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Monitoring of Landslides in Mountainous Regions Based on FEM Modelling and Rain Gauge Measurements

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ABSTRACT

Vietnam is a country heavily influenced by climate change. The effect of climate change leads to a series of dangerous phenomena, such as landslides. Landslides occur not only in the mountainous province, but also in Delta provinces, where hundreds of landslides are reported annually in the North-Western provinces of Vietnam. These events have catastrophic impact to the community as well as the economy. In mountainous areas, the conditions for landslides to occur are met frequently, especially after heavy rains or geological activity, causing harm to the community as well as damaging or destroying much needed infrastructure and key transport routes. However, in Vietnam, investment in mountainous regions has been often lower than in urban areas. The meteorology monitoring and forecasting systems are ill equipped and overloaded, so they cannot deliver earlier and more accurate forecasts for complex weather events, unable to provide timely warnings. It can be seen that in countries that landslide often occur, researchers have been trying to develop low cost and efficient landslide detection system. This paper precisely addressed the problems mentioned, by designing and implementing an efficient and reliable Landslide Monitoring and Early Warning (LMnE) system based on the 3G/2G mobile communication system, and a rain gauge at the field site along with a carefully FEM (finite element method) simulation using the rain density information on the server. The system uses advanced processing algorithms combining obtained data at the central station.

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1. INTRODUCTION

Landslide is one of the most disasters happening around the world. This disaster has catastrophic impact to the community as well as the economy [1]. Landslide occurs by the fallen movements of rock, soil, and organic materials under the gravity force. There are four groups that lead to this hazard: rainfall induced landslides, earthquake induced landslides, endogenetic landslides, and pre-existing landslides. Among of these groups, it is about 90% of landslides is triggered by rainfall. In mountainous areas, the conditions for landslides to occur are met frequently, especially after heavy rains or geological activity, causing harm to the community as well as damaging or destroying much needed infrastructure and key transport routes. We intend to implement a real-time landslide monitoring in Vietnam, where the annual damage due to the landslide is very high [2]. For the technology aspect, wireless sensor network (WSN) is the most applicable in these areas (i.e. difficult to access, and real-time requirement) [3]-[5]. In [3], a complete functional system consisting of 50 geological sensors and 20 wireless sensor nodes was deployed in Idukki, a district in the southwestern region of Kerala State, India, a highly landslide prone area. It can be seen that this kind of system costs a lot of money and thus, it is difficult to applied popularly. In [4], the authors use the slip surface localization method for detecting landslide. Their proposed network uses devices to detect the slope movements and then estimate the displacements of sensor nodes embedded in the slope. Similar to [3], it costs a lot of money and thus, it is difficult to applied popularly. In [5], they only proposed wireless accelerometer network to detect the landslide. Although it is a low-cost solution but it can only detect landslide but can not predict the rainfall induced landslide. In [6], the saturated hydraulic conductivity is considered as a random field and once coupled with Monte-Carlo simulations, it is possible to determine the failure probability and then deduce the landslide risk. In [7], author also investigate the in filtration of rainwater into slopes and thus the dependence of slope stability on the water in ltration. However, these simulations in [6],[7] are not robust enough to model arbitrary shape of natural slopes.

In this paper, an efficient and reliable Landslide Monitoring and Early Warning (LMnE) system is developed to remotely monitor and automate the warning about the possibilities of the landslide. This is a low-cost solution when a rain gauge can be used to provide the rain intensity and accumulation. This information is pre-processed by using a microcontroller, and then transmitted to the server through the 3G/2G mobile communication protocol. The rain data are brought into a designed FEM model in GEO-SLOPE to evaluate the factor of safety. This information is compared with the determined thresholds in order to make an alert about the possibilities of the landslide. The monitored data can be observed by the designed website and the alert message can be received by both feature and smart phones.

2. RESEARCH METHOD

2.1. Rain induced landslide

The main trigger of landslides is heavy or prolonged rainfall [6],[7]. Figure 1 illustrate of a slope that is under the risk of landslide. The slope can be divided into two regions which are safe and potential slide areas. Therefore, our WSN is designed based on two areas. The sensing and transmitting modules are placed in the potential slide area, and the storing module and the rain gauge are placed in the safe area.

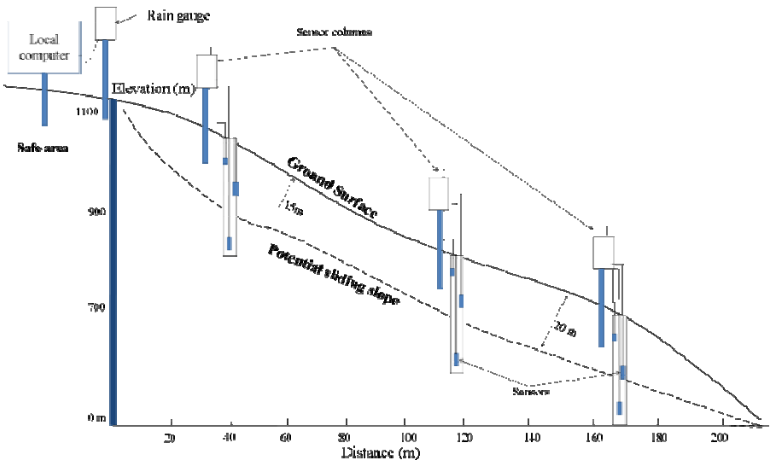

Figure 1. Illustration of a slope that is under the risk of landslide

2.2. Modeling the rain induced landslide using finite element method

There are two kinds of shear stresses existed in a slope: one that hold the slope and one that split the slope down (see Figure 2). The shear strength Fs (i.e. holding stress) is determined by the normal stress FN and the cohesion. The shear stress (i.e. down-sloping stress) is determined by the angle of the slope ɵ and the weight of the potential material. The ratio of shear strength to shear stress is called the factor of safety (FS). When this ratio is greater than 1, shear strength is greater than shear stress and the slope is considered stable. When this ratio is close to 1, shear strength is nearly equal to shear stress and the slope is unstable (i.e. the landslide would occur) [8]. Note that hill slopes (e.g. the safe region in Figure 1) are more stable than the others.

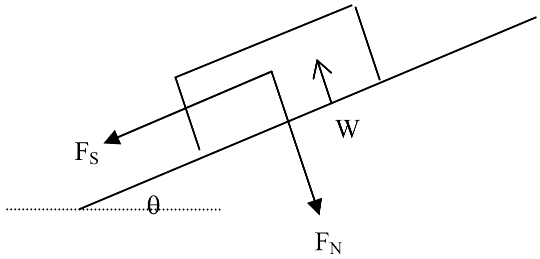

Figure 2. Illustration of the slope stability using Factor of Safety (FS), where W is height of water table

Slopes would be weakened by several reasons such as the deforestation, the weathering, and the undercutting by river flow, waves, or human activities. However, the most important trigger for a landslide is the rainfall. When it rains, the water infiltrates into the ground. The infiltration process has happened faster than the drain process. Thus, the pore spaces in the slope are filled with water. It leads to a hydraulic uplift force that reduces the balance that we have mentioned previously. Obviously, the prediction or the measurement of rainfall on an actual slope is very important to determine the probability of the landslide.

The mass conservation equation in a form extended to unsaturated conditions is

$$\frac{\partial}{\partial x}(k_x \frac{\partial H}{\partial x}) + \frac{\partial}{\partial y}(k_y \frac{\partial H}{\partial y}) + Q = m_w \gamma_m \frac{\partial (H-y)}{\partial t} \tag{1}$$

where H is total head (m), k_x is the coefficient of permeability with respect to the water phase in the x-direction (m/s), k_y is the coefficient of permeability with respect to the water phase in the y-direction (m/s), Q is the boundary flux passing in or out of an elementary cube (in this case an elementary square, given that the equation is in two-dimensions) (m^2/m^2s), m_w is the specific water capacity, γ_m is the unit weight of water, and t is time (s). The boundary conditions for the water-head and the flux are needed to solve this equation [9]. Furthermore, the initial condition of the water head distribution is also need to solve this equation. Positive and negative pore water pressure distributions obtained by the seepage analysis SEEP/W [10] are then used as input data for the stability analysis (i.e. the determination of FS). The equation for the factor of safety is

$$FS = \frac{Shear\ Strength}{Shear\ Stress} = \frac{c + (\rho g H \cos\theta - \rho_w g\ W)\tan\varphi}{\rho g H \sin\theta} \tag{2}$$

where c is cohesion, ρ is density of regolith, g is gravity acceleration, ρ_w is density of water, and ϕ is angle of internal friction. This computation is performed using the SLOPE/W. Note that, both SEEP/W and SLOPE/W problems were solved by the finite element method (FEM). Figure 3 illustrates of a meshed model of a potential slide slope in GEO-SLOPE.

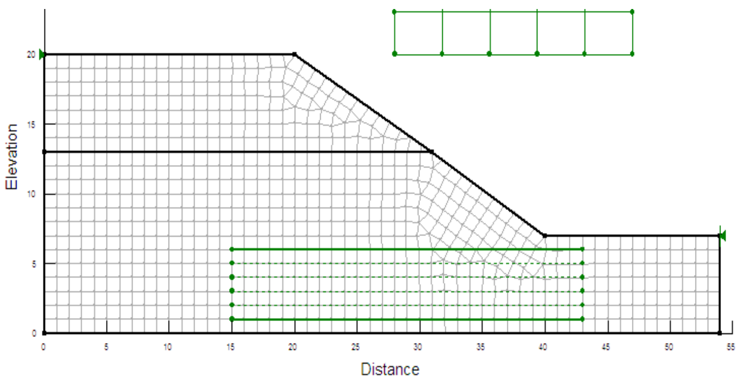

Figure 3. Meshing of a 2D hydrogeological conceptual model that consist of two different layers

3. PROPOSED SYSTEM

3.1. Integration system and its working principle

Figure 4 shows the diagram of the proposed system applied for a potential slide slope. After a field investigation, a real model of the slope is built for SEEP/W and SLOPE/W simulation. Multiple scenarios are run with different value of rain intensities. It will help us to determine the threshold of rain intensities that lead to landslide. However, in real application, the rain intensity may be changed due to time. Thus, a prediction and monitoring are proposed as follows:

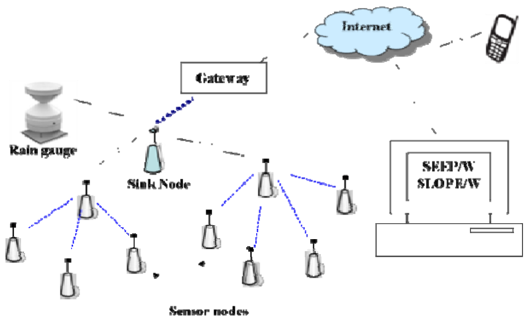

Figure 4. The diagram of the proposed system

Case 1 (no rain or light rain): the value of the rain gauge will determine this situation. In this case, the data from the rain gauge are acquired and forward to a web database. There is no need to execute SEEP/W or SLOPE/W in this case.

Case 2 (rain intensity is below the alert region): Not only the data from the rain gauge are acquired then forward to a web database, but also the SEEP/W or SLOPE/W is executed every five hours. Note that, the output of the previous simulation time is the initiation parameters for the next run with the real-time updated rain intensity from the rain gauge.

Case 3 (rain intensity is in the alert region): Not only the data from the rain gauge are acquired with higher data rate then forward to a web database, but also the SEEP/W or SLOPE/W is executed every one hours to predict the time that landslide may occur. The output of the previous simulation time is the initiation parameters for the next run with the real-time updated rain intensity from the rain gauge.

3.2. Weather station WS-3000

Weather Station WS-3000 is a kit that comprises three sensors: wind gauge, anemometer and wind vane (see Figure 5). It is a reliable and accurate weather kit available for just a fraction of the price of other standard weather stations [11]. Some experiments are performed to test the performance of the Libelium WS-3000 against one of the Weather Stations from Davis and a pluviometer from Rain'o'Matic (both devices are known for being accurate, reliable, and expensive).

Figure 5. The weather station WS-3000

3.3. Microprocessor and GSM/GPRS module

In this research, the Atmega328 microprocessor is a member of the high-performance Atmel 8-bit AVR RISC-based microcontrollers [12]. It is used to receive and process observed data from WS-3000. The Atmega328 have many special features suitable for building a WSN, such as high performance, low power, advanced RISC architecture up to 20 MIPS throughput at 20 MHz and 23 programmable I/O lines [13].

In the case of giving alert, the system automatically sends an SMS message through GSM/GPRS [14] to the responsive contact to act in time (see Figure 6).

Figure 6. The photo of the GSM/GPRS: SIM900 model

4. RESULTS

4.1. Estimation of FS using FEM

In the central computer, the Geo Slope software is set up. Figure 7 shows the distribution map of the pore water pressure with the rainfall density of 12.6 mm/h. In order to understand the stability of the landslide site under different rainfall intensity were introduced to the model to conduct the coupled stability analysis. The factor of safety was computed and can be used to establish the relationship between the rainfall intensity and slope stability.

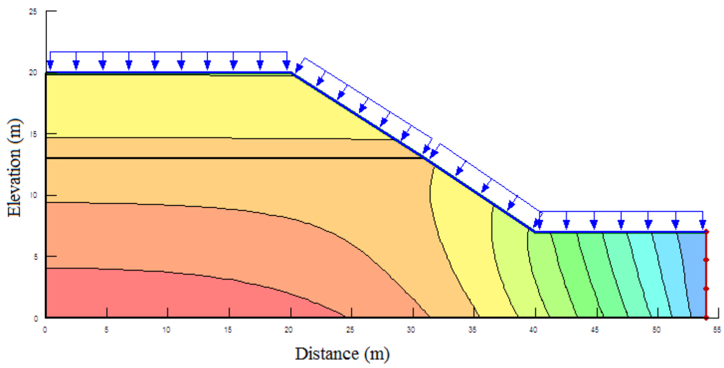

Figure 7. Distribution map of the pore water pressure with the rainfall density of 12.6 mm/h

Figure 8 shows the relationship between the rainfall intensity and the factor of safety (FS). It can be seen that the slope stability decreased as the rainfall amount increased. The value of FS significantly reduced in a linear trend when the rainfall intensity increased from 3 to 6 mm/hour. However, the pace of decline eased significantly after the rainfall intensity reached to 6.7 mm/hour. As the above section described, the groundwater at the landslide site is mainly located in the fractured weathered bedrock. Most rainfall may flow downward to the hillside through the fractures and difficult to remain in the pore space. As we mentioned in Section 3, the rainfall intensity from 3 to 6 mm/hour is corresponds to the case 2, and the rainfall intensity equal or larger than 6.7 mm/hour is corresponds to the case 3.

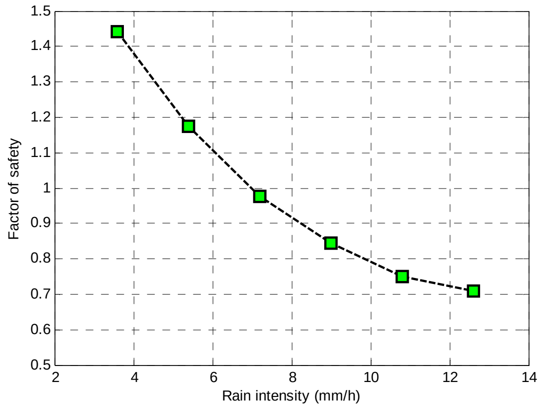

Figure 8. The relationship between rainfall conditions and factor of safety, the rain pattern is uniform.

4.2. Data monitoring and warning mechanism

4.2.1. Real-time data monitoring using web interface and a mobile application

The data acquired in the field site will transmit wirelessly from WS-3000 to the gateway, and then to the data logger. Consequently, the data is automatically uploaded to a MySQL database on a web server. Finally, the web application for remote monitoring is built using web services (see Figure 9). After that, the data is needed to process to give alert or not [15].

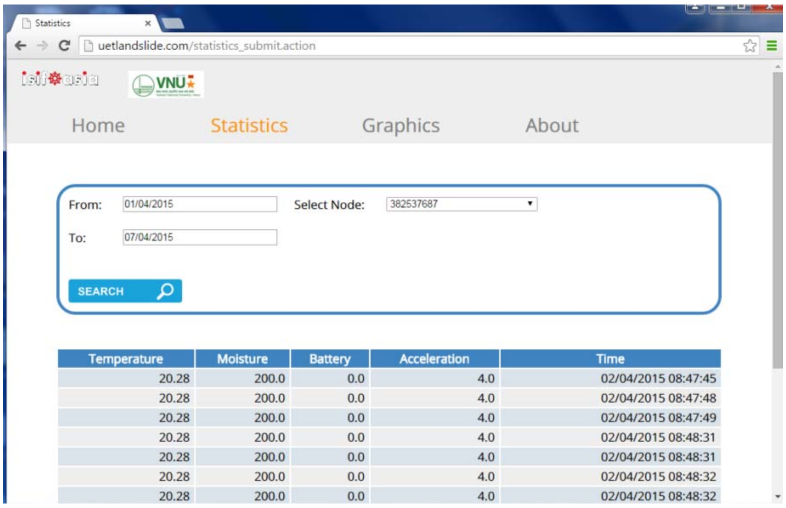

Figure 9. Real-time data monitoring using web interface

4.2.2. Warning SMS to any phone

To give a warning about the levels of landslide to any phone (i.e. smart or feather phones), a GSM/GPRS module is connected to the central computer. In the case of warning, an SMS would send automatically to the designed phone (see Figure 10).

5. CONCLUSIONS

In this paper, a simple and effective system is developed to remotely monitor and automate the warning about the possibilities of the landslide. This is a low-cost solution when a rain gauge can be used to provide the rain intensity and accumulation. This information is extracted and brought to a designed model in GEO-SLOPE to evaluate the factor of safety. This information is compared with the determined thresholds in order to make an alert about the possibilities of the landslide. This monitoring system is completed, simple, low-cost, and effective compared to other works as shown in [3]-[7].

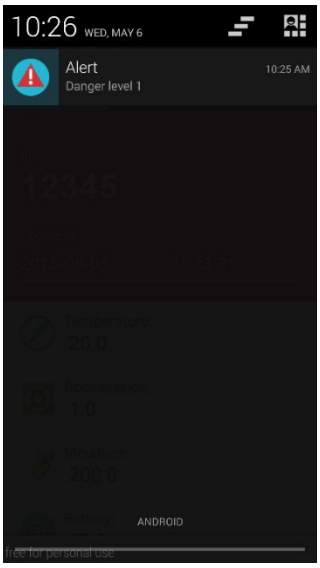

Figure 10. Real-time alert to the phone

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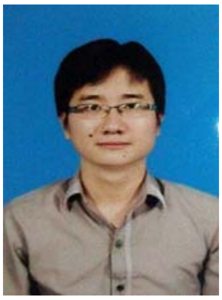

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