



A Multi-Source Early Warning System of MEMS Based Wireless Monitoring for Rainfall-Induced Landslides

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Abstract: Landslide monitoring and early warning systems are the most successful countermeasures to reduce fatalities and economic losses from landslide hazards. The traditional strategies such as GPS and extensometers are relatively expensive and difficult to be installed in steep, high mountains. In this study, a MEMS (Micro Electro Mechanical Systems) based multivariate wireless monitoring sensor unit was used to build a monitoring and early warning system for rainfall-triggered landslides, as one of the most practical and cost-effective countermeasures for hard-reached mountains. The multi-source wireless monitoring system and its well-developed equipment were tested in a landslide-prone slope to monitor the triggering of landslides and debris flows in the Wenchuan earthquake region, China. The variations of several state variables were observed, including the soil moisture content, soil matric suction, rainfall, inclination and ground vibration. The results of a slope stability analysis were benchmarked with the in situ measurements to identify the multivariate early warning parameters for rainfall-induced landslides. The proposed early warning system for the slope stability analysis can provide a more accurate prediction for rainfall-induced landslides and debris flows in earthquake hit regions.

Keywords: wireless early warning system; portable sensor unit; cost-effective equipment; multivariate thresholds; rainfall-induced landslides

1. Introduction

The prediction and early warning of rainfall-induced landslides is critical in preventing landslide disasters. Typical non-structural landslide monitoring systems use inclinometers, GPS and extensometers to observe the displacements of slopes. These measures have been widely used and proved to be an effective way for early warning of landslide hazards. However, these methods usually come with a high cost, both in terms of the equipment and in terms of its installation, meaning that their application is limited to well-funded projects. Moreover, instrumental installation for this equipment, such as boring holes, is impossible in unreachable high mountains. Therefore, a low-cost and portable monitoring method is needed for early warning of landslides in mountainous areas with a large number of landslides, for example in the Wenchuan earthquake region of China. Recent studies stated that the Micro Electro Mechanical Systems (MEMS) based slope stability monitoring instruments and systems are practically versatile and effective, thus it was widely used in landslide monitoring and early warning, and generated considerable recent research interest [1–4].

Despite the applicable equipment and system, an accurate criterion to predict the slope instability is necessary to quantify the threshold of rainfall-triggered landslides, and it requires an appropriate formulation of the mechanism of slope instability. High-intensity precipitation is the most commonly attributed trigger of landslides in the Wenchuan earthquake-affected region [5]. Recent studies on the initiation of rainfall-induced shallow landslides have broadly indicated that the slip surface may be located above the water table, without the development of positive pore pressures, and the slope failure can be caused by the infiltration of rainwater that decreases the matric suction under unsaturated conditions [6–9]. According to large-scale field investigations following the Wenchuan earthquake, shallow rainfall-induced landslides less than 1 m thick are the typical form of gravitational erosion in the depression areas of debris flows [5,10,11]. These landslides dominate the geomorphologic processes. The landslides in the upstream areas play an important role in the initiation and formation of debris flows. Consequently, rainfall-induced mass remobilization has gained more significance in terms of disaster relief in earthquake-affected regions in China. To predict the slope instability for partially saturated landslides, the criteria as a function of multiple parameters based on a real-time landslide monitoring system has been demonstrated for years [12–14], however, to date, the multivariate thresholds criteria that combine the unsaturated hydro-mechanical methods and in-situ measurement for rainfall-induced landslides early warning is not well documented in the literature [15,16].

In this study, a low-cost and portable monitoring equipment for real-time monitoring and early warning system of rainfall-induced landslides is developed. A wireless sensor unit composing of a MEMS tilt sensor, as well as tensiometer, soil moisture sensor and rain gauge was chosen to establish a monitoring system for rainfall-induced landslide prediction. This sensor unit, together with all the equipment inside can be easily installed into the slope ground. The proposed system allows a low-cost and easy installation of the instrument in landslide-prone slopes. The in situ real-time monitoring big data in a landslide-prone slope and catchment in Wenchuan earthquake region in China was used as input for hydro-mechanical analysis, and a multiple thresholds criteria method was used to predict the rainfall-triggered landslide.

2. Methodology & Case Study

2.1. The Low-Cost & Portable Monitoring System

The schematic figure (Figure 1) describes a portable and cost-effective multi-source wireless monitoring system for measuring several state variables, which is including the rainfall intensity, soil moisture content, matric suction and inclination of slope. The device of the system can be directly installed and stabilized in the slope, and the sensor units that can be inserted into the soil by using a small hammer. The sensor unit is small in size ($16 \times 12 \times 8$ cm) and easy to install. The weight of the sensor unit shown in Figure 2a is only 400 g, so that the proposed system can be used extensively in hard-reached places in a landslide-prone area. The system can measure multivariable parameters at certain points on a slope surface at the same time. The total cost for one monitoring site including a soil moisture sensor is only 1500 US dollars, far below the conventional GPS system that costs around 6000 US dollar for a single device. The system can be powered with batteries, and the real-time data can be transferred via a wireless network, providing all the data to the internet on time. The applicability and effectiveness of the multi-source wireless monitoring system have been tested in a natural slope under heavy artificial rainfall [17]. Considering the proposed system is cost-effective and easy to install, it can be widely used in large-scale landslide-prone areas in developing countries.

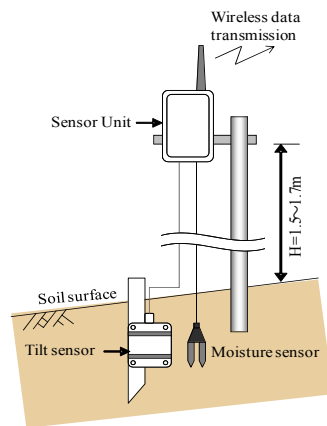


Figure 1. Wireless sensor unit with tilt and water content sensors on a slope, rain gauge and tensiometer are also compatible with the sensor unit as an alternative.

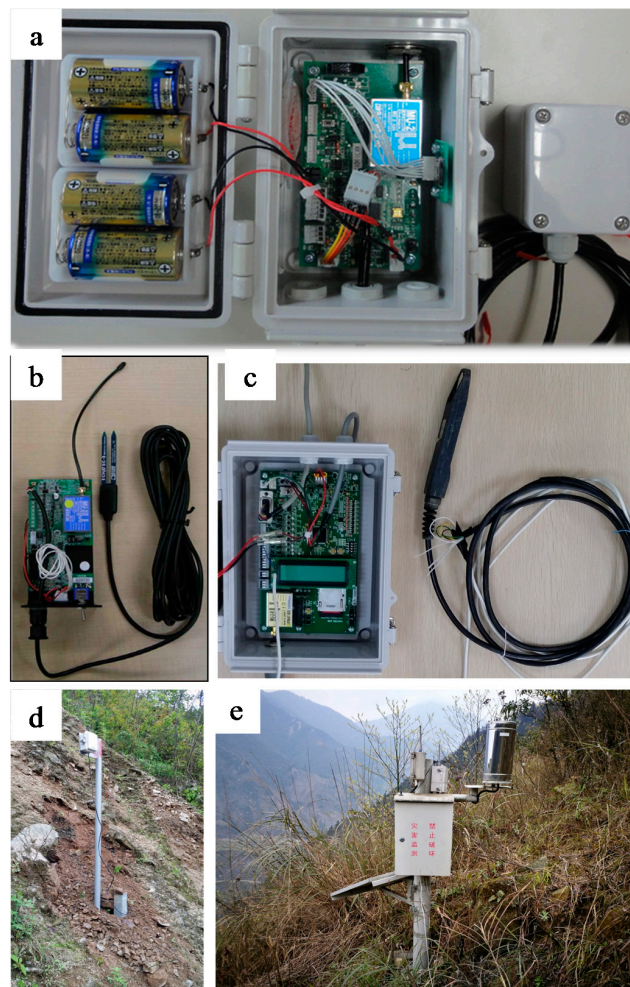


Figure 2. Pictures of instruments proposed for landslide real-time monitoring and early warning system. (a) The tilt sensors, (b) soil moisture sensors and (c) tensiometer integrated with (d) sensor unit and installed at the head of the slope in hollow in Yindongzi landslide and (e) a tipping bucket rain gauge was connected to the data logger.

2.1.1. Wireless Data Transmit Method

Figure 2 shows a sensor unit of the wireless device installed into a landslide site. One unit consists of a MEMS tilt sensor, and is compatible with different sensors. A sensor unit can work automatically with a microcomputer powered by solar cells or independent batteries. The 434 MHz ISM band radio modems have 127 pre-programmed channels, an alternative 1/10 mW power source, and they fit the European Radio and Telecommunications Equipment (R&TTE) Directive and the European Conformity (CE) Marking. They are integrated in the proposed sensor unit, therefore the sensor unit is capable of creating a series of wireless data transmit systems, from simple control systems to wide network systems. The sensor units collect real-time data every 10 min in rainy season and every 1 h in the dry season. The data can be transferred to a gateway unit placed next to the monitoring slope, by adopting energy-saving radio modules. The gateway unit receives data from all the sensor units installed, and transfers data to a server through a mobile network. The distance for data communication is more than 300 m in field circumstances. Therefore, monitoring data can be acquired anywhere and anytime via the internet. The data is arranged in time, and any abnormal variation of the parameters in the slope can be observed as a precaution of possible failure when the thresholds are identified.

2.1.2. Micro Electro Mechanical Systems (MEMS) Based Sensor Unit

In each sensor unit, the MEMS tilt sensors can observe the rotation and abnormal displacement on the ground surface, which avoids the usage of a long extensometer wire. The installation and maintenance is relatively simple and cost-effective. The resolution of the MEMS tilt sensor is sufficient for landslide research, its measurement range is ± 30 degrees and the resolution of rotation angle is 0.0025 degree. High resolution, low noise and low temperature dependency, together with a robust sensing element design make this MEMS based inclinometer an appropriate choice to detect slope displacements and failures.

Despite the displacements, the slope stability mechanism indicates that the soil matric suction and water content are significant for the state of stress and stability in shallow slopes, and the correlation of soil moisture and suction can manifest the soil hydraulic characteristics, so that both the soil moisture and the soil suction are essential for monitoring of rainfall-induced landslides. The soil moisture is detected at a shallow position of the slope, typically 30 cm deep. The soil moisture sensor measures volumetric moisture contents by detecting the corresponding dielectric constant of the surrounding soil. In addition, measurements of soil suction in unsaturated soils as well as precipitation are also achievable with the sensor unit by using tensiometers and rain gauges which do not need frequent maintenance. In this study, the measuring range of the soil moisture sensor (Decagon EC-5, Decagon Devices, Pullman, WA, USA) is technically 0–1 with an accuracy of ± 0.01 , and the measuring range of the soil suction sensor (Tensiometer TS2, Stevens Water Monitoring Systems, Portland, OR, USA) is 0–300 kPa with an accuracy of approximately ± 0.15 kPa. The rain gauges (CAWS 100, Huayun Group, Beijing, China) can measure rainfall with a resolution of 0.2 mm and a 0–4 mm/min measurement range. These sensors can be integrated with the wireless sensor unit into the real-time monitoring system and are capable of detecting the magnitudes of the values of the parameters in this area.

2.1.3. Low Power Consumption Design

To design a cost-effective and easy-maintaining monitoring system, the power consumption of the CPU controller is also important. The 16-bit Ultra-Low-Power Microcontroller unit (MCU) (MSP430, Texas Instruments, Dallas, TX, USA, 1996), which includes extensive performance of 7 channel 12 bit Analog-to-Digital converters with synchronization, and 2 USART (Universal Asynchronous Receiver/Transmitter), pronounced I-two-C (I2C) modules, were integrated into the sensor unit. This MCU is ultra power-saving in standby mode with an electricity current intensity of 1.1 μ A, and can operate at a low supply-voltage range from 1.8 to 3.6 Volt, thus it is very suitable to work in the

field where commercial power is unavailable. 4 Standard Power 7 Alkaline batteries can keep a single sensor unit continuously working for more than 1 year. By attaching an optional solar battery, which costs around 5 US dollar, the sensor unit can work semi-permanently without changing the batteries.

2.2. Case Study

The proposed real-time monitoring systems with automated instrumentation, which allows for remote observations to be collected wirelessly, have been of great value in monitoring landslide-triggering under the impact of precipitation and soil moisture dynamics. However, the limitation of such a system is that it is suitable for monitoring and early warning for shallow landslides, thus this system can only have a superficial record of variables. In this study, this system was tested and established on a real landslide-prone slope in the Wenchuan earthquake region, China. The in situ monitoring slope is located in the catchment of the Yindongzi valley in Dujiangyan County, in the central part of Sichuan Province (Figure 3). The monitoring catchment is situated in the subtropical humid monsoon climate zone, with an annual average temperature of 16.7° . The annual average rainfall is more than 1200 mm. Precipitation is mostly concentrated in the period from May to September. The landform of the Yindongzi valley can be categorized into middle mountains, the elevation ranges from a minimum of 1030 m above sea level (a.s.l.) to a maximum of 2050 m a.s.l. with about 1000 m height difference along a 2500 m gully length. The strata exposed are from the Proterozoic era, which include igneous rocks, andesitic rocks and granite. The slope failure was triggered by the Wenchuan earthquake and is composed of deeply weathered granite and andesitic gravel and sand. The total volume of this landslide is about 500,000 m³. After the Wenchuan earthquake, the landslide's body was remobilized and transformed into debris flows during subsequent rainstorms. These storms exceeded 130 mm over 24 h on 13 August 2009, 17 July 2010 and 9 July 2013 respectively. The Yindongzi landslide and the secondary debris flows threaten the totally rebuilt community residences of Lianhe Village, Dujiangyan County.

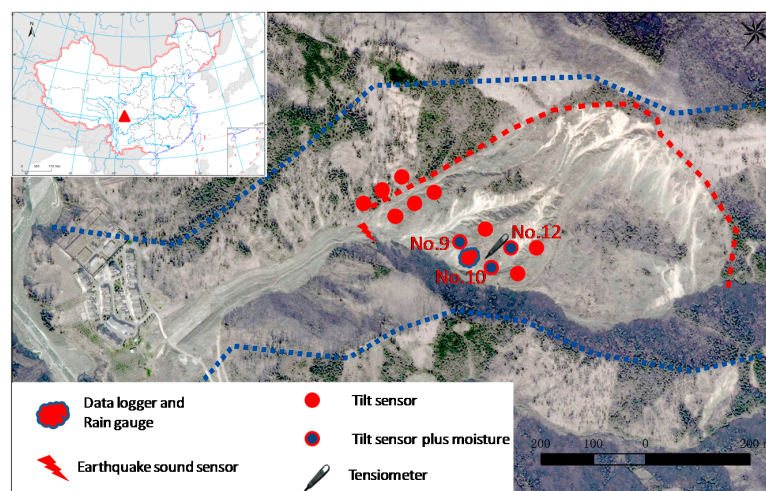


Figure 3. Location of the in situ monitoring site, which is conducted on a natural landslide site in Yindongzi valley, Dujiangyan County, Chengdu City, Sichuan Province, China.

A total of 15 sets of equipment were installed to collect real-time data for the Yindongzi landslide (Figure 3). In May 2014, a real-time monitoring system of multiple parameters including inclination, rainfall, ground vibration and hydrologic measurements were installed in the shallow subsurface of the Yindongzi landslide site in Dujiangyan. In this landslide, 3 soil moisture sensors were installed with NO. 9, 10 and 12 tilt sensors. In particular, the NO. 12 moisture sensors were installed with a tensiometer to study the hydraulic characteristics of the soil. Moreover, a ground vibration detector was installed on 24 April 2016, to record the number of responses when ground vibrations overpassing

the acceleration threshold of 0.375 g were detected. These may possibly have been induced by the bounce and tumble motion of the landslide against the underlying ground (Figure 3). Although the installed sensors were at risk of break-down due to the extreme humidity and temperature in the field, most of the sensors have worked normally with limited maintenance. The monitoring system has been collecting real-time data and long-term changes of precipitation and soil moisture at the Yindongzi landslide site from 21 May 2014 to 22 August 2017. However, our monitoring tilt sensor has not observed any positive displacements during the monitoring period, nor any changes in inclination. As a result, the tilt data are not shown and discussed in this paper.

2.3. Slope Stability Analysis

For transient infiltration conditions, the factor of safety F_s (-) at a depth Z (m) below the ground surface at time t (day) is given by the following equation:

$$F_s(Z, t) = \frac{\tan \varphi'}{\tan \beta} + \frac{c' - \sigma^s(Z, t) \tan \varphi'}{(\gamma_s + \gamma_w * \theta(Z, t)Z \sin \beta \cos \beta)} \quad (1)$$

where φ' ($^\circ$) is the angle of internal friction for effective stress, β ($^\circ$) is the slope angle, c' (kPa) is the effective cohesion, γ_s (N/m^3) is the soil unit weight, γ_w (N/m^3) is the water unit weight, θ (-) is soil moisture content, and σ^s (kPa) is the suction stress defined by Lu and Gods [6]:

$$\sigma^s = S_e \psi \quad (2)$$

where S_e (-) is the effective degree of saturation, ψ (kPa) is the matric suction. The hydro-mechanical infinite-slope stability analysis is based on the factor of safety approach coupling the Brooks–Corey equations [18] and suction stress [6] in variably saturated soils.

$$S_e = \begin{cases} |\alpha\psi|^{-n}, & \alpha\psi < -1 \\ 1, & \alpha\psi > -1 \end{cases} \quad (3)$$

and a (kPa^{-1}), l (-), n (-), are fitting parameters.

The soil parameters for the slope stability analysis from the topsoil of the slope and parameterization of soil hydraulic properties for the hydro-mechanical models [19] are based on the soil water characteristic curves (SWCC). Its parameters of hydrology are presented in Table 1.

Table 1. Soil parameters for the slope stability analysis. SWCC denotes soil water characteristic curves.

Symbol	Parameter	Value
c'	soil cohesion for effective stress; (kPa)	3.0
φ'	angle of internal friction for effective stress; ($^\circ$)	33
γ_s	dry soil unit weight; (kN/m^3)	15
β	Slope angle; ($^\circ$)	60
θ_r	residual water content; (-)	0.05
θ_s	saturated water content; (-)	0.45
Z	Soil depth;(m)	0.5
a	SWCC parameter of the Brooks–Corey model	11
n	SWCC parameter of the Brooks–Corey model	0.53

3. Results & Discussions

3.1. Field Monitoring Results

Long-time series data of precipitation and volumetric water content at the Yindongzi landslide site during a four-year period from 21 May 2014 to 22 August 2017 were observed. Figure 4 shows the daily rainfall and accumulated annual rainfall during the monitoring period.

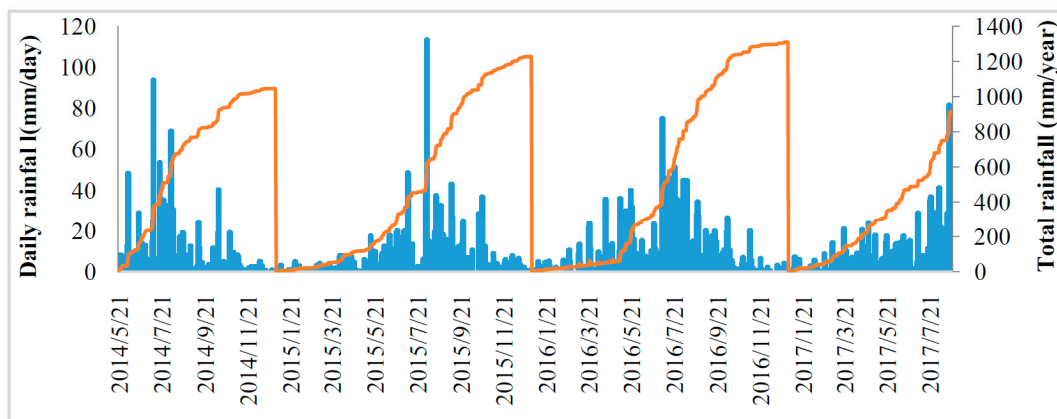


Figure 4. Daily and accumulative rainfall were recorded by the rain gauge at the Yindongzi landslide site from 21 May 2014 to 22 August 2017. Instruments were installed on 3 May 2014 and data collection began on 19 May 2014.

The real-time monitoring has shown that the soil moisture content is strongly related to rainfall. Precipitation was notably seasonal, most of the precipitation was observed during the monitoring period, with most precipitation from May to September. Particularly, an extreme daily rainfall of 113 mm was recorded on 4 August 2015, while the rainfall intensity is lower than that in 2008 to 2013, and the maximum value of daily rainfall is recorded to be 250 mm in this area on 7 July 2013. This explains why there are no debris flows during these years, considering the rainfall intensity and total amount of rainfall may not be sufficient to cause displacements and inclination during the monitoring period. The soil moisture fluctuated significantly during the wetting and drying periods caused by evaporation and infiltration processes. Soil wetness increased episodically with respect to rainfall. Theoretically, the soil moisture content may exceed 0.45, because the porosity of the topsoil is reported to reach 0.49 in this area [20]. In the analyzed period, the soil moisture content ranged between about 0.03 and 0.17 in the topsoil. During the rainy season, soil moisture storage increased rapidly by an additional 5–13% caused by rainfall (Figure 5).

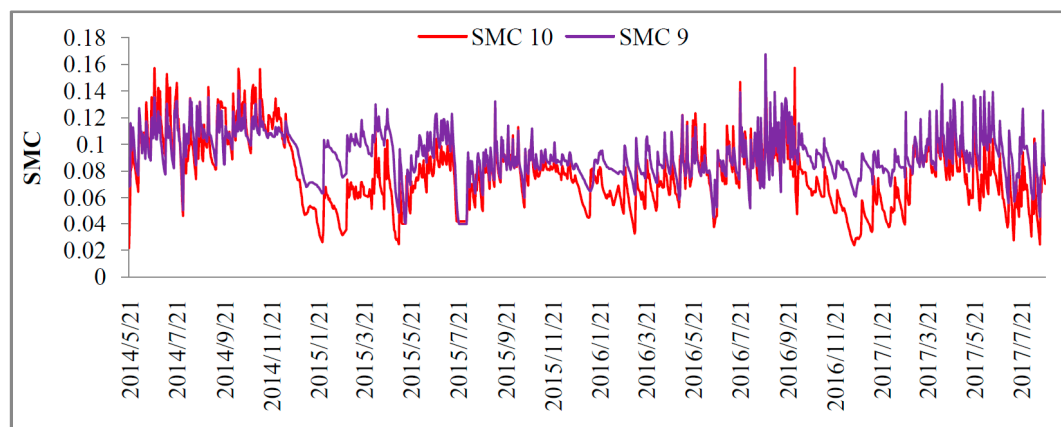


Figure 5. Soil moisture content (SMC) recorded by soil moisture sensors (Decagon EC-5) at the Yindongzi landslide site from 21 May 2014 to 22 August 2017.

3.2. Soil Water Characteristic Curves (SWCC)

The SWCC of wide-gapped topsoil in the Yindongzi landslide site describes the relations between the matric suction and moisture content, and it can be quantified by the data measured by the tensiometer, as well as moisture in exactly the same location. Figure 6 shows that the precipitation

and soil suction exhibited different trends during the wetting and drying periods. The topsoil of the natural slope frequently underwent drying and wetting processes. Although instrumentation breakdown occurred after one month of installation, resulting in the loss of matric suction data, some suction data is still available from the period of 5 May to 1 June 2016, when the soil suction underwent notable changes following rainfall events that exceeded about 39 mm in 24 h at its maximum (Figure 6). During this period, the soil moisture content fluctuated rapidly by an additional 0.01~0.08, and matric suction also underwent a homologous change by 2~40 kPa in response to rainfall. Therefore, the SWCC can be established according to the monitoring soil wetness and matric suction.

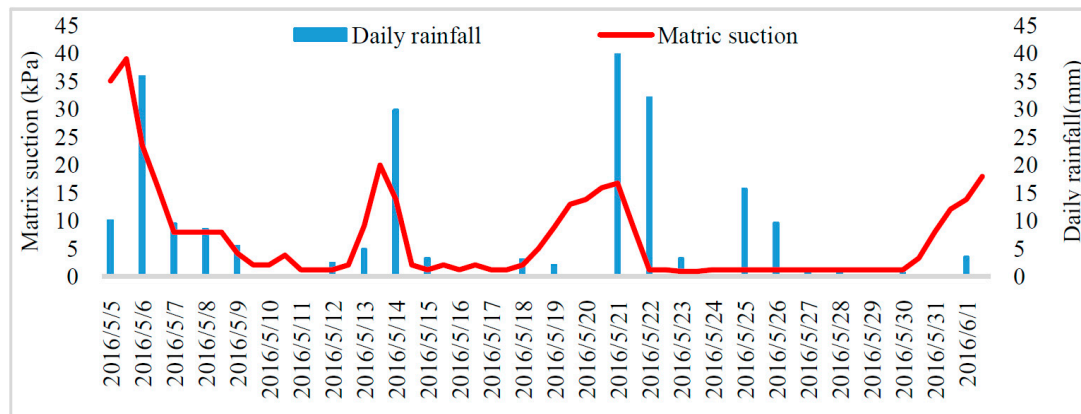


Figure 6. Times series of the daily rainfall and matric suction observed by real-time monitoring sensors from 5 May to 23 May 2016 in the top soil of the landslide monitoring site.

Figure 7 shows the estimated SWCC based on the Brooks-Corey model [18]. Table 1 provides the parameters for the unsaturated topsoil in the Yindongzi landslide site for slope stability analysis, the SWCC parameters were estimated by the in situ moisture and suction data, and soil mechanic parameters were determined by triaxial shear test. As shown in this table, the value of α is high, whereas the values of n are small, especially for the wetting process. The result is similar to a recent study of the SWCC of a wide gapped gravel loamy landslide in the Wenchuan earthquake region [20], which is reasonable for a post-earthquake landslide deposit, because the landslide is composed of gravelly loamy soil, features a smaller air-entry pressure due to the scarcity of fine grains and a broad grain-size distribution. The air-entry pressure ($1/\alpha$) was found to be 0.09 kPa.

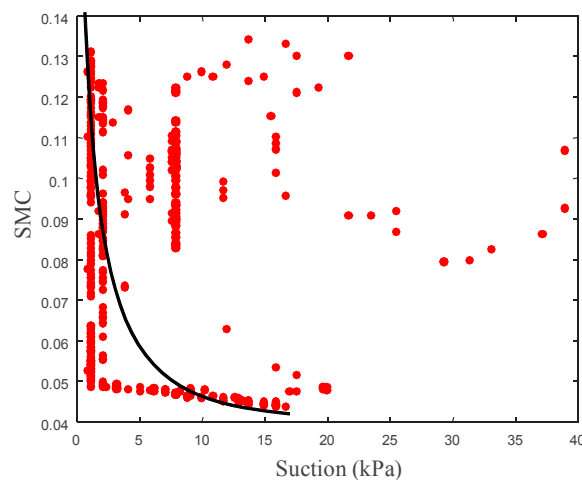


Figure 7. Soil water characteristic curves (SWCC) of the Brooks–Corey model in the top soil of landslide monitoring site over the analyzed period.

3.3. Slope Stability Analysis of the Unsaturated Slope

The slope stability analysis under partially saturated conditions is based on the factor of safety approach combining the hydrological and soil-mechanical analyses. Classical methods for rainfall-triggered shallow slope stability analysis can also be extended to unsaturated conditions by considering the suction stress in this study [6].

The transient effect of infiltration on the factor of safety is shown in Figure 8. The safety factor of the slope ranged mainly from 1.01 to 1.25 between May 2014 and August 2017. Figure 8 shows the safety factor of the corresponding monitoring slope considering the suction stress in the unsaturated condition. The safety factor of the slope featured continuous fluctuations due to the variations of the suction stress in response to the rainfall-infiltration and evaporation in the unsaturated topsoil. Correspondingly, the ground vibration detector has recorded responses during the rainy periods. Particularly Figure 9 shows that ground vibrations caused 20, 17 and 33 responses to be recorded (70 responses in total) from 23 August to 25 August 2016 as a result of precipitation of 27.8 mm, 34.2 mm, and 27.4 mm on those days (89.4 mm in total). The modeled factor of safety dropped to the lowest point of 1.01 during these days. The evidence of ground vibration responses must have been due to some small-scale slope instability. When the modeled factors of safety came close to unity, it indicated the quasi-stable state of the slopes.

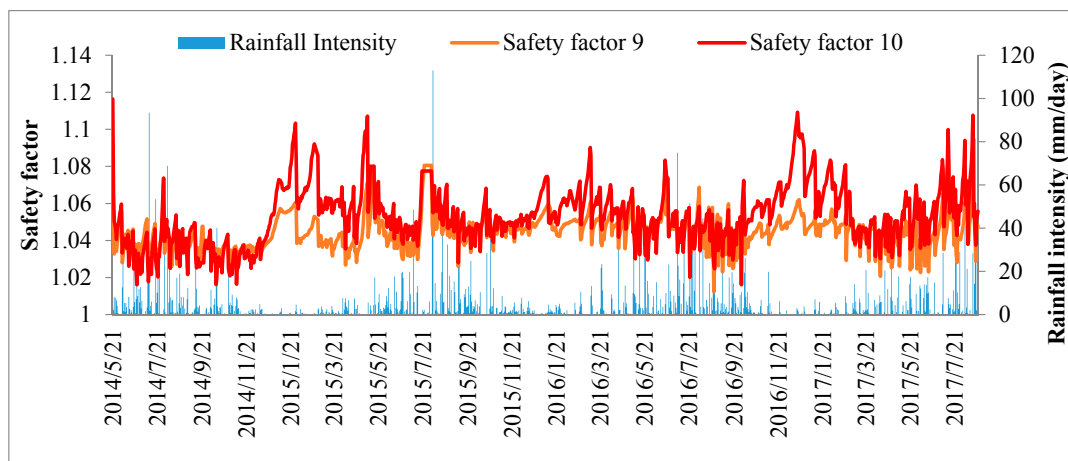


Figure 8. Modeled factors of safety based on fluctuation of suction stress for different position in the slope during 21 May 2014 to 22 August 2017.

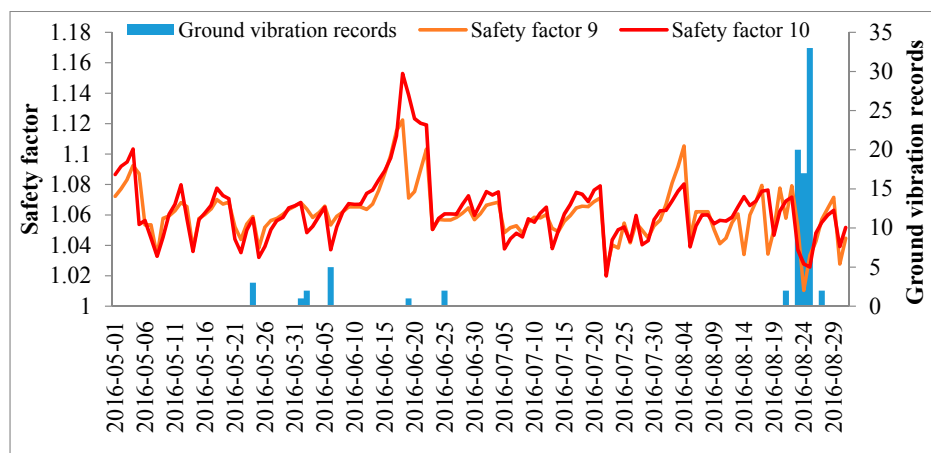


Figure 9. Ground vibration records and modeled factor of safety changes in the Yindongzi landslide site from 1 May to 30 August 2016.

3.4. Hydrological Thresholds

Figure 10 illustrated the correlations of factor of safety with soil moisture content, matric suction, and daily rainfall. The results indicated that the thresholds of volumetric water content and matric suction for triggering landslides were about 0.16 and 2 kPa respectively. However, the correlation of factor of safety with daily rainfall exhibited a rather poor relationship. The hydrological processes and slope stabilities were affected by infiltration, evaporation, drainage, soil hydraulic properties, and the antecedent rainfall, all these factors brings uncertainty in the statistical rainfall threshold. The rainfall threshold shall be calculated by including long-term historical monitoring information [11]. By means of the in situ big data analysis and slope stability analysis of partial saturation in response to rainfall infiltration, the hydrological parameter criteria of moisture content and matric suction for early warning of rainfall-induced shallow landslides in the Wenchuan earthquake regions can be established by coupling the factor of safety with these parameters.

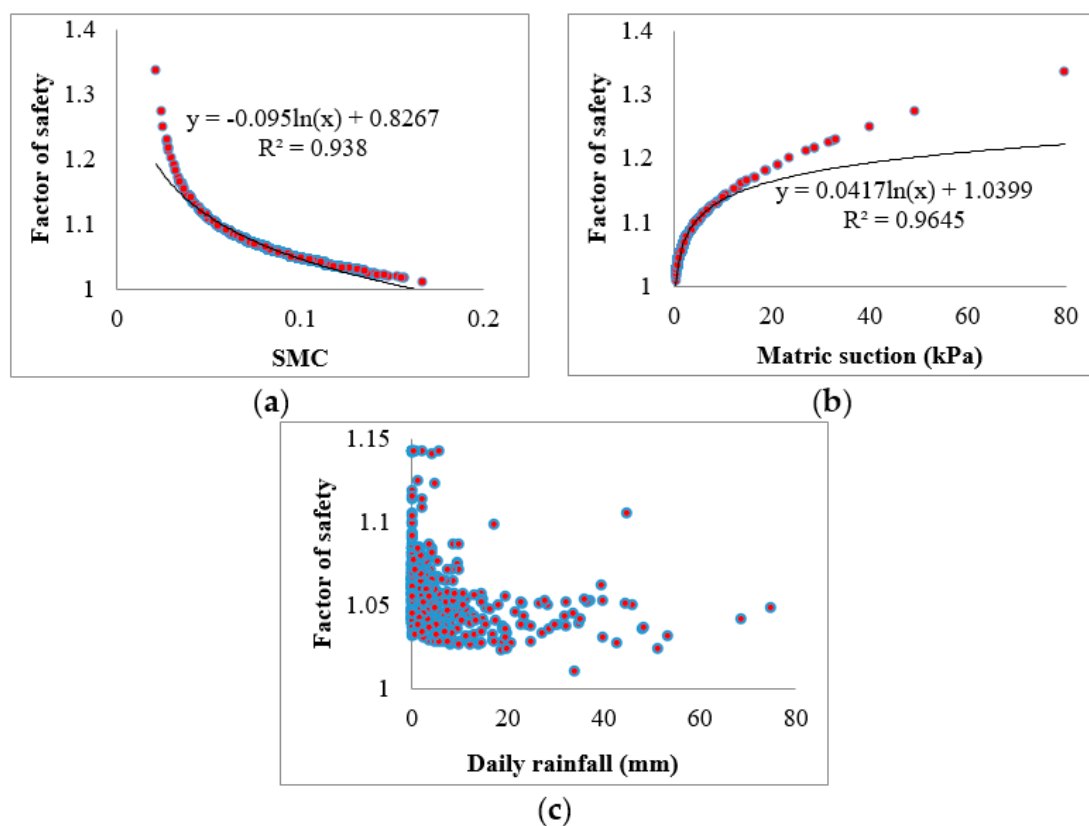


Figure 10. Correlation of slope stability and soil moisture content, matric suction and daily rainfall, plotting by the stability analysis. Modeled factor of safety versus (a) observed volumetric water content, (b) observed suction and (c) observed daily rainfall which indicates the water contents and suction thresholds models for early warning of the mass-remobilization in the Yindongzi landslide site in hollows of debris flows of the Wenchuan earthquake region.

4. Conclusions

An early warning system of MEMS based multi-source wireless monitoring for rainfall-induced landslides is proposed. This system was tested and established on a real landslide-prone slope in the Wenchuan earthquake region, China, and long-term monitoring data was observed.

(1) The proposed real-time monitoring system is composed of low-cost and portable wireless sensor units, which, when integrated with a MEMS based inclinometer, tensiometer, rainfall gauge and soil moisture sensor, renders the system capable of measuring multi-source parameters corresponding

to rainfall-induced landslides. The sensor unit features ultralow power consumption so as to be easy-to-maintain for landslide monitoring.

(2) The long-term fluctuations in the soil moisture content, matric suction, and rainfall were observed and slope stability in response to rainfall infiltration was simulated. The corresponding slope failures during a rainy period could have been observed by ground vibration, indicating that the reduction in matric suction and the rise in soil moisture in response to rainfall infiltration contributes enormously to slope stability of rainfall-triggered landslides, especially in terms of shallow mass movement.

(3) Based on instrumental field observations and the quantitative slope stability analysis for an unsaturated slope, a method to determine multi-source thresholds of hydrological parameters, including daily rainfall intensity, soil moisture content and matric suction, for use as early warning criteria for rainfall-induced landslides in the Wenchuan earthquake region was proposed.

The proposed explorations indicate that field measurements and a threshold model including precipitation, soil wetness, and pore pressure (soil suction) are significant in identifying states under which rainfall-induced landslides are likely to initiate. The proposed low-cost and effective early warning method combined with a multi-parameter threshold for anticipating rainfall-induced landslide activity provide powerful tools to conduct a landslide early warning system that could be adopted to reduce landslide risk.

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Author Contributions: Zongji Yang and Taro Uchimura conceived and designed the early warning system; Zongji Yang, Jianping Qiao, Dong Huang, and Hongling Tian established and performed the early warning system; Wei Shao and Xiaoqin Lei contributed analysis tools; Zongji Yang wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

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