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RAINFALL-INDUCED LANDSLIDE RISK MITIGATION - DEVELOPMENT AND TESTING OF AN INTEGRATED EARLY WARNING SYSTEM -

Muhammad Nurjati Hidayat

Department of Civil Engineering, Kyushu University, Japan. E-mail: hidayat.muhammad.606@s.kyushu-u.ac.jp

Hemanta Hazarika

Department of Civil Engineering, Kyushu University, Japan. E-mail: hazarika@civil.kyushu-u.ac.jp

Haruichi Kanaya

Department of Electronics, Kyushu University, Japan. E-mail: kanaya@ed.kyushu-u.ac.jp

Masanori Murai

Geotechnical Engineering Department, Shimizu Corporation, Japan. E-mail: m.murai@shimz.co.jp

Tatsuya Kouno

Department of Civil Engineering, Kyushu University, Japan. E-mail: kouno.tatsuya.404@s.kyushu-u.ac.jp

Landslides often occur without warning, making it challenging to implement timely evacuation and mitigation measures. Therefore, development of real-time early warning systems is crucial for reducing the risks associated with rainfall-induced landslides. This study aims to evaluate the effectiveness of a cost-effective landslide early warning system using internet networks. The system is designed with moisture sensors, acceleration sensors, and pore water pressure sensors, which provide comprehensive monitoring of slope conditions. Slope model tests were conducted using silica sand number seven with a 45° slope angle, under simulated rainfall intensities of 45 mm/h and 70 mm/h. The tests demonstrated that landslide initiation typically began with layered vertical collapses along the surface of the slope, originating at the slope toe and progressively accumulating beneath the failure point. As rainfall continued, both water content and pore water pressure within the soil increased, indicating that the slope was approaching an unstable condition. Once instability occurred, the acceleration sensors recorded slope deformations.

Keywords: Landslide, early warning system, rainfall, internet of things, slope, monitoring, model test.

1. Introduction

Frequent and intense torrential rainfall-induced disaster such as landslides claim numerous lives and cause significant damage to infrastructure and properties. These events often occur without warning, making timely evacuation and mitigation measureschallenging. Climate change is exacerbating this issue by altering rainfall patterns, leading to an increase in the frequency and severity of extreme rainfall events(Myhre et al., 2019).Increased rainfall intensity contributes to soil saturation, which can resultin erosion and slope failure. Case studies show that high precipitation events have directly resulted in landslides and infrastructure damage, particularly in vulnerable regions(Gall et al., 2024). Therefore, development of real-time early warning systems is crucial for reducing the risks associated with rainfall-induced landslides. Existing landslide early warning systems (LEWS) tend to depend on costly geotechnical instrumentation or complicated modelling methodologies, making them unsuitable for widespread deployment. Furthermore, some systems are unable to monitor in real-time, limiting their effectiveness in real-time hazard mitigation. This study addresses these limitations by developing a cost-effective, real-time monitoring system that leverages internet of things (IoT) technology using internet networks under controlled rainfall conditions in a laboratory setting.

2. Materials and Methods

2.1. *Experiment material*

This study was using commercial silica sand grade seven (K7 sand) as it is frequently utilized in slope model experiments to examine the failure mechanisms associated with rainfall-induced landslides. Soil analysis was conducted based on Japanese Geotechnical Society (JGS) standard, and shown in Table 1. The average particle mean grain size is 0.17 mm.

Table 1. Soil properties of K7 sand.

Parameter	$Á_t$ (g/cm^3)	$Á_d$ (g/cm^3)	$Á_{d\ max}$ (g/cm^3)	$Á_{d\ min}$ (g/cm^3)	e
Value	1.51	1.4	1.6	1.19	0.87

$Á_t$ - density of soil; $Á_d$ - dry density of soil; $Á_{d\ max}$– max. dry density of soil; $Á_{d\ min}$– min. dry density of soil; e - void ratio

2.2. *Slope model and sensor configuration*

Two series of slope model tests were built in a flume tank with slope dimension of 80 cm in length, 40 cm in width, and 45 cm in height. The slope angle was set to 45° and the initial water content was set to 10%. This slope angle was selected because it provides a reasonable balance between stability and potential of failure, enabling for simulation of real-world settings. The slope model was built by compacting soil layers and embedded the sensors according to model design (Fig. 1). Three types of sensors are used: moisture sensor, pore water pressure sensor, and acceleration sensor (Fig. 2). Moisture sensors were used to measure soil moisture contents by detecting capacitive changes on the sensor surface. Low-power consumption acceleration sensorswere used to measure soil deformation. Both the moisture and acceleration sensors were connected to microcontroller units (IoT boards), which transmitted the data to a server. Pore water pressure sensors, connected to a data logger, were used to measure the pore water pressure in the soil.

A rainfall simulator, which produced controlled rainfall, was attached to a flume tank at a height of 48 cm above the slope model. Artificial rainfall with intensities of 45 and 70 mm/h was evenly distributed through nine nozzles to simulate a variety of typical rainfall situation that might cause slope instability, allowing for the assessment of slope behavior under different precipitation scenarios.In addition, two sets of raspberry-pi cameras were used to capture the images of the slope model from front and side views.

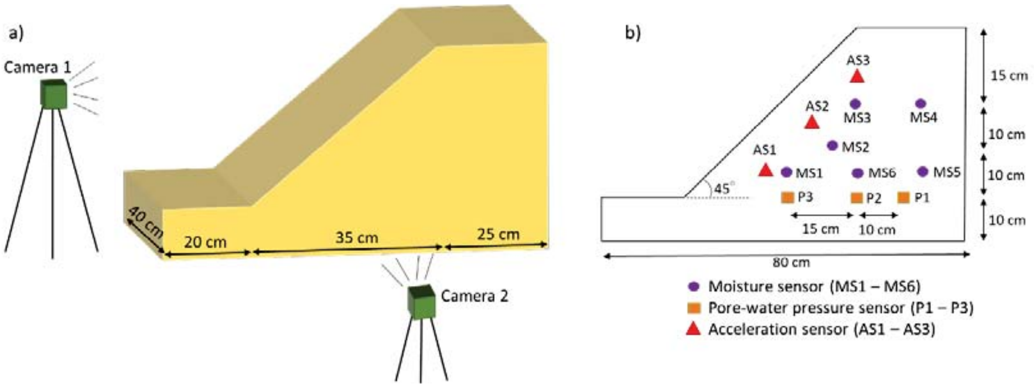

Fig. 1. Slope model illustration: a) 3D view of slope model and camera position, and b) sensor layout

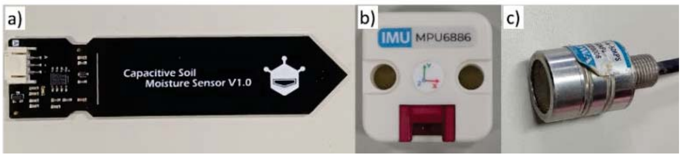

Fig. 2. Sensors used: a) moisture sensor, b) acceleration sensor, c) pore water pressure sensor

3. Results and Discussions

3.1. *Sensors monitoring results*

Monitoring results of slope model tests are shown in Fig. 3. The model tests began by activating the rainfall simulator according to the specified rainfall intensity. In both model tests, soil moisture sensors MS1-MS4 detected a quicker rise in moisture content than the other moisture sensors, as they were positioned near the soil surface. MS5 and MS6 were the last to detect the increase in moisture content due to their deeper placement. Rainwater infiltrates the soil and accumulates at the bottom, resulting in the formation of pore water pressure. Sensors P1-P3 detected this pressure, with P3, placed at the base near the slope toe, responding first to the pore water pressure increase. As the soil becomes saturated, the pore water pressure increases while the shear strength decreases. When the shear strength of the soil is insufficient to resist the gravitational forces acting on the slope, instability occurs, and deformation is detected by the acceleration sensor. The first landslide was recorded when the tilt angle exceeded 0.01° for the model test with a rainfall intensity of 45 mm/h and 0.56° for the model test with a rainfall intensity of 70 mm/h. The small value of deflection angle recorded during the first landslide in the model test with a rainfall intensity of 45 mm/h was due to the acceleration sensor being disconnected before the landslide occurred, resulting in a loss of data and the inability to record the slope angle before the landslide.

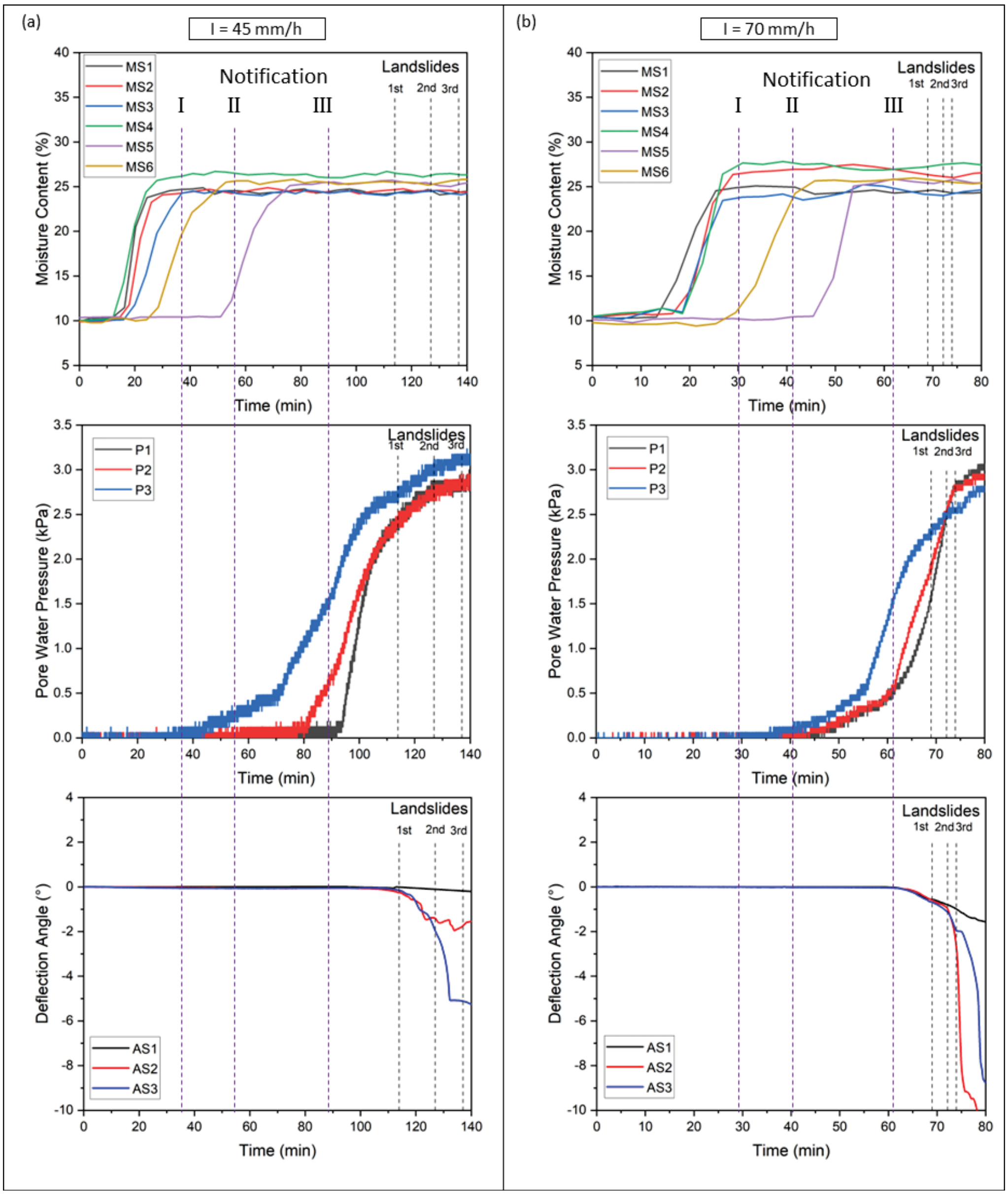

Fig. 3. Sensors monitoring results: a) rainfall intensity of 45 mm/h, b) rainfall intensity of 70 mm/h

3.2. *Early warning procedures*

Among the moisture sensors, pore water pressure sensors and acceleration sensors used, the order in detecting subsurface changes begins with an increase in moisture content, followed by a rise in pore water pressure, and then an increase in the deformation angle. Based on these findings, the proposed early warning protocol consisting of three stages: (1) an initial alert when the surface soil moisture content reaches saturation or a stable reading, (2) a warning notification when the pore water pressure begins to rise, and (3) a final alert when the pore water pressure exceeds 1.5 kPa. Given the time intervals observed between the third notification/alert and slope failure, evacuation should be completed within 25 minutes for rainfall intensity of 45 mm/h and within 16 minutes for a rainfall intensity of 70 mm/h to ensure safety.Uncertainties in the experimental results may arise from sensor accuracy, variations in soil compaction, and temperature. These variables can influence the experiment results and timing of early warning notifications, potentially leading to variations in the estimated evacuation time.

3.3. *Slope deformation and failure characteristics*

Under rainfall intensity of 45 mm/h at 103 min, a transverse crack developed on the right side of the slope toe (Fig. 4a). Wider and more significant transverse crack developed two minutes after and forming a deposit at slope toe. After 105 min, the cracks continue extended upwards forming more cracks as the rainfall keeps continue over time. There were eight transverse cracks observed during the test and the deposit accumulates at the base platform spread towards the slope toe. In comparison to model test with rainfall intensity of 45 mm/h, the test with rainfall intensity of 70 mm/h had fewer cracks (Fig. 4b). With total of five observed cracks, they are combination of transverse and diagonal cracks. Under heavier rainfall, the rapid rise in pore water pressures sharply reduces effective stress and soil shear strength, which accelerates the slope failure, resulting in a massive landslide. The intense rainfall not only triggers the landslide but also leads to larger volumes of displaced material, a more extensive main scarp, and a broader zone of accumulation(Xu et al., 2022).

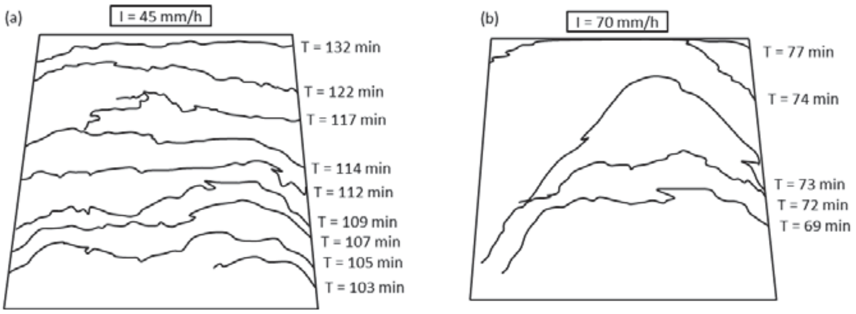

Fig. 4. Characteristic of slope failure over time: a) rainfall intensity of 45 mm/h, b) rainfall intensity of 70 mm/h

4. Conclusions

This study evaluates the effectiveness of a landslide early warning system (LEWS) using internet networksunder controlled rainfall conditions in a laboratory setting. Based on the monitoring and data analysis from moisture sensors, pore water pressure sensors, and acceleration sensors, the conclusions are as follows:

1. An LEWS consisting of cost-effective sensors can be utilized in mitigating rainfall-triggered landslides, as the system can send a final warning notification before the landslide occurs.
2. Moisture sensor and pore water pressure sensor are critical components for monitoring slope conditions, while the acceleration sensor is used to detect slope failure. The time difference between the initial slope failure and the final warning the from pore water pressure sensor data represents the evacuation time.
3. Lower rainfall intensities result in the development of more transverse cracks, while higher rainfall intensitieslead to fewer cracks but increase the likelihood of rapid and large-scale landslides, with greater volumes of displaced material.

Acknowledgments

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