a threshold angle value, the IoT protocol provides a warning signal via serine, or smartphones/laptops, as a disaster risk reduction mitigation effort.

MATERIALS AND METHODS

The research was conducted in Tawiri Village, Teluk Ambon District, Maluku. To conduct the research, there are three stages, namely system design, data acquisition, and analysis of research data outlined in mixed research methods (Figure 1), including: i) Step 1 and step 2, Laboratory Experiment carried out IoT device design work with internet networks, solar panel platform design, IoT device calibration, IoT technology integration and cloud communication tests; ii) Step 3, Field Research carried out the installation of all GsIC devices on slopes that are prone to landslides and former landslides, as well as data acquisition; and (iii) Step 4, Computing laboratory carried out field data analysis to identify the physical conditions of landslides, and derive a physical landslide model to explain the speed and distance mechanisms of landslide flight, and verify the model with local geological conditions. In determining the speed and time of landslide runaway, a lumped mass model is used (Hungr et al., 2005; Yang et al., 2014; Souisa et al., 2018) with the assumption that the landslide mass is viewed as a rigid sliding mass block (Souisa, 2018; Souisa et al., 2018).

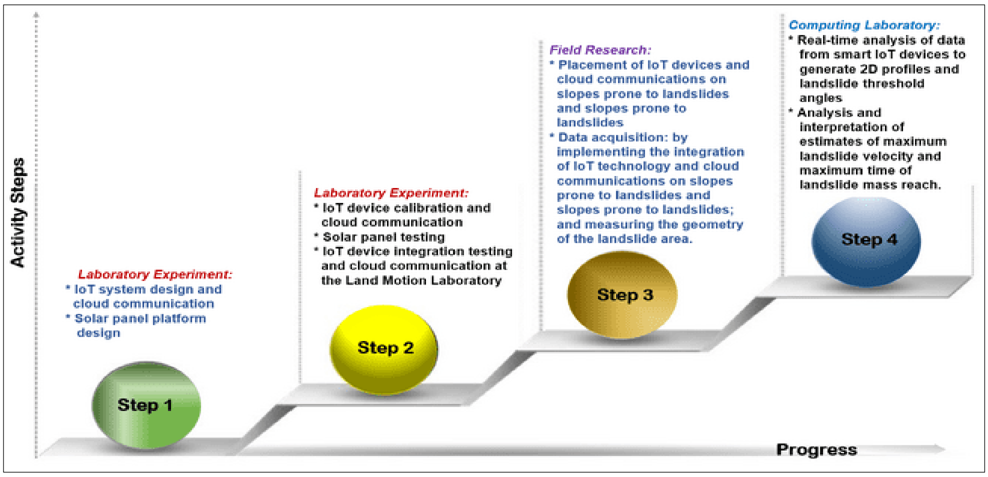

Figure 1. Research activity stages

The results of the solar panel platform device design are used to channel electrical energy to IoT devices. After the solar panel and IoT systems are integrated and connected to the cloud communications network (Figure 2), the GsIC is calibrated. The next step is to install the IoT system in areas prone to landslides.

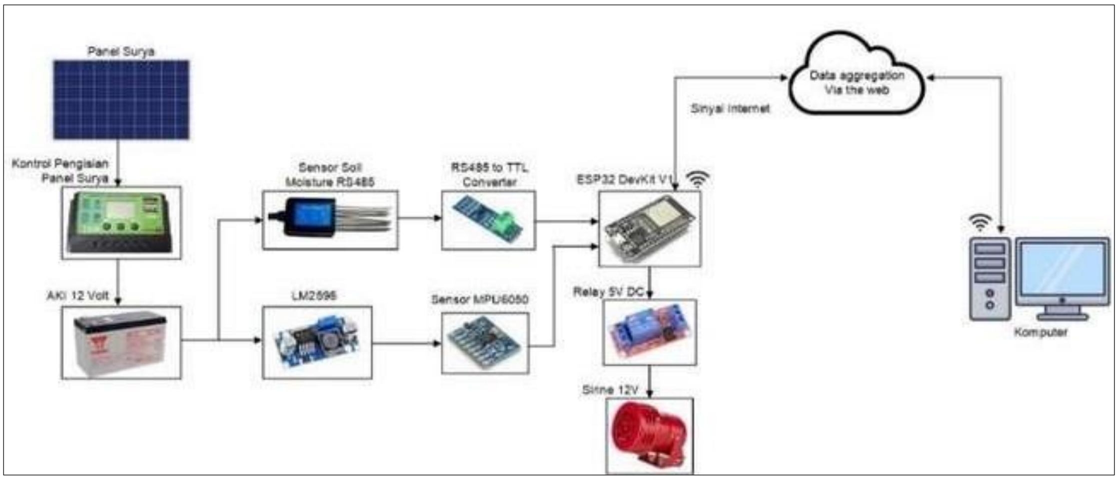

Figure 2. Integration diagram of IoT technology sent via cloud communication and received by a laptop or smartphone.

The solar panel and IoT system integrated with the cloud communication network is installed on the slope crown (Figure 3), and GsIC (slope angle, temperature, humidity, conductivity, and rainfall) is planted in the middle of the slope area so that it can detect and monitor the movement of the slope cover soil until the threshold angle, then the early warning sign via siren sounds automatically.

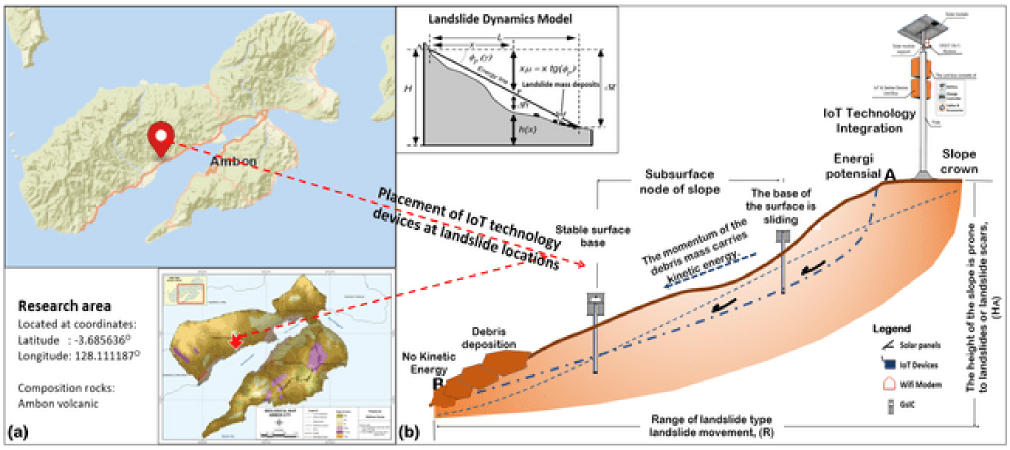

Figure 3. (a) Map of the research area, (b) Schematic of the installation of solar panels and IoT systems connected to the cloud communication network.

RESULTS AND DISCUSSION

Working of Data Acquisition System with IoT Technology

Based on the process of soil material movement on the slope, the IoT system sends GsIC data via cloud communication, and this data is received by laptops and smartphones in real time at a time duration of (14.0 – 15.0) seconds in the form of angle versus time graphs, and THCR versus time. GsIC (T, H, C, pH) and slope geosensors were installed in the middle of the slope in a flat position (0.0 degrees) as shown in Figure 3 below. These instruments began operating from September 6, 2025, to October 7, 2025, to detect and monitor ground motion in real time during the onset of rain and heat (Figure 4).

On September 29, 2025, when the landslide threshold angle was 32.5 degrees, the serine automatically sounded at 13:11:55 EIT, and the slope cover soil was destroyed nd moved to slide down the slope (Figure 4). Conditions where the landslide threshold angle is 32.5 degrees, detected soil temperature of 30.8 oC, soil moisture of 23.2%, soil conductivity of 29.0 mS/cm, and rainfall of 215 mm. Then, on October 7, 2025, a subsequent landslide occurred with a threshold angle of 32.5 degrees, and this threshold angle automatically sounded at 12:43:00 EIT (Figure 4). At this threshold angle, the detected soil temperature was 26.8 °C, soil

moisture was 21.0%, soil conductivity was 17.0 □S/cm, and raifall was 203 mm. Thus, the slope landslide threshold detected through the IoT system is the same as the realistic conditions that occur on the slope (Manuhutu et al, 2024). The designed IoT-based real-time landslide method is very accurate and can be disseminated to communities living in areas prone to landslide disasters, as stated by Wu et al (2020)..

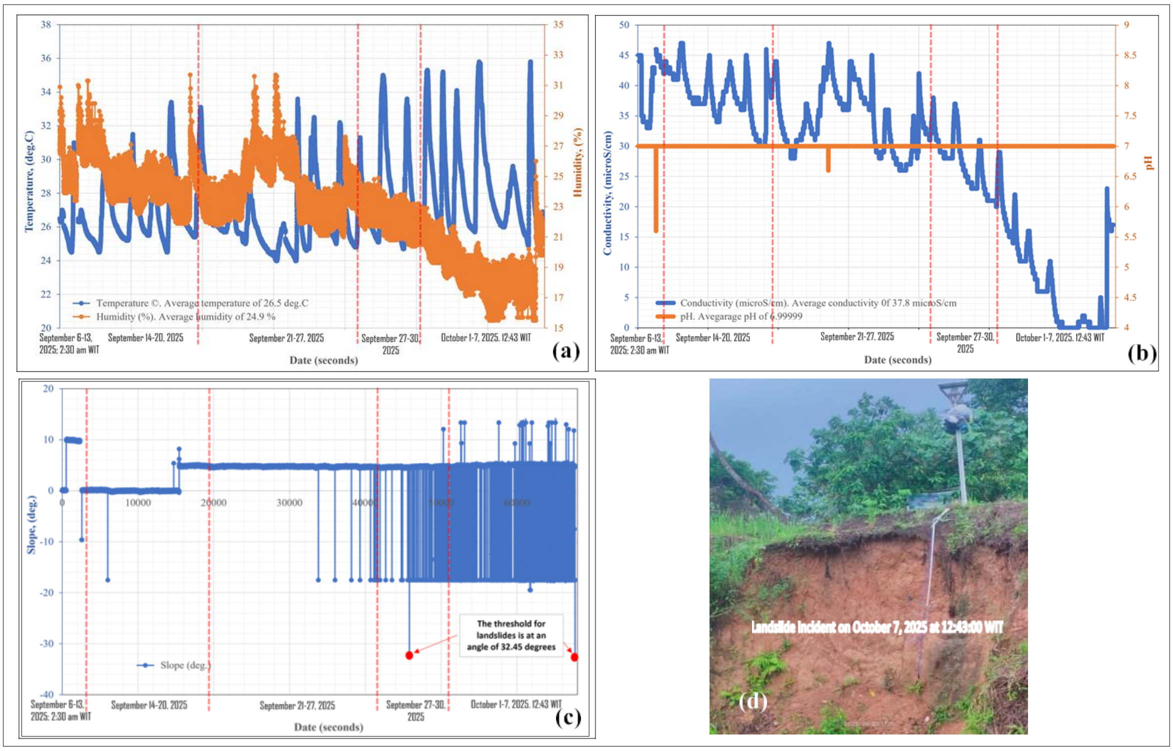

Figure 4. (a) Graph of the relationship between temperature and humidity variables against time from September 6 to October 7, 2025, (b) Graph of the relationship between conductivity and rainfall variables against time from September 6 to October 7, 2025, (c) Graph of the relationship between geosensor slope variables against time from September 6 to October 7, 2025, and (d) Location of the landslide type landslide incident in RT.02/RW.07 Riang Negeri Tawiri, Teluk Ambon District on October 7, 2025 at 12:43 WIT.

Calculation of Landslide Speed and Time

The calculation of maximum velocity and landslide run time is obtained from the geometric parameters of the landslide plane, landslide range, gravitational acceleration, friction coefficient, and internal friction angle.

Geometry of the Landslide Slope Plane

Once a landslide has occurred, the geometry of the landslide surface is redesigned (Figure 5). The soft soil lithology, which constitutes the landslide layer, is thought to consist of low- to medium-cohesion sediments, soft clay, water-saturated sandy clay, and unconsolidated sandy clay. This soft soil layer is loose, so the slope area of this layer will become landslide material. With the presence of low-cohesion soil, water can penetrate to the impermeable soil that acts as a slip plane. If the soil has low cohesion, water can penetrate to the impermeable soil, which acts as a slip plane, the soil becomes slippery, and the soft soil above it, which acts as landslide material, will move along the slope due to the force of gravity and also the high rainfall factor in the research area, which occurred from April to October 2025.

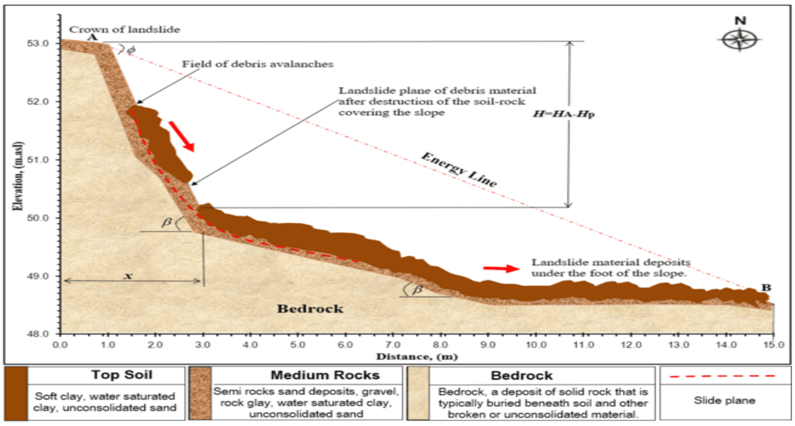

Figure 5. Interpretation of the redesign of the geometry of the landslide plane with a slope of 7.2° – 85.0°.

Calculation of the Maximum Velocity and Time of a Landslide

The displaced slope cover material moves along the landslide plane, generally due to the Earth's gravitational pull and the component of gravity parallel to the slope surface. Rainwater infiltrates the soil and rock due to heavy rainfall over a prolonged period, preventing water from flowing onto the surface and instead entering the surface layer of the soil and rock. The calculation of the landslide velocity and time is based on slope angles $\beta = 85.0°$ and $\beta = 41.2°$.

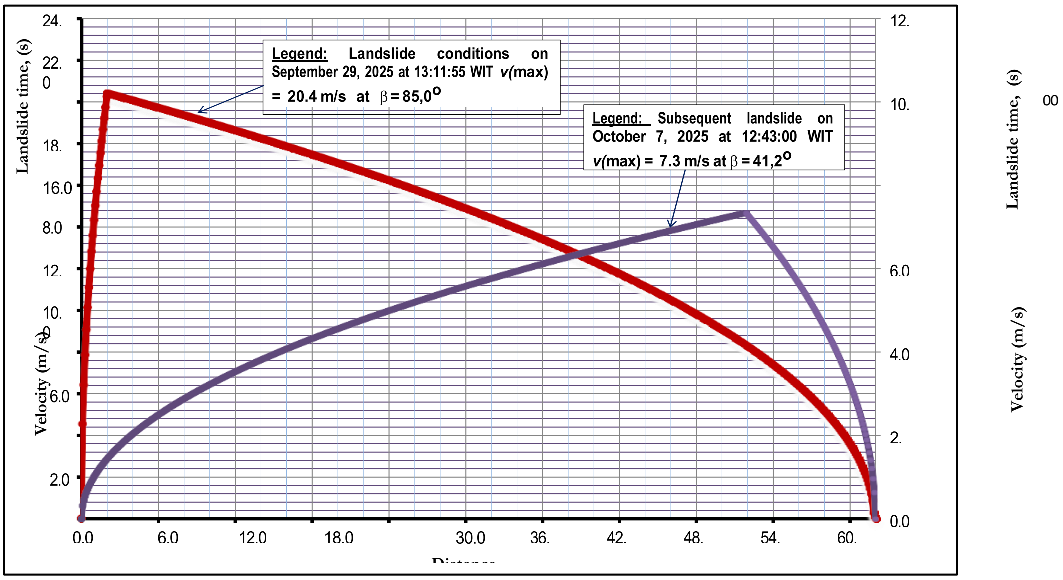

Figure 6. Slope landslide velocity as a function of distance under dry conditions for landslide scars

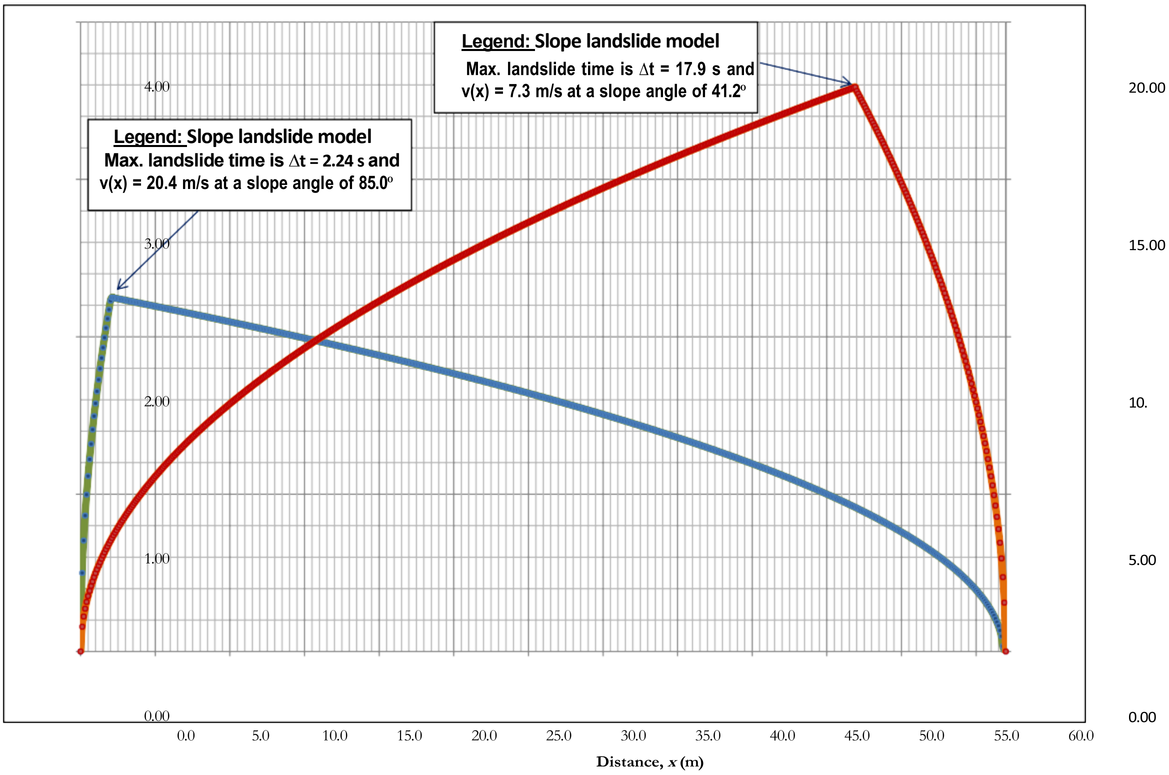

Figure 7. Landslide reach time as a function of distance under dry conditions for landslide scars

Based on the results of this analysis, a $v(x)$ graph can be drawn as shown in Figure 6, and the landslide reach time (□ t) as a function of x as in Figure 7. The infographic shows that at the slope break at $x = 4.5$ m and a height of 49.8 meters above sea level for $\beta = 85.0°$, the maximum landslide speed is 20.4 m/s, and the maximum landslide reach time is 2.24 s. Meanwhile, for $\beta = 41.2°$ at $x = 8.5$ m and a height of 47.1 meters above sea level, the maximum speed at the slope break is 7.3 m/s, and the maximum landslide reach time is 17.9 s.

Three-Dimensional (3D) Profiles of Landslide Velocity, Distance and Time Range

The 3D cross-section profile (Figure 8, 9) it shows that landslides have occurred and are caused by decreasing surface cohesion, decreasing soil density, a friction coefficient of 0.82, and increasing porosity at slopes of 85.0° and 41.2°. The factors causing landslides are due to landslide physics parameters such as cohesion, porosity, and apparent friction angle (□) or decreasing friction coefficient (□), or in other words, the slope retaining force decreases because the soil-rock covering the slope is saturated with water, so the soil- rock material covering the slope becomes heavier, or the driving force is large. So if the retaining force is smaller than the driving force, the slope is in an unstable state, and a rotational landslide-type movement occurs.

The research site was originally used as agricultural land planted with short-rooted (fibrous) plants such as sweet potatoes and shrubs. This resulted in decreased soil cohesiveness at the roots, resulting in low- to moderate-cohesive soil deposits. Soft clay, water-saturated sandy loam, and unconsolidated soil are easily eroded downward. Human activity, including land conversion in this area, is a factor that increases the risk of landslides.

The top of Figures 8 and 9 shows a variogram versus distance. A variogram is a useful tool in geostatistics for demonstrating spatial correlations between measured data. This figure illustrates that low landslide velocity values are close to low landslide reach times. Likewise, high runaway velocity values tend to be close to low landslide reach times. These differences can be expressed in a variogram graph as a function of distance.

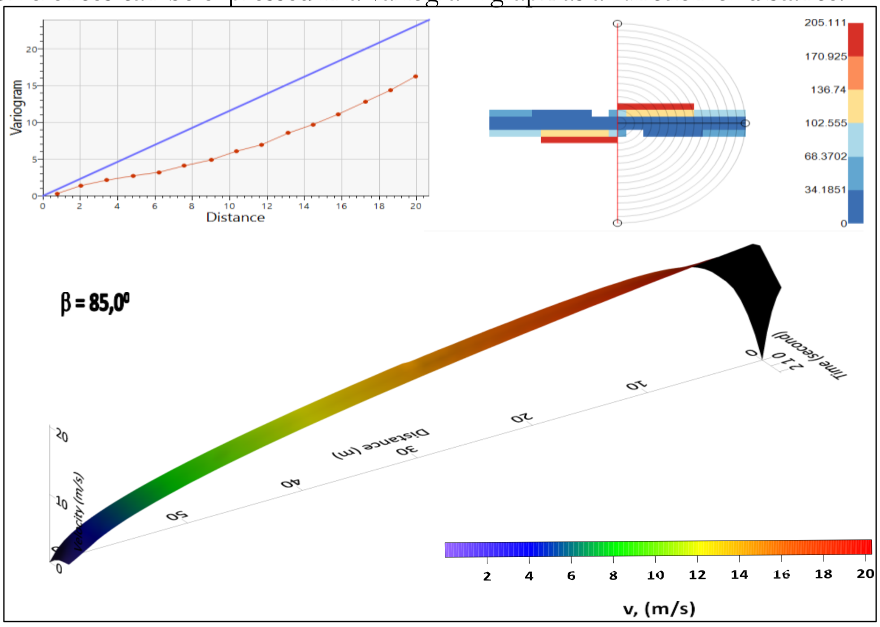

Figure 8. Time profile of landslide reach as a function of slope, landslide speed, and distance at a slope angle of 85.0□ .

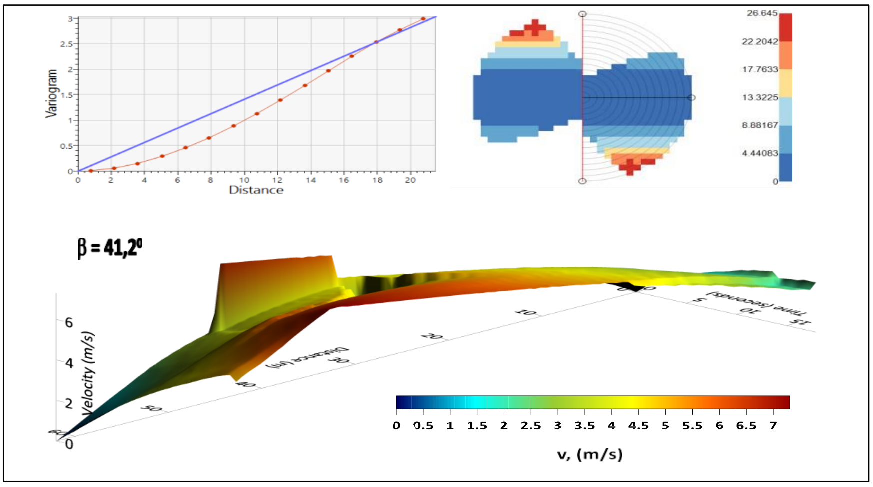

Figure 9. Time profile of landslide reach as a function of speed and distance of landslide reach on a landslide slope angle of 41.2□ .

Based on Figures 8 and 9, the bottom shows the relationship between landslide run speed and landslide reach time to landslide reach distance. At a threshold angle of 32.5°, the slope is in a critical condition, and the debris material covering the slope (soil, rocks, sediment, grass) moves and settles under the foot of the slope. The results of the calculation of the estimated maximum landslide run speed at a slope angle of 85.0° and an altitude of 49.8 masl are 20.4 m/s, with a maximum landslide reach time of 2.24 seconds (Figure 8).

Meanwhile, for a slope angle of 41.2 degrees and a height of 47.1 masl, the maximum speed of landslide run is 7.3 m/s in a maximum landslide reach time of 17.9 seconds (Figure 9). As a result, the triggering factors for this slope landslide are high rainfall, reduced surface cohesion, reduced friction coefficient (0.82), and increased porosity. Or the slope retaining force decreases because the soil and rock covering the slope are saturated with water, so the soil and rock material covering the slope becomes heavier, or the driving force is large. Therefore, if the retaining force is smaller than the driving force, the slope will be unstable and a landslide will occur.

Thus, through the integration of IoT technology with cloud communication networks, it is possible to detect and monitor landslide thresholds for slope landslide disaster mitigation efforts. Slope strengthening efforts to increase the slope retaining force so that the slope is stable, it is necessary to take several preventive steps (Souisa et al., 2023 and Souisa et al., 2025) including: (i) Increasing the slope retaining force at the research location where landslides have occurred by slope engineering where the slope is made terraced and the top of the terrace is planted with vetiver grass (bioengineering), and (ii) Slope prevention with vetiver grass increases the cohesiveness and density of the soil, and reduces pore water pressure through increased infiltration, reduced saturation, and as a bio-protection layer that strengthens the soil's resistance to lateral pressure and shear forces.

CONCLUSIONS

A slope landslide threshold detection and monitoring system using IoT technology has been designed. This technology was applied to a landslide-prone location on Ambon Island. Based on the research results, the landslide threshold was found to be at an angle of 32.5°, both for the main landslide on September 29, 2025, and the subsequent landslide on October 7, 2025. At this threshold angle, the slope's overburden was destroyed and moved along the slope until it was deposited beneath the toe.

The development of IoT technology integration through cloud communication networks can transmit data information in real time to create highly accurate and timely early warnings of landslides in locations prone to landslides. Smart IoT devices can be portable and permanent to detect and monitor slope landslide thresholds for smart communities via smartphones, due to their high sensitivity, relatively short information delivery and analysis times, low cost, and environmental friendliness. This product can also be applied for landslide disaster prevention and mitigation in areas of Indonesia prone to landslides.

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