An EWS of Landslide and Slope Failure by MEMS Tilting Sensor Array

Lin Wang, Makoto Fukuhara, Taro Uchimura, Gallage Chaminda, and Tharindu Abeykoon

Abstract

A low-cost and simple method of monitoring rainfall-induced landslides is proposed, with the intention of developing an early-warning system (Uchimura et al. 2015). Surface tilt angles of a slope are monitored using this method, which incorporates a Micro Electro Mechanical Systems (MEMS) tilt sensor and a volumetric water content sensor. In several case studies, the system detected distinct tilt behaviour in the slope in pre-failure stages. Based on these behaviours and a conservative approach, it is proposed that a precaution for slope failure be issued at a tilting rate of 0.01°/h, and warning of slope failure issued at a rate of 0.1°/h. The development of this system can occur at a significantly reduced cost compared with current and comparable monitoring methods, which such as extensometer or borehole inclinometers. Increasing the number of installed sensors, thus increasing the accuracy of the early warning thresholds and predictions, so that given the cost reduction, slopes can be monitored at many points, resulting in detailed observation of slope behaviours, but the potentially large number of monitoring points for each slope does induce a financial restriction. Therefore, the selection of sensor positions needs to be carefully considered for an effective early warning system. These case studies will henceforth be helpful in determining the installation of the sensor array of early warning system.

Keywords

Landslide • Slope failure • Early warning • MEMS tilting sensor

Introduction

There is a long history of prevention and mitigation of rainfall and/or scouring-induced landslides. Mechanical countermeasures to prevent slope failure have been widely used, including retaining walls and ground anchors. However, these methods can be expensive and are not always realistically applicable for all slopes of varying scale and potential risk factors. Therefore, careful monitoring of slope behaviour and consequent early warning of failure provides a reasonable and slope-specific alternative.

In this paper, an early warning system for slope failure is proposed and its development is described (Fig. 1) (Uchimura et al. 2015). The system consists of a minimum number of low-cost sensors strategically placed on a slope, with monitoring data that are collected being transmitted via a wireless network. It is anticipated that this low-cost and simple system will provide at risk residents with access to accurate and timely precautions or warnings of slope failure.

Uchimura et al. (2015) summarized case studies of slope tilting rates during pre-failure stages obtained on several natural slope sites under natural or artificial heavy rainfall. Figure 2 presents an example of the typical monitoring data obtained, in which the tilting rate (X-axis) can be related with the time elapsed until slope failure or slope stabilization (Y-axis). Figure 3 shows the definition of the tilting rate and

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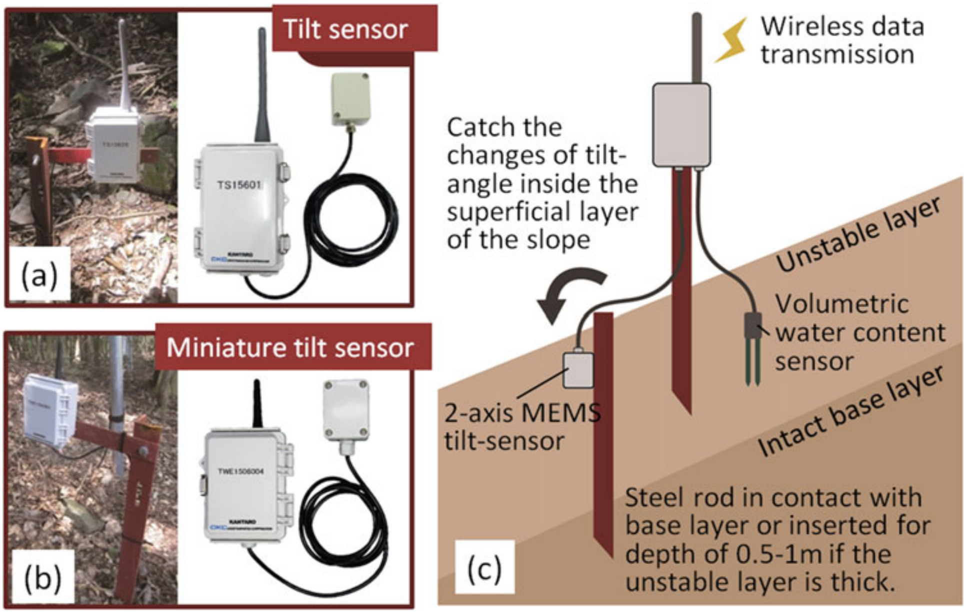
Fig. 1 Schematic illustration of MEMS tiltmeter sensor for early warning

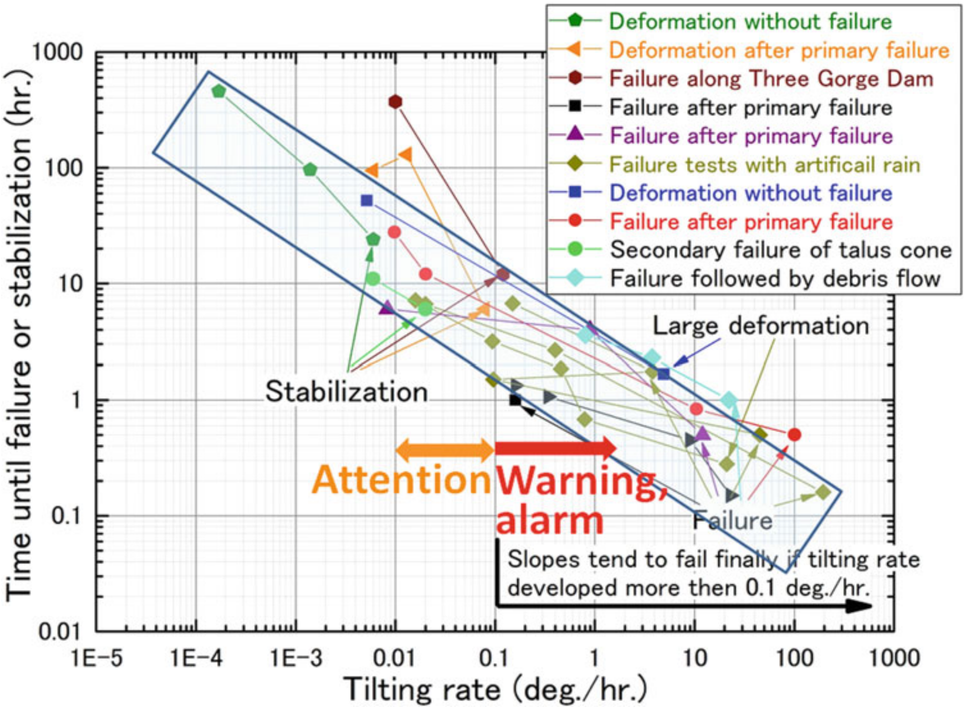


the time in Fig. 2, in which Ti is the time until failure or stabilization, and Ri is tilting rate.

In cases where the slope failed at the position of the tilt sensor, the elapsed time is measured from the time when tilting accelerated to the time of failure. In cases where the slope did not fail but instead stabilized, the time is measured from when tilting decelerated to the time when the slope stabilized.

According to Fig. 2, the order of tilting rate observed with slope deformation varied widely, from 0.0001 to 10°/h depending on a number of factors. The tilting rate tends to increase towards failure with a relatively short time until failure, when a higher tilting rate is observed. The observed tilting rate was >0.01°/h for all the cases in which the slope failed or nearly h was observed before failure for a tilting rate of 0.1°/h.

Fig. 2 Graphic illustration of the tilting rate as a function of time before slope failure (or stabilization) for several case studies



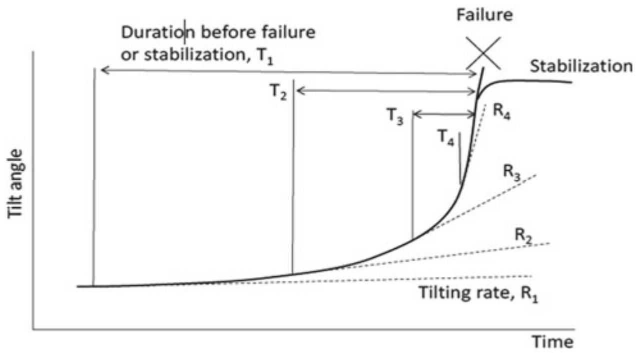


Fig. 3 Definition of the tilting rate and the durations

Based on the past case studies, it is proposed that when the tilting rate exceeds 0.1°/h a warning of slope failure should be issued, and a precaution issued at a tilting rate of 0.01°/h, taking safety into account. Additionally, this paper explores efforts by the current authors to improve the applicability of the monitoring and early warning system. The miniature tilt sensors are modified from that currently available to be more cost-effective, smaller in size and weight, and simpler to install, maintain and operate. As a result, it is possible to install a larger number of sensors on a given slope, thereby providing greater coverage and higher data density.

Figure 4 illustrates the typical arrangement of two types of proposed sensors, with data transfer pathways also shown. Despite the advantages described above, the new type miniature tilt sensors have relatively short radio transmission distances (∼30 m in non-ideal conditions). They are arranged densely on high-risk areas of a slope, with one conventional tilt sensor unit collecting all the data of each area. The data are transmitted over greater distances (300–600 m), and uploaded to an internet server. If the data transfer is interrupted for other reasons, the data is reacquired and an alert is issued when the signal is restored.

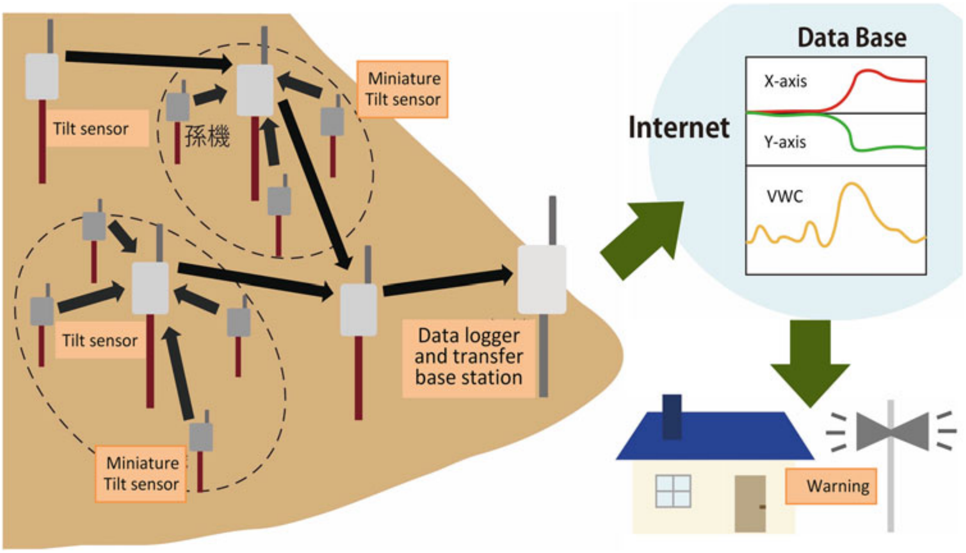
Field Validation in Japan and Australia

A Case of Detection of Rain Induced Landslides in Critical Slopes the Lake Baroon Catchment, Maleny Plateau, Brisbane, Australia

This case study investigated the applicability of real-time monitoring and wireless data transmission in predicting rain-induced slope instability in critical slopes. The ground inclinometers equipped with MEMS tilt sensors, volumetric water content sensors, a rain gauge and a wireless data transmission unit (DTU) for real-time slope monitoring. The study employed a wide range of data collected in the period from 10th May 2016 to now, this year of 2020, for the prediction of the slope failure under rainfall infiltration.

Study area is Lake Baroon catchment, Maleny (Fig. 5) is located approximately 100 km north of Brisbane (26.76 0S 152.85 0E). Mapleton—Maleny plateau, which contains Lake Baroon catchment have been documented and discussed since the mid-1950s as a highly susceptible area for rainfall-induced slope failure. Slope failure and mass movement of sediment into the waterways within the Lake Baroon catchment are recognized as a significant risk to water quality and the water storage capacity of Lake Baroon, which is used to supply water to South East Queensland. Approximately 170 mass movement landforms have been identified within the Baroon catchment, and the study area is one such high-risk slope. This landslide site hosted a voluminous, single-failure rotational landslide in 2008 following heavy rainfall (Abeykoon et al. 2018).

Fig. 4 An early warning system of slope failure by multi-point tilt and volumetric water content



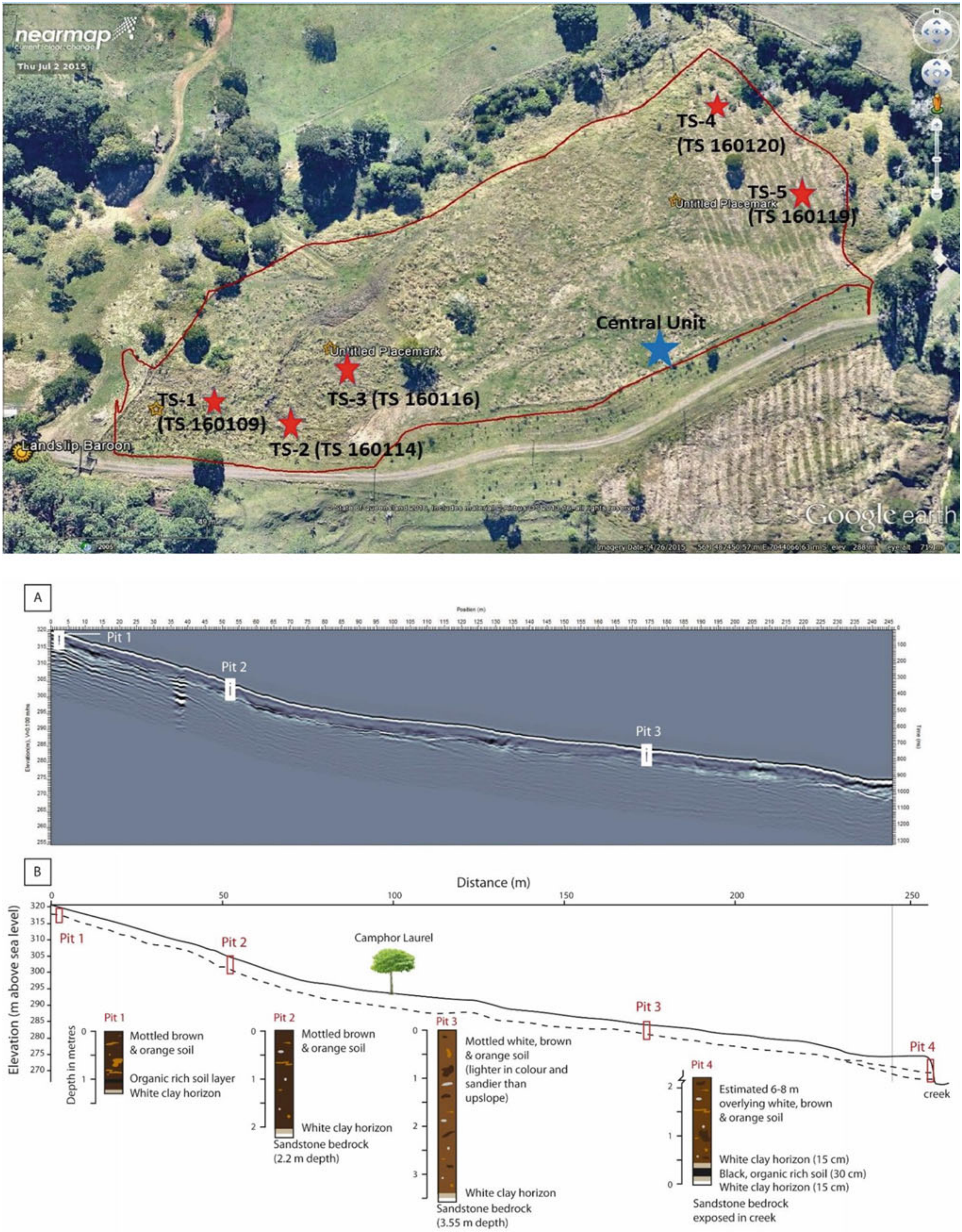


Fig. 5 **a** Locations of the sensors. X denotes the local downslope direction, whereas Y denotes the direction perpendicular to downslope. **b** Cross-section from the above GPR profile, showing the position of the white clay/bedrock reflector (dashed line)

Table 1 Soil index properties

Classification test	Results
Grain size	% finer than 75 μm > 79%
Distribution	Clay % = 41.0%
Atterburg limits	LL = 67.2% PI = 28.2%
Linear shrinkage	LS = 13.4%

Soil Properties

The soil extracted from the monitoring site was subjected to laboratory tests to determine the required soil properties for the numerical analysis. Table 1 summarises the results of the laboratory tests conducted to determine the index properties of the soil according to Australian standards.

Strength Properties

Strength properties of the soil were determined by the direct shear test, in which all the samples were prepared to achieve a dry density of 1.25 g/cm^3 to replicate the in situ dry density of the soil. Direct shear tests were conducted for four different water contents. Figure 6 shows the variation of apparent cohesion with gravimetric water content. However, the soil friction angle did not significantly vary with the gravimetric water content, which was determined as 15.90.

The pre-2008 landslide topography was subsequently reset by pushing failed soil and colluvium back onto the original slope. Vegetation (planting and growing trees) was suggested as an effective slope stabilization method for this area. Additionally, the five inclinometers slope monitoring experiment were installed. The real-time slope monitoring system aimed to measure the efficacy of revegetation as a slope stabilization method for this slope (Abeykoon et al. 2018).

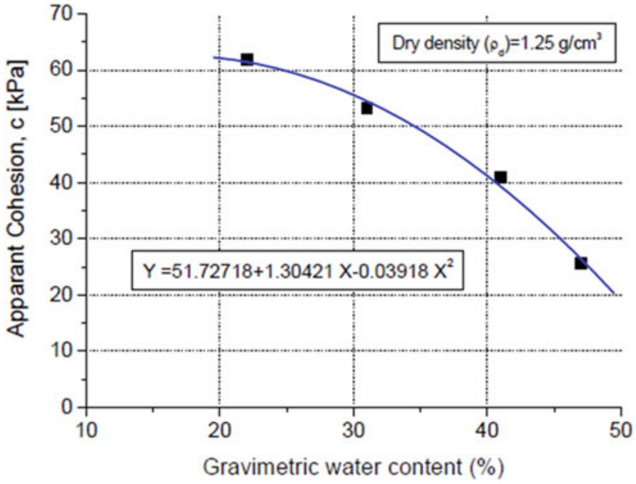


Fig. 6 The variation of apparent cohesion with gravimetric water content

The real-time monitoring system that consists of five sensor units (TS1, TS2, TS3, TS4, and TS5) and a central logging station was installed in the slope as shown in Fig. 5. Each sensor unit consists of a logging and transmission unit, MEMS tilt sensor, volumetric soil moisture sensor, and temperature sensor. The central unit comprises a central data logger, power supply unit (solar panel and back-up battery), data receiving unit (from sensor units), rain gauge as shown in Fig. 5a.

After characterizing the soil profile by determining the interface between soil and underlying bedrock by ground penetrating radar (GPR) survey, four locations were selected to excavate pits for determining the composition of soil layers, soil layer thicknesses and verification of GPR survey results. Figure 5b illustrate the longitudinal GPR profile and the GPR survey transect line and a cross-section of soil profile along the transect line with the locations of excavation pits, respectively.

The tilt angles accumulated distribution due to each rain are summarized as Fig. 7, which included the accumulated distribution results from 15/Jun/2016 to 01/Nov/2016. Red means the inclinometer is tilted in the direction of the landslide slope, and blue means the inclinometer is tilted in the opposite direction of the slope. It was found that the slope was clearly deformed as the time was increased. This slow movement is considered a typical landslide deformation.

TS1, which is located at top of the slope failed area, tilted (rotated) more than 2 degree in slope-direction during this period. TS2 which is located outside the failed area did not respond to the failure of the slope. However, TS2 started showing minor rotation with the reactivation of the failure above its location, which could be due to overloading the area of TS2 by the failed soil mass above its location. TS3, which is located at center of the slope, tilted (rotated) more than 2 degree in opposite direction of landslide slope. TS5, which is located at bottom of the landslide slope, is rotating in the direction of the slope, was pushed by the top mass of slope failure.

These results clearly show the movement of the entire slope shown in Fig. 7 as time order. It can be seen that the head and the bottom of the slope are inclined in the direction of landslide slope inclination, and the middle of the slope is a circular arc slide. By arranging five sensor arrays, it is thought that false alarms can be prevented by issuing an alert based on the movement of the entire slope, instead of local fluctuations based on a single sensor result.

Figure 8 shows the aerial view of the landslide area that the photos were taken in 28/Oct/2017, and Fig. 9 shows the aerial view of the landslide deformation area that the photos

Fig. 7 Distribution of accumulated tilt angle of year 2016

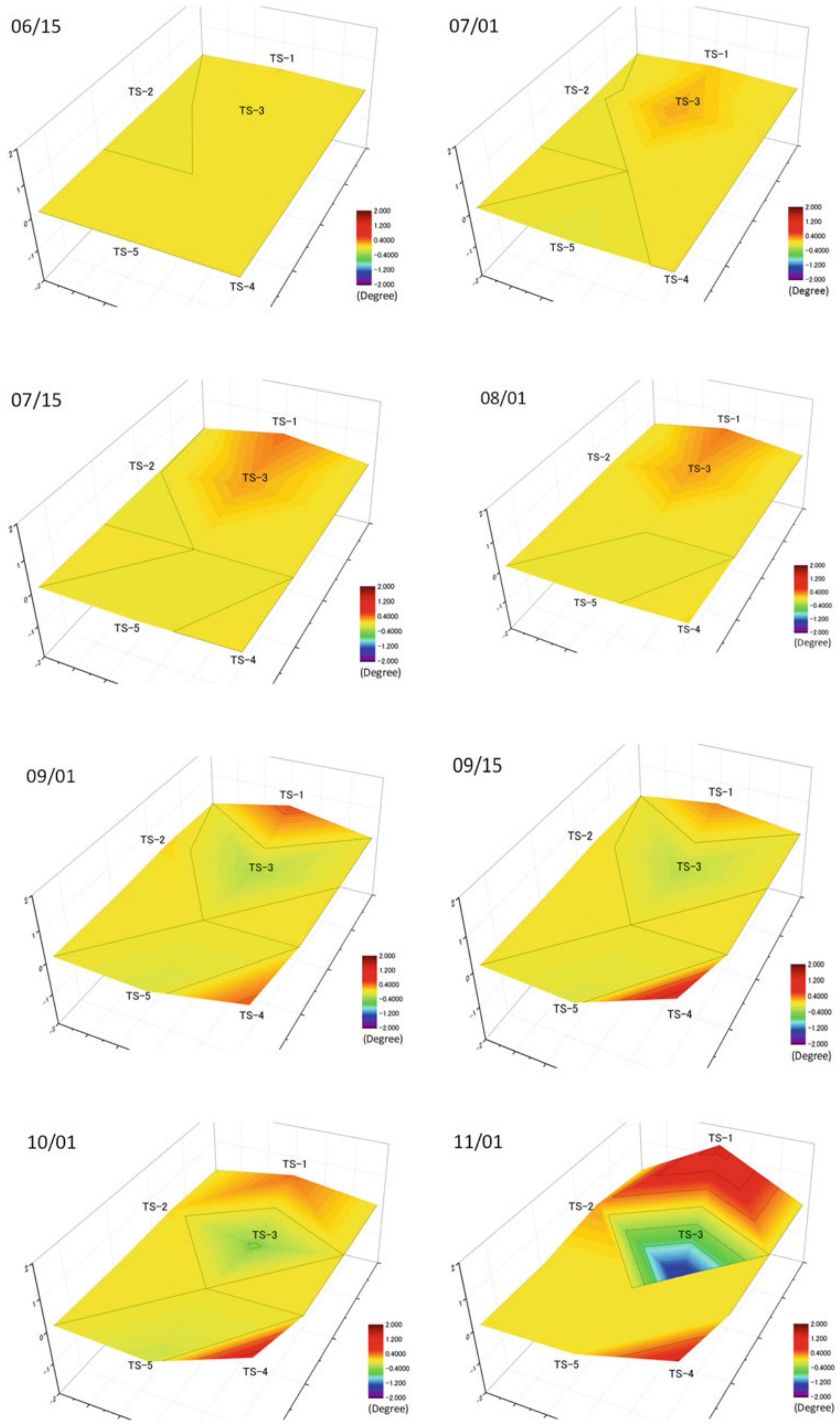


Fig. 8 Areal view of the landslide area (28/Oct/2017)

Fig. 9 View of the landslide area (20/Feb/2018)

taken in 20/Feb/2018. These photographs show that the results correspond to the landslide collapse measured by the sensor array.

Monitoring Slope Failure at Manzawa, Yamanashi, Japan

The Manzawa area in the Yamanashi Prefecture of Japan contains a large-scale reactivation of old slope failures featuring rockfalls that involve the detachment and rapid downward movement of rock.

Because most traditional slope monitoring methods are expensive, difficult to control and may not be suitable for application in this civilian area, the simple and low-cost monitoring system was deployed on a test slope to validate field performance. It should be noted that the research is supported by the Japanese Government, and the following result that is reported in this paper is intermediate.

Figure 10 shows the scale of Manzawa slope failure site, and Fig. 11 shows the arrangement of the multi-point tilt sensors and locations, where two types of tilt sensor were used. The arrangement interval of the sensor is designed to 5 m. A total of 66 sets of sensors were deployed.

The system proposed in this study implemented wireless sensors consisting of MEMS accelerometers to measure tilt from angular movements. This orientation change data from the MEMS accelerometers were transmitted wirelessly to a remote monitoring facility. A real-time monitoring system would be an effective tool for the transmission of alerts and immediate activation of emergency procedures, thus providing ample time to save lives and property.

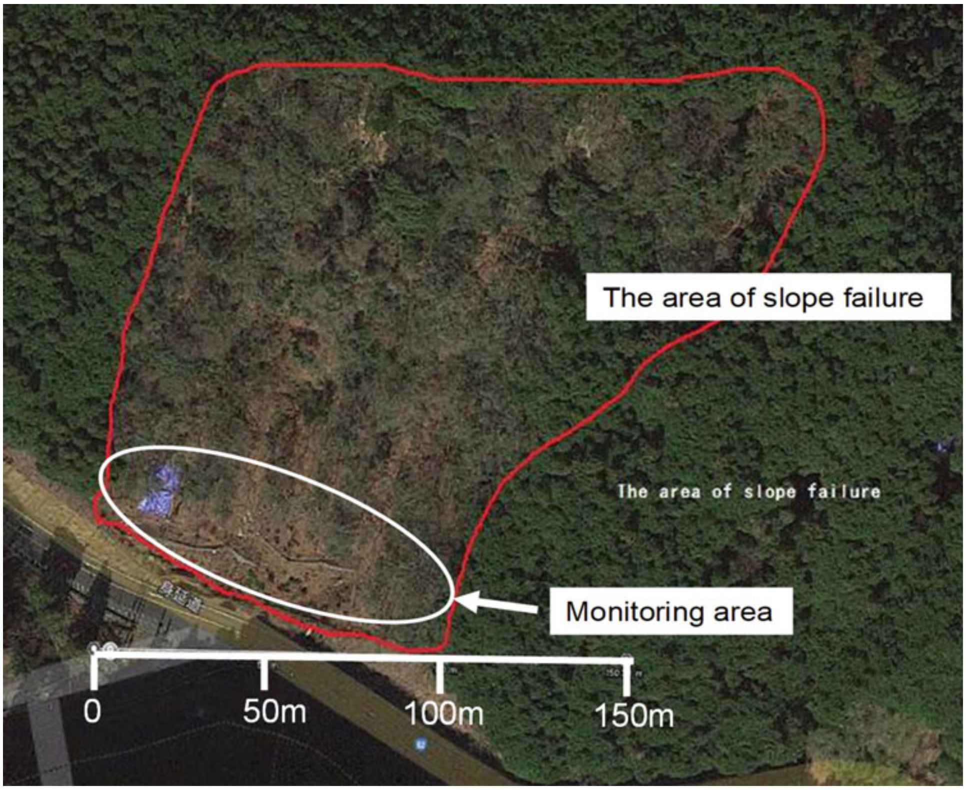


Fig. 10 Area of slope failure at Manzawa site, Japan

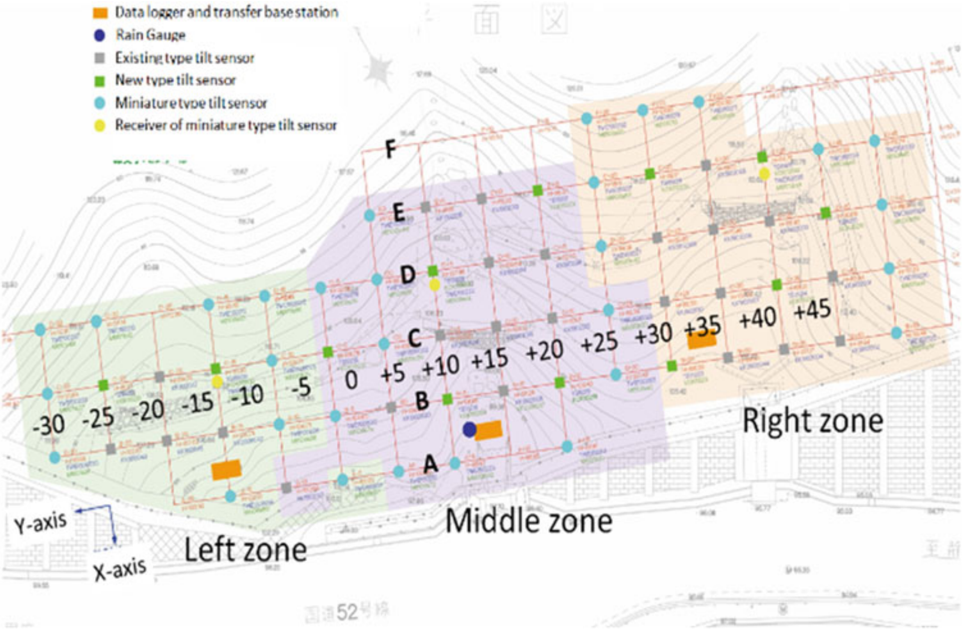


Fig. 11 Arrangement of the multi-point tilt sensors

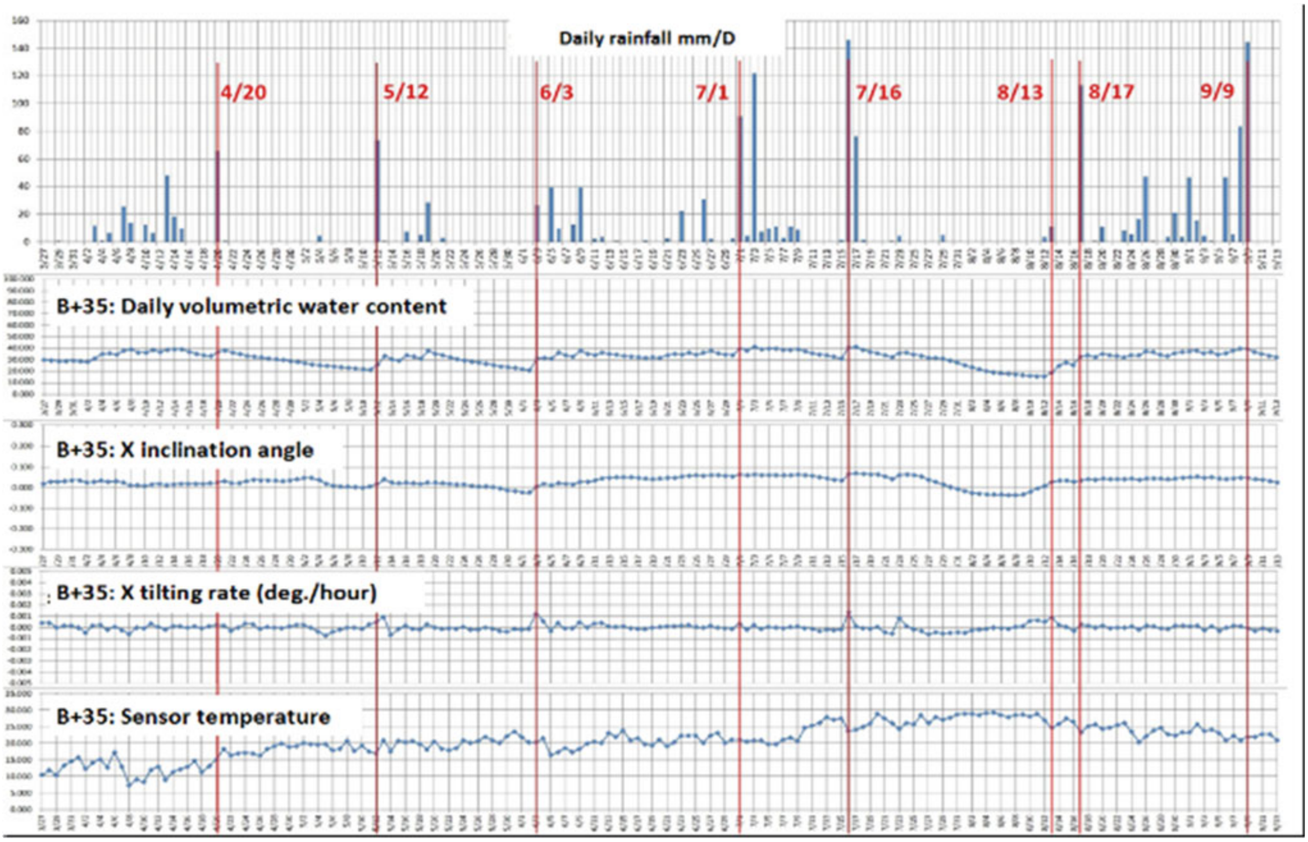


Fig. 12 Time histories of movements in rainy days

Necessary components of the system include sensors with the required resolution and software with the capacity for signal interpretation and failure alert algorithms. The challenges exist in identifying methods to minimize energy consumption of the units (i.e. improving battery life), keeping the appropriate number of devices for deployment and recognizing patterns of movement so that incipient sliding can be distinguished from random movements and environmental effects. The requirement for battery lifetime should ideally be longer than one year to reliably monitor the most critical time period without interruption and multiple year lifetimes should be achievable given the progress being made in battery technology.

Algorithms can then be developed to account for these movements and the sensitivity of these to varying threshold values can be evaluated. Finally, an effective early warning system can be developed.

The 66 sensor units are divided into three groups, left/middle/right zone, and one data receiver unit and one logger/gateway unit for internet collect all the data from respective group as shown in Fig. 11. There were eight heavy rainfall events during summer of 2015 shown in Fig. 12, and the tilt angles accumulated distribution due to each rain are summarized as Fig. 13. The tilting rate averaged during each rainfall event is shown in Fig. 14. Distribution of tilting behaviours is figured out by multi-point monitoring.

For practice, criteria for issuing early warning have to be defined based on data from the large number of sensors. One of very simple index for the criteria is simple sum of tilting rate from the sensors:

$$V_{alarm} = \sum_{n=1}^{n} \left(|V_n| * \frac{A_n}{A_0} * \partial_n \right) \tag{1}$$

Here, n is serial number of tilt sensors, V_n is tilting rate of slope sliding direction at the n-th sensor, An is the area of installation of the n-th sensor, A_0 is the total area of monitored slope, and ∂_n is a constant weight for the n-th sensor decided considering geology, geography, vegetation, and other factors. As the simplest example, values calculated with n = 1 for all the sensors are indicated in Fig. 14. The rain on 4/20, 6/3, and 8/13 caused relatively higher value of V_{alarm} in this case, but did not exceed precaution threshold of 0.01°/h.

Fig. 13 Distribution of accumulated inclination angle

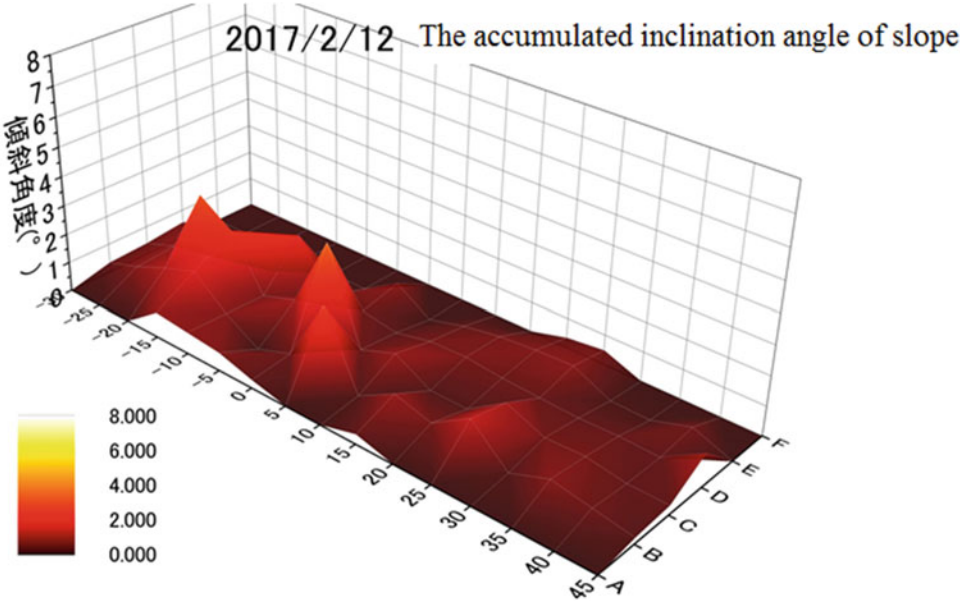
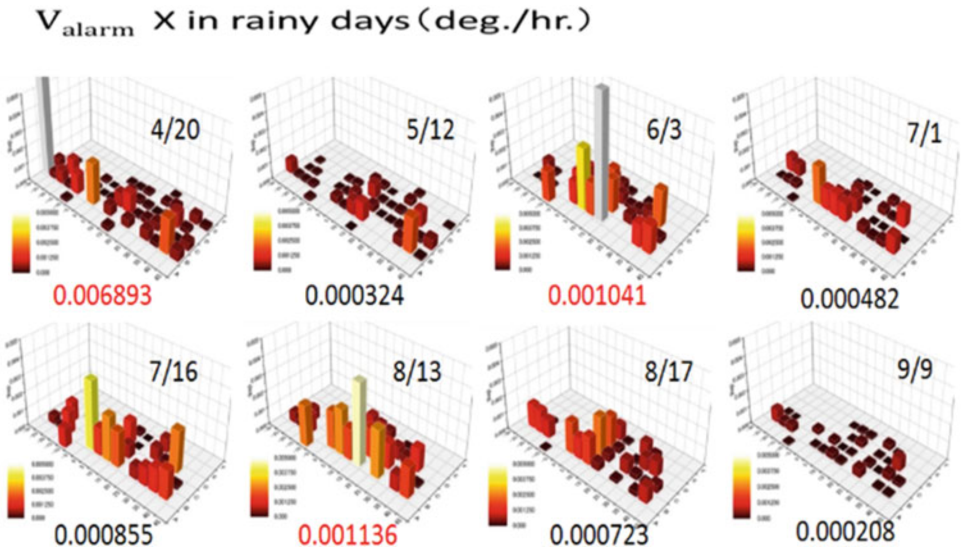


Fig. 14 Distribution of tilting rates during each rain day



Conclusion

A low-cost and simple monitoring method for an early warning system of rainfall-induced landslides has been proposed. Tilting angles in the surface layer of the slope are mainly monitored using this method and, in several case studies, distinct behaviours in the tilting angles in the pre-failure stages were detected. From this behaviour it is recommended that, from a regulatory perspective, a precaution is issued when the tilting rate of a slope is 0.01°/h, and a warning issued when the tilting rate is 0.1°/h.

Improvement in the applicability and development of the monitoring and early warning system has been made by modifying the equipment to be lower in cost, smaller in size and weight, and simpler to operate. It is estimated that the total cost for the monitoring system is reduced by one third, compared to regular systems, and thus a larger number of sensors can be deployed at the same cost (if desired). This will assist in improving data density and real-time feedback on slope behavior. These case studies will henceforth be helpful in determining the installation of sensor array of early warning system.

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