Proposed early warning system of slope failure by monitoring inclination changes in multi-point tilt sensors

Proposition de système d'alerte précoce de défaillance d’inclinaison, en surveillant les changement s d'inclinaison dans les capteurs d'inclinaison multipoints.

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ABSTRACT: A low-cost and simple method of monitoring rainfall-induced landslides is proposed, with the intention of developing an early-warning system. 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, including a slope failure test conducted on a natural slope using artificial heavy rainfall, the system detected distinct tilt behavior in the slope in pre-failure stages. Based on these behaviors 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 (approximately one-third) compared with current and comparable monitoring methods. Given the cost reduction, slopes can be monitored at many points, resulting in detailed observation of slope behaviors, 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.

RÉSUMÉ : Un faible coût et une simple méthode de surveillance des glissements de terrain induits par les précipitations ont été proposés, avec l’intention de développer un système d’alerte précoce. La surface d’inclinaison des angles d’une pente est contrôlée suivant cette méthode qui est, d’incorporer un Mems de capteur d’inclinaison et un capteur de teneur volumique en eau. Dans plusieurs études de cas, y compris le test de défaillance d’inclinaison réalisé sur une pente naturelle à l'aide de fortes précipitations artificielles, le système a détecté un comportement d'inclinaison distinct dans la pente dans les stades pré-échec. Sur la base de ces comportements et une approche prudente, on a proposé que, la précaution contre la défaillance de la pente soit émise à un taux de 0,01 ° / h de basculement. Le développement de ce système peut se produire à un coût réduit de manière significative. Compte tenu de la réduction des coûts, les pistes peuvent être surveillées à de nombreux points, résultant dans l'observation détaillée des comportements d’inclinaison, mais le nombre potentiellement élevé de points de surveillance pour chaque inclinaison fait induire une restriction financière. Par conséquent, la sélection des positions de capteurs doit être soigneusement prise en considération pour un système d'alerte précoce efficace.

KEYWORDS: landslide, slope failure, monitoring, early warning.

1 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 behavior and consequent early warning of failure provides a reasonable and slope-specific alternative.

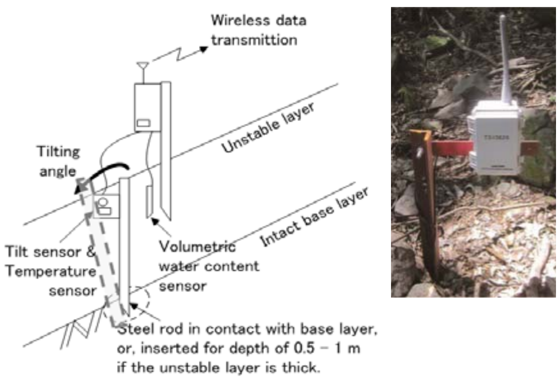

Figure 1. Schematic illustration of MEMS tiltometer sensor for early warning

In this paper, an early warning system for slope failure is proposed and its development is described (Figure 1) (Uchimura et al. 2010). 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

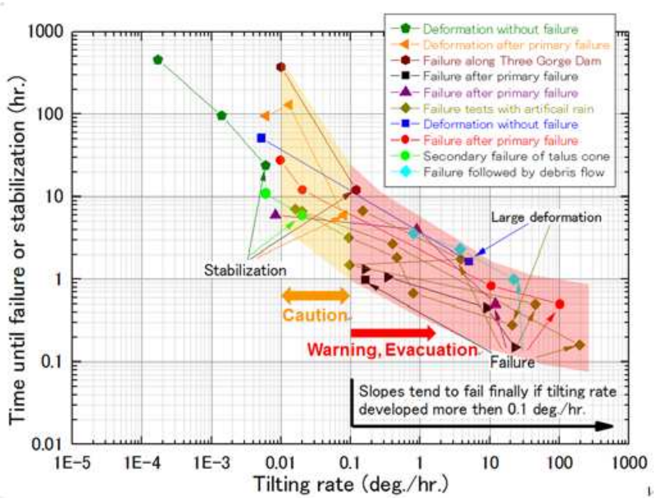

Figure 2. Graphic illustration of the tilting rate as a function of time before slope failure (or stabilization) for several case studies

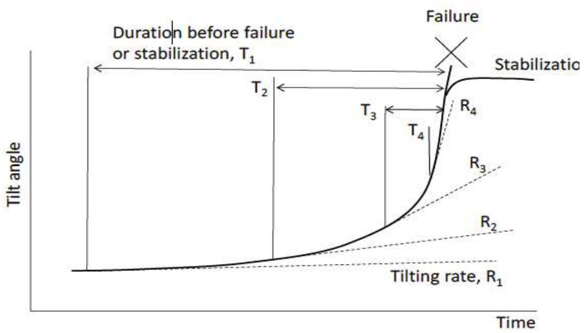

Figure 3. Definition of the tilting rate and the durations

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 the time in Figure 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 Figure 2, the order of tilting rate observed with slope deformation varied widely, from 0.0001°/h 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 failed, while it was <0.1°/h for all other cases. Durations of 1–10 h were observed before failure for a tilting rate of 0.1°/h.

Based on these 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 is 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

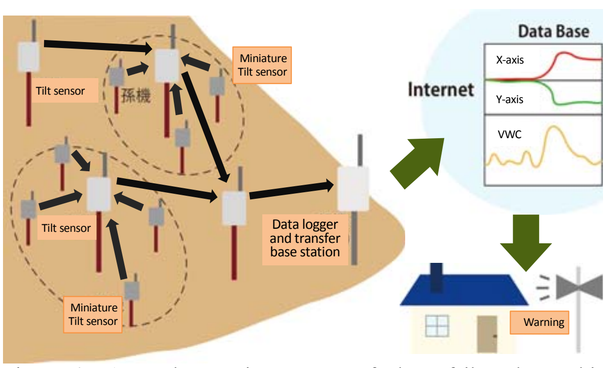

Figure 4. An early warning system of slope failure by multi-point tilt and volumetric water content

(~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.

2 DESIGN OF PROPOSED SENSOR UNIT.

2.1 *Basic specification of more cost-effective miniature tilt sensors*

The appearance of the proposed new sensor units is shown in Figure 5. A steel rod is inserted into the slope surface to a depth of 0.5–1.0 m, and the tilt sensor module is attached to the rod at a surface position to reduce data drift caused by temperature changes. It can be noted that the controller/radio module is smaller than a conventional one. As a relatively shorter transmission distance is required, the unit can be placed at a lower position, only 30–50 cm above ground. The reduction in size and weight results in a lower cost and ease of operation.

2.2 *MEMS inclinometer technology embedded to sensor unit*

The proposed system measures the inclination on the slope surface and the volumetric water content in the slope. A MEMS tilt module (nominal resolution = 0.04 mm/m = 0.0025 degree) is embedded in each sensor unit. The tilt module is a 3D-MEMS-based dual axis inclinometer that provides sensor unit grade performance for leveling applications. The measuring axes of the sensing elements are parallel to the mounting plane and orthogonal to each other. Low temperature dependency, high resolution, power-saving and low noise, together a with robust sensing element design, if we keep on leveling installation, this MEMS type inclinometer is ideal choice for slope failure sensors.

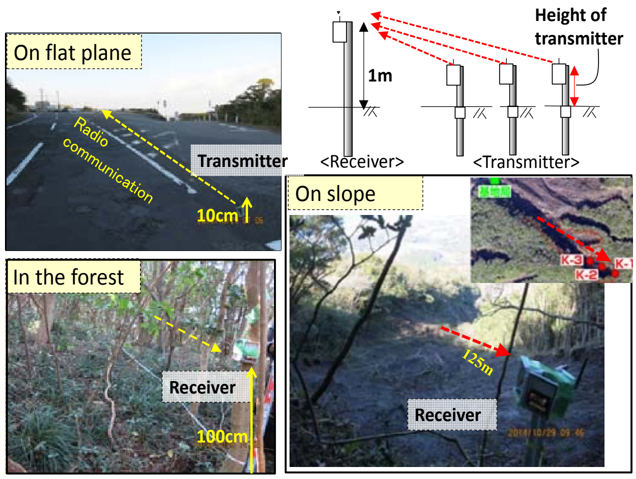

Figure 5. Evaluation of radio transmission distance of miniature tilt sensors

2.3 *Radio transmission distance*

A conventional sensor unit has sufficiently long radio transmission distance, from 300 m to 600 m under ideal conditions in the 430 MHz band. However, the proposed new sensor units have shorter transmission distances because of its use of higher radio frequency (2.4 GHz band). The available distance was carefully evaluated to allow for a reasonable arrangement of sensors (Figure 5). The receiver was fixed at a height of 1 m above the ground surface, while transmitters were set at different heights and distances from the sensors, following which the radio signal was checked.

High-frequency radio signals tend to propagate best in a straight line, and thus obstacles between the transmitter and receiver have a significant negative effect on the signal transmission.

3 FIELD VALIDATION IN JAPAN AND TAIWAN.

3 .1 *A case of detection of a cut slope at Yenchao, Kaohsiung, Taiwan*

Prototypes of the proposed new sensor units were installed on a cut slope site in Yenchao, Kaohsiung, Taiwan at the end of 2014. The slope is on a municipal waste disposal site, and the cut slope began moving gradually after excavation works were conducted during construction. The slope, consisting of modern clay shale, is sliding along the established geological jointing direction (Figure 6).

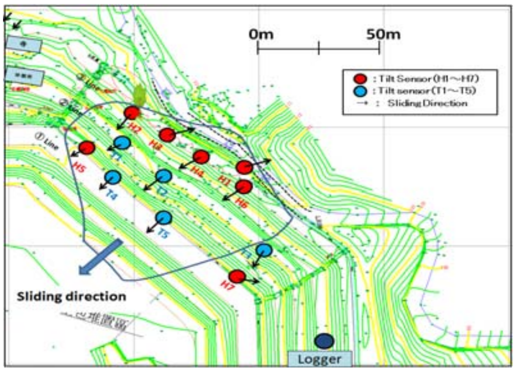

Figure 6. Arrangement of the tilt sensors on the moving cut slope

Thirteen tilt sensors were installed to adequately cover the moving block, with the tilt angle being measured every 10 minutes and corrected using data from a receiver on the opposite slope (Figure 6).

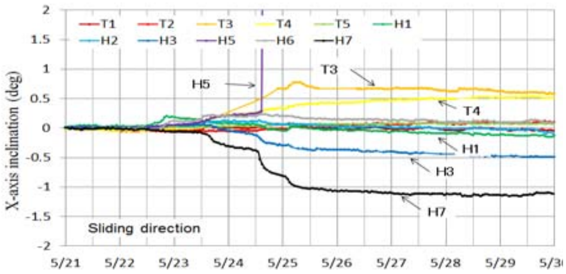

Figure 7. Time histories of X-axis inclinations

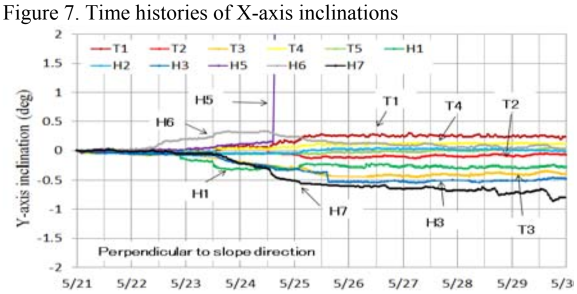

Figure 8. Time histories of Y-axis inclinations

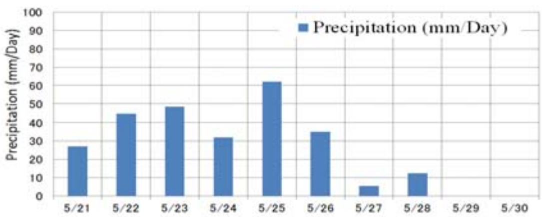

Figure 9. Rainfall record during the disaster in 2015

Figure 7 shows typical tilt behaviors of X-axis, and Figure 8 shows Y-axis behaviors with time histories. These data were obtained from 21 to 30 May 2015. Because of one week continuous rainfall shown in Figure 9, the Sensors H5, T4, T3 showed some significant inclination changes. The tilt behavior varied across sensors and there was some time delay following the heavy rainfall event. Notably, it was also found that T3, which is outside of the sliding block, recorded movement after the heavy rainfall event. Distribution of surface tilt behaviors, together with time histories, can be determined based on these data, the movement histories of every sensors can be recorded as shown in Figure 6.

3 .2 *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.

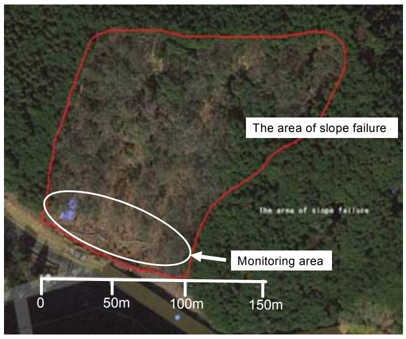

Figure 10. Area of slope failure at Manzawa site, Japan

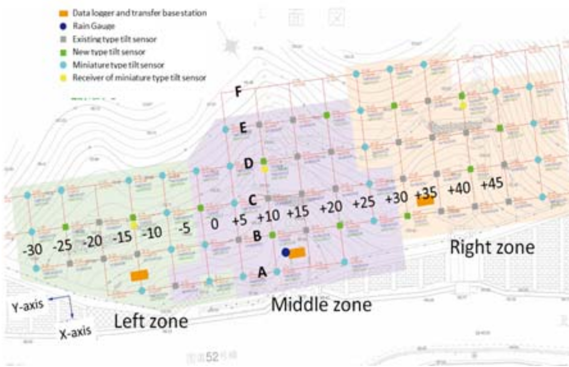

Figure 11. Arrangement of the multi-point tilt sensors

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 Figure 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 five meters. 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.

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.

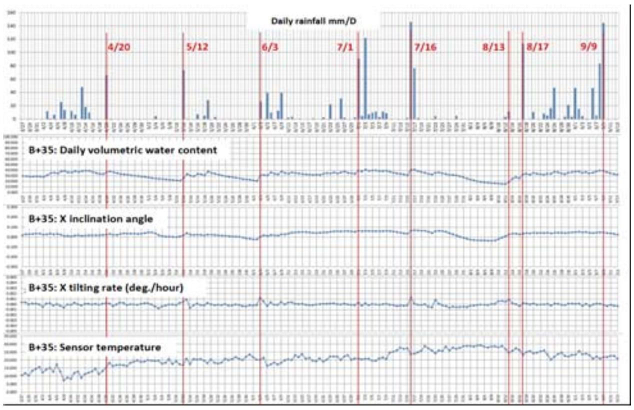

Figure 12. Time histories of movements in rainy days

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 Figure 11. There were eight heavy rainfall event during summer of 2015 shown in Figure 12, and the tilt angles accumulated distribution due to each rain are summarized as Figure 13. The tilting rate averaged during each rainfall event is shown in Figure 14. Distribution of tilting behaviors 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:

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

Here, n is serial number of tilt sensors, V_n is tilting rate of slope sliding direction at the n-th sensor, A_n 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 Figure 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.

4 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 behaviors in the tilting angles in the pre-failure stages were detected. From this behavior 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.

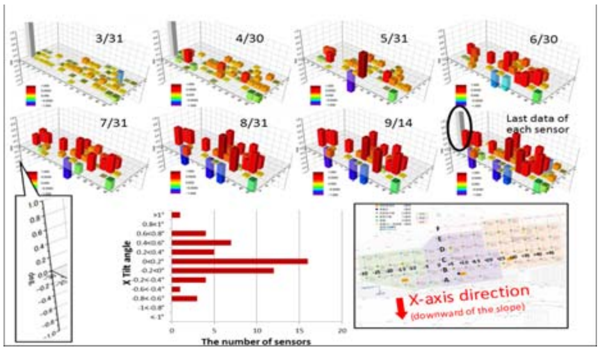

Figure 13. Distribution of accumulated inclination angle

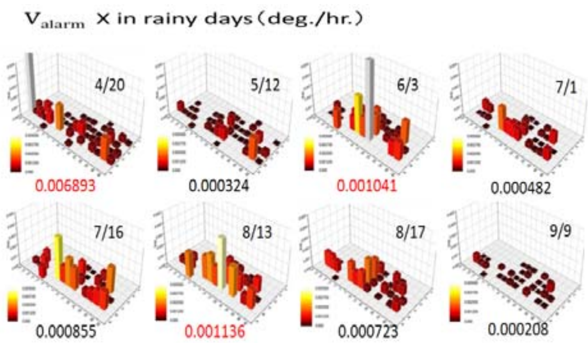

Figure 14. Distribution of tilting rates during each rain day

The prototype of the proposed new sensor units were installed on a cut slope site in Yenchao, Kaohsiung, Taiwan at the end of 2014. Whilst monitoring has only just begun, and some tilt behavior has been observed, more significant behavior may be recorded in the 2015 rainy season, which the current authors will report on.

5 ACKNOWLEDGEMENTS

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