Application of multipoint measurement using tilt sensor to slope failure and landslide monitoring

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ABSTRACT

A multipoint measurement method of monitoring rainfall-induced slope failure and 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 our past 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. This paper introduced the applications of multipoint measurement using tilt sensor to slope failure monitoring in Japan, and another two case studies of landslide monitoring in Taiwan. As result, distinct behaviors in the tilting angles of distributed tilt sensors were detected. Because of the movements of the slopes have not stopped, the warning monitoring is still necessary.

Keywords: landslide; slope failure; monitoring; multipoint measurement; early warning

1 INTRODUCTION

In this paper, an early warning system for slope failure is proposed and its development is described (Figure 1) (Uchimura, et al. 2010, 2015, and Wang, et al. 2017). The system consists of a minimum number of low-cost sensors strategically placed on a slope, with monitoring data that are collected and 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.

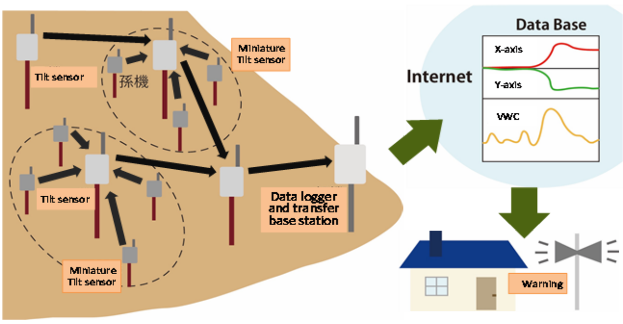

Fig. 1. An early warning system of slope failure by monitoring multi-point tilt and volumetric water content

Uchimura et al. (2015) summarized case studies of slope tilting rates during pre-failure stages obtained on several natural slope sites undergoing 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).

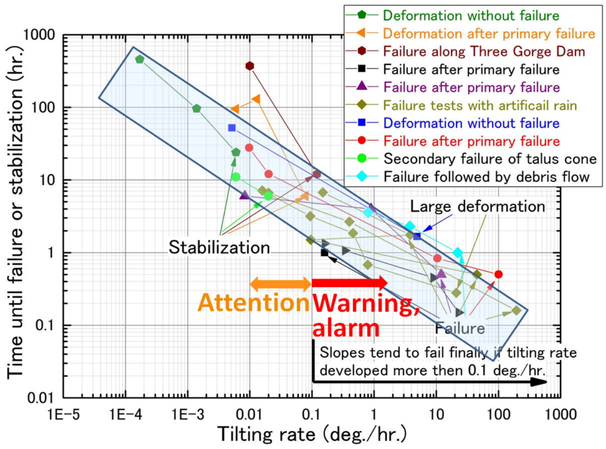

Fig. 2. Illustration of the tilting rate as a function of time before slope failure (or stabilization) for several case studies.

According to Figure 2, the extent 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 by using less expensive multi sensor technology.

2 DESIGN OF PROPOSED SENSOR UNIT

The proposed system measures the inclination at 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 with a robust sensing element design, if we keep on leveling installation, this MEMS type inclinometer is an ideal choice for slope failure sensors. The unit has sufficiently long radio transmission distance, from 300 m to 600 m under ideal conditions in the 430 MHz band (Uchimura et al. 2015).

3 FIELD VALIDATION IN JAPAN AND TAIWAN

3.1 Monitoring slope failure at Manzawa, Yamanashi Prefecture, Japan

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

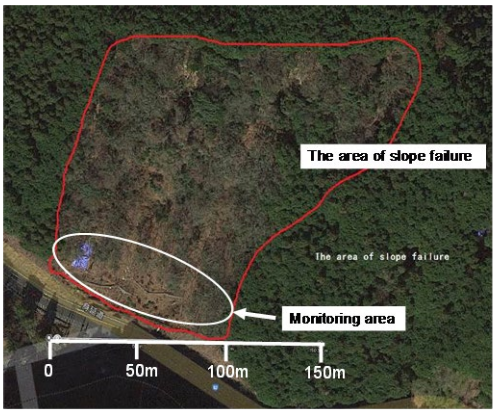

Fig. 3. Area of slope failure at Manzawa site, Japan.

Because most traditional slope monitoring methods are expensive, difficult to control and may not be suitable for application in this civilian area, the multipoint measurement monitoring system was deployed on a test slope to validate field performance.

Figure 3 shows the scale of Manzawa slope failure site, and Figure 4 shows the arrangement of the multi-point tilt sensors and locations. 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 tilt angle 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.

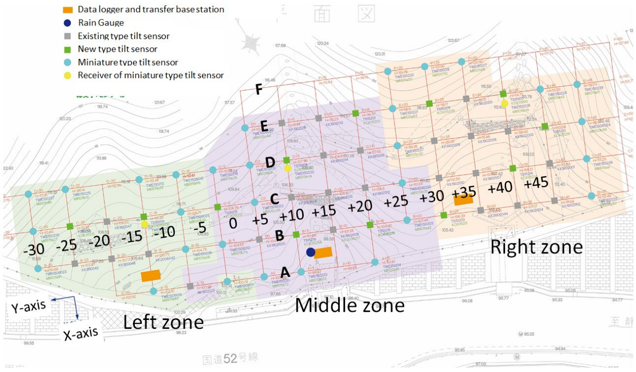

Fig. 4. Arrangement of the multi-point tilt sensors

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.

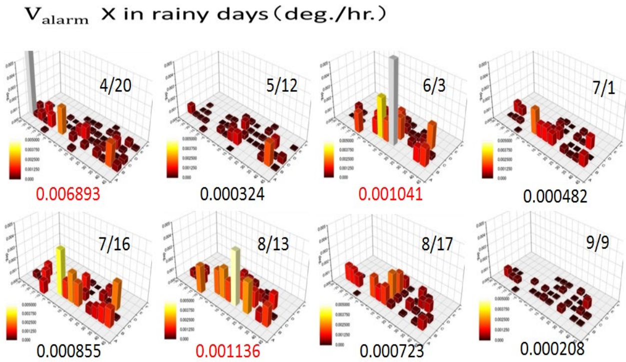

Fig. 5. Distribution of accumulated tilting rates during each rainfall event day.

The 66 sensor units are divided into three groups(Fig.4), left/middle/right zone, and one data receiver unit and one logger/gateway unit for internet collect all the data from respective group. There were eight heavy rainfall events during summer of 2015, and the tilting rate averaged during each rainfall event is shown in Figure 5. Distribution of tilting behaviors is demonstrated 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 the very simple indices for the criteria is a simple sum of tilting rate from the sensors(Wang et al. 2017):

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

Here, n is serial number of tilt sensors, V_n is tilting rate in 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. 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. It means that this slope is not in emergency situation.

3.2 The application of landslide monitoring at Zhongpu Township, Chiayi County, Taiwan

Multi-point tilting monitoring units were installed on a landslide site in Zhongpu, Chiayi County from Jun. of 2017. The slope is close to national route No.135-2, shows typical landslide phenomena, and is moving gradually after rainfall. Figure 6 shows the full appearance of slope, which consist of shale and sandstone shale interbed with shaly sandstone and limestone. The slope is sliding along the established geological joint direction.

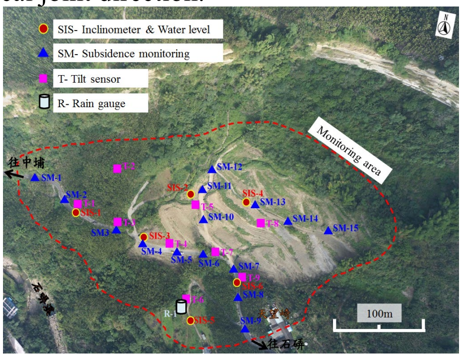

Fig. 6. Arrangement of the tilt sensors on the moving slope of national route No.135-2

To investigate the road subsidence and the possible sliding movement mechanism of slope movement, following survey methods such as geology and hydrological survey, monitoring of slope movement using tilt sensros, borehole inclinometer and water level were carryied out from Jun. of 2017. Especially, multipoint measurement is a feature of this monitoring as shown in Figure 6. Nine tilt sensors were installed to adequately cover the moving block, with the tilt angle being measured every 10 minutes and collected using data from a receiver on the opposite slope (Figure 6).

The cracks and lateral deviation of the retaining wall outside the national route No.135-2 is shown in Figure 7. The traffic was stopped by these damages.

Figure 8 shows the results of XY combined inclination value and daily rainfall of tilt sensor T9 at the top of the slope, which is near the retaining wall where many cracks and lateral deviation happened. Tt was found that the rate of inclination clearly changed on rainiy days based on a half year observation from Jun. of 2017.

Fig. 7. The cracks and lateral deviation of the retaining wall outside the national route No.135-2

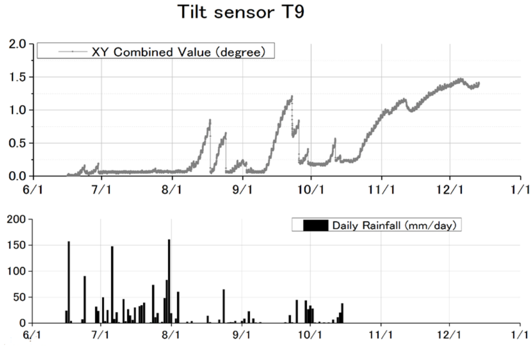

Fig. 8. The inclination value and daily rainfall of tilt sensor T9 on top of Zhongpu slope sit, near to national route No.135-2

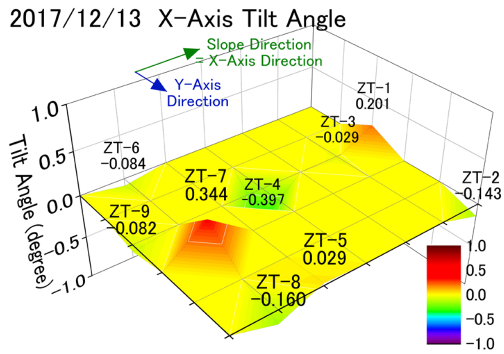

Fig. 9. Distribution of tilt angle at X-axis (slope) direction.

A three-dimensional view of the inclination distribution of slope direction is illustrated in Figure 9. The half year result shows that the head (Sensor ZT-9) and the bottom(Sensor ZT-1) of the slope had a relatively large incline toward the slope direction. A relatively large tilting/inclination also occurred in the middle part(Sensor ZT-4) of the slope toward the opposite direction of the slope. However, all cumulative tilt angles(TS-2 = 0.201deg, TS=-0.394deg and TS-9=0.082) do not exceed 1 degree. At the same time it became clear that all values did not exceed 0.01°/h of the alarm value. Even so, the movement of the slope has not stopped. Therefore warning monitoring is still necessary.

3.3 The applications of landslide monitoring at Zhuqi Township, Chiayi County, Taiwan

Another monitoring slope site is near to national route No.119 in Zhuqi, Chiayi County. Monitoring started with the same purpose as Zhongpu site (Fig.10). It also showed typical landslide phenomena of sliding down at top of slope, and cracks in the national route No.119 as shown in Figure 11.

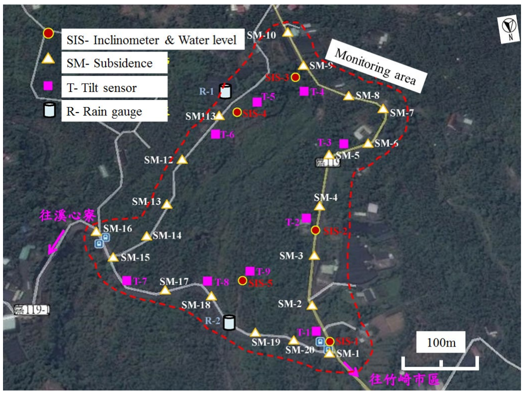

Fig. 10. Arrangement of the tilt sensors on the moving slope of the national route No.119

Fig. 11. Head scarp at top of slope and cracks in the national route No.119

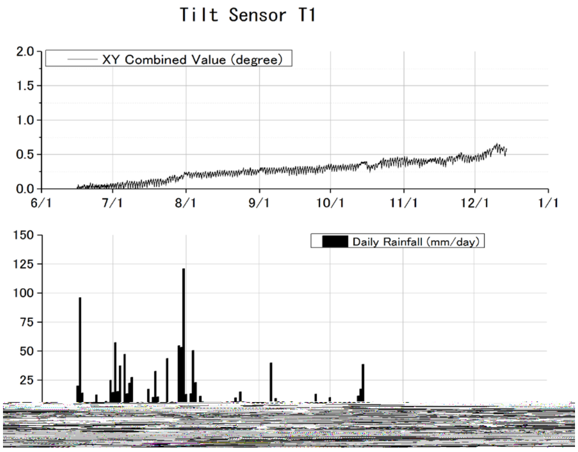

Fig. 12. The inclination value and daily rainfall of sensor T1

Figure 12 shows typical sensor T1 behaviors of XY combined inclination with time histories for which data were obtained from Jun. to Dec. 2017. Notably, sensor T1 is located intersection of route No.119, and constantly recorded the change of inclination regardless of rainfall.

Fig. 13. Distribution of tilt angle at X-axis (slope) direction.

A three-dimensional view of the inclination distribution of slope was shown in Figure 13. The result shows that the top (ZHT-6) and bottom(ZHT-1) of the slope have relatively large changes of inclinations. However, all cumulative tilt angles(T1=0.541deg, T6=0.481deg,etc) were very small value with more than half a year observation, and never exccessed the 0.1°/h of predetermined threshold value, but the movement of the slope has not stopped.

4. CONCLUSION

Multi-point tilting monitoring method for an early warning system of rainfall-induced landslides was proposed. Tilting angles at the surface of a 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. Based on a recommended method of precaution issue, above sites never exceeded the predetermined threshold value, but the movement of the slope has not stopped, and it is recommend that warning monitoring is still necessary.

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