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Research Paper

An early warning monitoring of Earthquake-induced slope failures by monitoring inclination changes in multi-point tilt sensors

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A B S T R A C T

An early warning monitoring system is one of the most effective ways to reduce disasters induced by slope instability. The 2016 Ms 7.3 Kumamoto earthquake, which occurred in Kumamoto prefecture, Japan, induced more than 190 large scales of slope failures (123), debris flows (57) and landslides (10). A system of distributed tilt sensors for early warning monitoring of earthquake-induced landslides and slope failures has been proposed. Tilt angles in the surface layer of a slope were monitored using this method and, in several case studies, distinct behaviors in tilt angles in pre-failure stages were detected. Based on this behavior, it is recommended, from a regulatory perspective, a precaution be issued when the tilting rate of a slope is 0.01°/h, and a warning be issued when the tilting rate is 0.1°/h.

1. Introduction

An early warning monitoring system is one of the most effective ways to reduce disasters induced by slope instability. The 2016 Ms 7.3 Kumamoto earthquake, which occurred in Kumamoto prefecture, Japan, induced more than 190 large scales of slope failures (123), debris flows (57) and landslides(10) (Ministry of Land, Infrastructure, Transport and Tourism of Japan HP). Moreover, there are more than 270,000 potential slope failures in Japan (Osanai et al., 2009). To reduce vulnerability to such slope and landslide hazards, it is important to develop a system of low cost, in comparison with the traditional instrumentation of inclinometers and extensometers, which can provide effective early warning. For this purpose, a new monitoring method, developed by the authors, of using distributed tilt sensors has been adopted by SIP (Cross Ministerial Strategic Innovation Promotion Program) of Cabinet office, Government of Japan. This system comprises a simple multipoint method of monitoring landslides and slope failures, with the intention of developing an early warning system. Surface tilt angles of slopes are monitored using this method, which incorporates a MEMS (Micro Electro Mechanical Systems) tilt sensor and a volumetric water content sensor. This system has been applied on some disaster fields of earthquake-induced slope failures in Kumamoto prefecture. In several case studies, the system detected distinct tilt behavior in the slope in the pre-failure stages. Based on the detected behaviors and with the adoption of a conservative approach, it is proposed that a precaution for slope failure be issued at

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Note: Discussion on this paper is open until September 2018.

a tilting rate of 0.01°/h and a warning of slope failure be issued at a tilting rate of 0.1°/h (Uchimura et al., 2015). The deployment of the developed system can be achieved at significantly reduced cost compared with

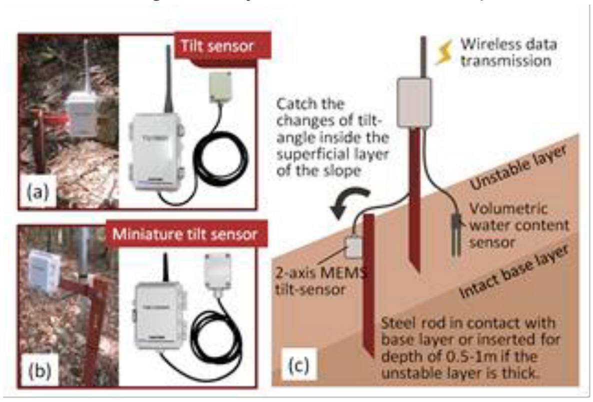

Fig. 1. Schematic of MEMS tiltometer sensor used for early warning.

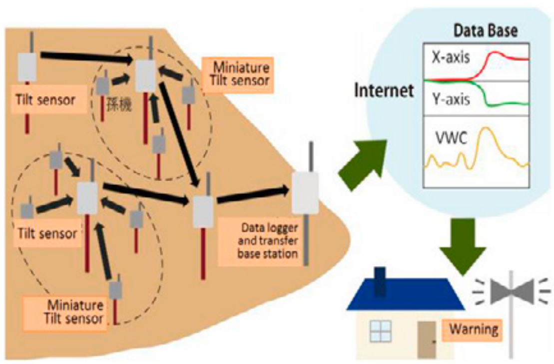

Fig. 2. Early warning system for slope failure based on multipoint tilt and volumetric water content

current and comparable monitoring methods.

Figure 2 illustrates a typical arrangement of the two proposed sensors with their data transfer pathways also shown. Despite the advantages described above, the modified miniature tilt sensors have relatively short radio transmission distances (~30 m in non-ideal conditions). The sensors are distributed densely on high-risk areas of a slope, where one conventional tilt sensor unit collects all the data of that area. These data are then transmitted over greater distances (300–600 m) and uploaded to an Internet server.

2. Micro electro mechanical systems inclinometer technology embedded within sensor unit summary and conclusions

The proposed system measures the inclination on the slope surface and the volumetric water content in the slope. A Micro Electro Mechanical Systems (MEMS) tilt module (nominal resolution = 0.04 mm/m = 0.003°) is embedded within 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. The inherent features of low temperature dependency, high resolution, power saving, and low noise, together with a robust sensing element design, if we keep on leveling installation, mean that this MEMS-type inclinometer is an ideal choice for slope failure sensors.

3. Field evaluation

3.1 Field evaluation of the new tilt sensor method and comparison with traditional instruments

A field evaluation of the new tilt sensor method and a comparison with traditional extensometers and borehole inclinometers was undertaken in Japan. A set of field measurements is shown in **Figure 3.** These concern a period of heavy rainfall in July 2011 that caused slope failure along a local highway in Kyushu, Japan. During road construction on that involved substantial earthworks, an emergency monitoring system using multiple borehole inclinometers, extensometers, tilt sensors, and rain gauges was established at the slope failure site. To validate the newly developed tilt sensor with field extensometer data, three tilt sensors were collocated near the fixed poles of the extensometers, as shown in **Fig. 3.** At this field location, four additional boring surveys have been undertaken and multiple borehole inclinometers have been installed. Two of the tilt sensors (K-2, K-3) were deployed near survey holes BI-2 and BI-3. **Figure 4** shows the temporal histories of the tilt sensor inclination in the direction of the extensometer wire (tilt sensor X-axis), movement of the extensometer (S-1, S-2), and displacement of the borehole inclinometers (BI-2, BI-3). **Figure 4d** shows the cumulative rainfall values

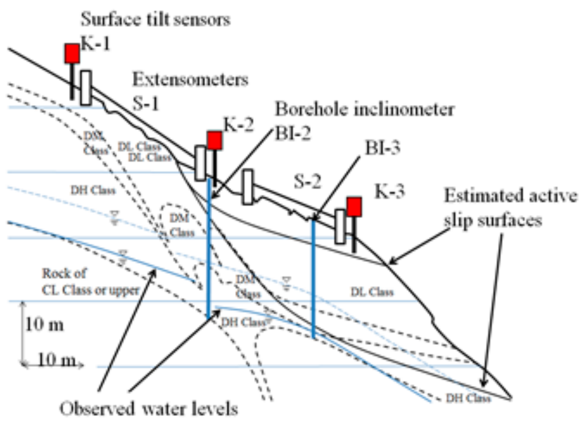

Fig. 3. Arrangement of instruments in the evaluation field

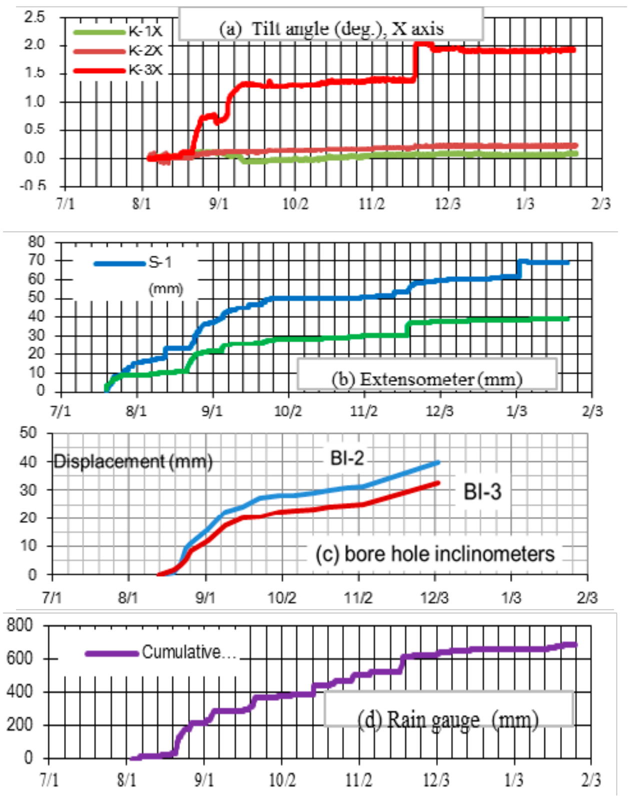

Fig. 4. The time histories of field evaluation results

recorded by the rain gauge.

Normally, the fixed pole of a tilt sensor is inserted into a slope surface to a depth of 1.0 m, such that the inclination of the tilt sensor corresponds to the average movement of the slope surface. The results show that the inclinations of the tilt sensors (especially K-3) and the movement of the extensometers increased with rainfall, and they showed strong correlation (**Fig.** 4a–d). Almost the same amount of movement was found between the extensometers, tilt sensors, and borehole inclinometers.

3.2 Field evaluation of the tilt sensor early warning system – Kumamoto, Japan

There is a long record of seismically induced slope displacements or failures triggered by changes in environmental conditions in Kumamoto. On April 16, 2016, the Ms 7.3 Kumamoto earthquake induced more than 190 slope failures and landslides. To reduce human vulnerability to such as second disasters and to improve the management of such events, an early warning system should be implemented. The development of an appropriate early warning system has been undertaken using real-time data monitoring of tilt angles, water content, and rainfall. The monitoring system have been deployed at 3 sites, where are located to the west of Aso Nishihara Village in the Kumamoto, to avoid second disaster when road reconstruction works by the authors. The equipment arrangements of each site are shown in **Fig. 5**. Two slope failures occurred in the early morning of June 20-21, 2016, triggered by ten hours of precipitation totaling 200 mm. Small-scale slope failure in site (a) occurred at the position of wireless sensor unit K-2 (**Fig. 6**) on June 21, 2016, with an accompanying increase in rainfall. Another two wireless sensor units maintained normal operations. The monitoring system perceived the abnormal behavior from the wireless sensor, and the caution notice and warning were issued automatically.

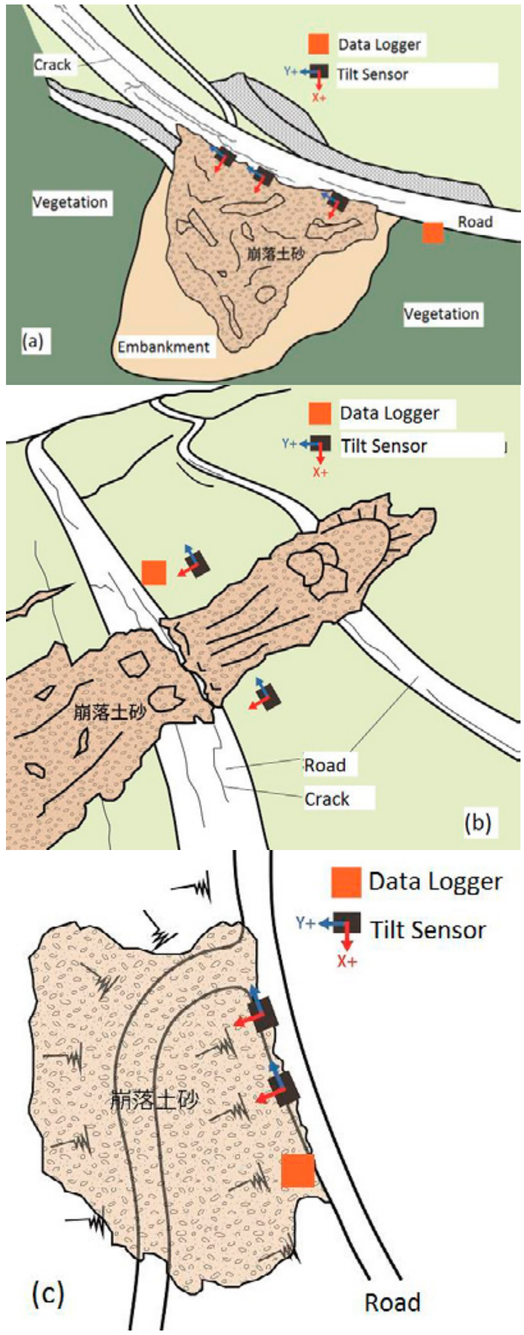

Fig. 5. Arrangements of tiltometer sensor used to 3 sites of disaster slope for early warning

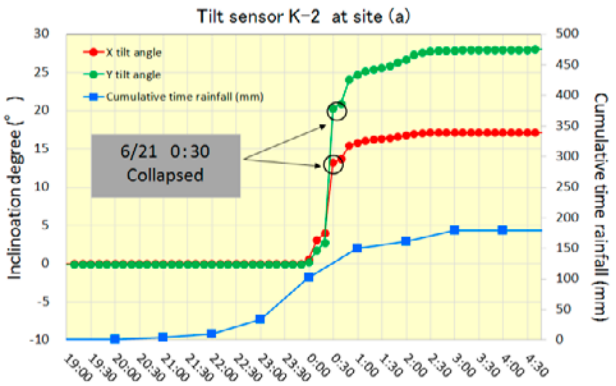

Fig. 6. Tilting and rainfall results of monitoring in site (a)

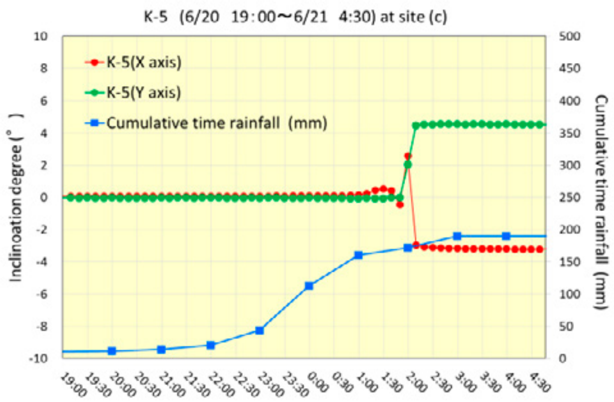

Fig. 7. Tilting and rainfall results of monitoring in site (c)

Figure 7 shows how the inclination of the tilt sensor K-5 and the cumulative rainfall in site (c). On this slope, the real-time monitoring system was initiated with three sensor units. The collapse of the slope was triggered by ten hours of precipitation totaling 200 mm. At 02:00 on June 21, the system showed that the tilt angles of the X- and Y-axes had notable changes. The output values of the tilt sensor reached the setting warning limits, and a warning issue was send out at same time.

Because of both the slope failures at the time of failure were detected successfully by the monitoring system. Based on the field site results, the new monitoring method is considered able to provide suitable information for assessing seismically induced slope failure hazards.

3.3 *Distributed tilt sensors monitoring of slope failure at Manzawa, Yamanashi, Japan*

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

Because most traditional slope monitoring methods are expensive, difficult to control, and might not be suitable for application in areas of large-scale slope failure, the simple and low-cost monitoring system was deployed on a test slope to validate its field performance. It should be noted that the research is supported by the Japanese Government, and that preliminary results only are reported here.

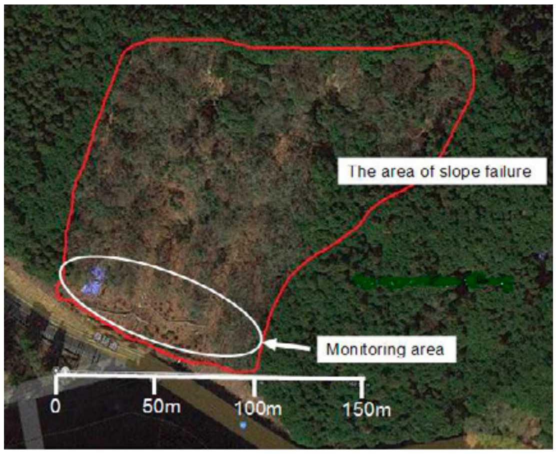

Fig. 8. Area of slope failure at Manzawa field

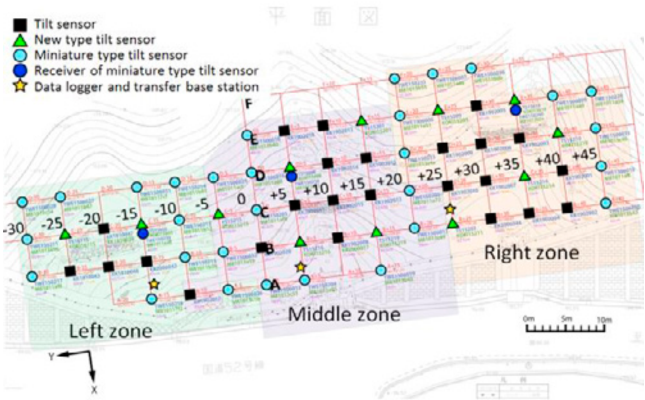

Fig. 9. Arrangement of the multi-point tilt sensors

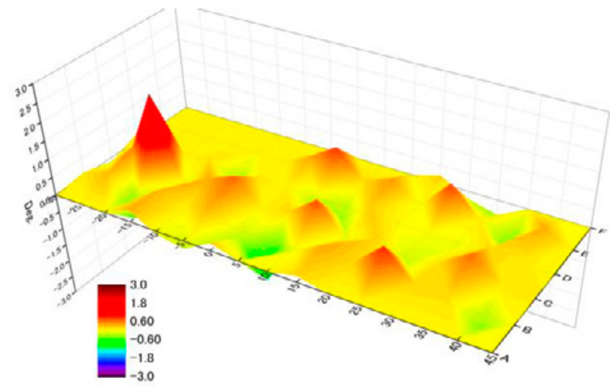

Fig. 10. Distribution of accumulated inclination angle

Figure 8 shows the scale of the Manzawa slope failure site and **Fig. 9** shows the arrangement of the multipoint

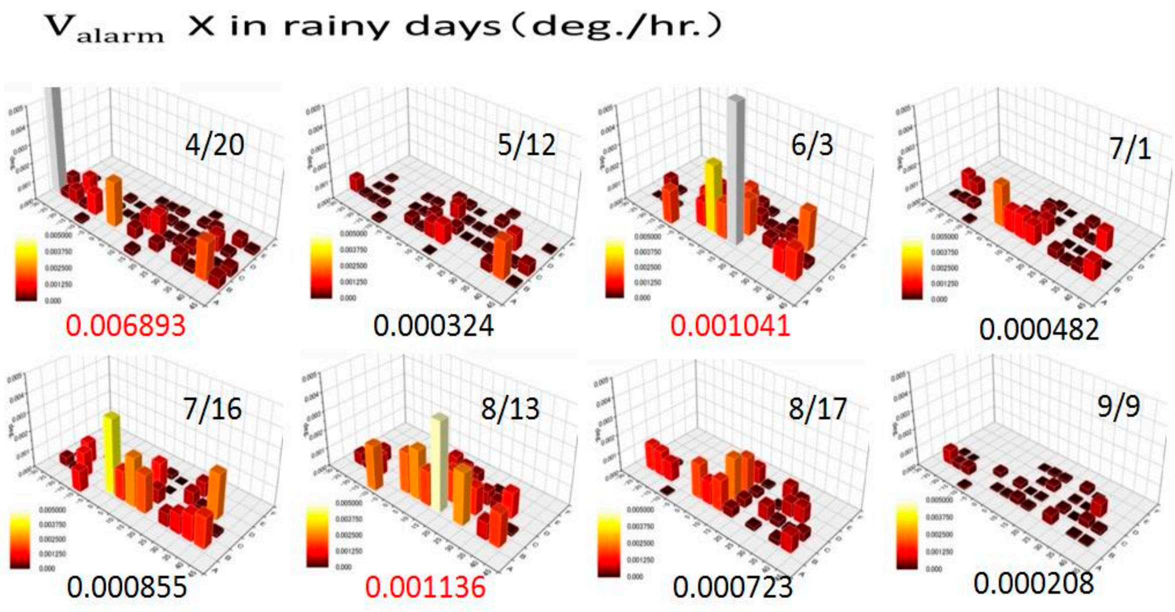

Fig. 11. Distribution of tilting rates during each rain day (>50mm/hr)

tilt sensors and their locations; note that two types of tilt sensor were used. The spacing between sensors was 5 m and 66 sets of tilt sensors were deployed. The necessary components of the system include sensors with the required resolution and software with the capacity for signal interpretation and failure alert algorithms. Challenges exist in identifying methods to minimize the energy consumption of the units (i.e., improving battery life), keeping the appropriate number of devices for deployment, and recognizing patterns of movement such that incipient sliding can be distinguished from random movements and environmental effects.

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 were divided into 3 groups (left, middle, and right zones), and 1 data receiver unit and 1 logger/gateway unit for Internet connectivity collected all the data from their respective groups, as shown in **Fig. 9**. There were eight heavy rainfall events during summer 2015, and the accumulated distribution of tilt angles is summarized in the 3D graph in **Fig. 10**. The tilting rate averaged during each rainfall event, when the rainfall was >50 mm/h, is shown in **Fig. 11**. The distribution of tilting behaviors is determined based on multipoint monitoring.

In practice, the criteria for issuing early warnings have to be defined based on data from a large number of sensors. One very simple index is based on the sum of the tilting rates from all the sensors:

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

Here, n is the serial number of tilt sensors, V_n is the tilting rate of the 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 the monitored slope, and n is a constant weight for the n-th sensor decided based on consideration of the geology, geography, vegetation, and other factors. As the simplest example, values calculated with n = 1 for all the sensors are indicated in **Fig. 11.** The rain on 4/20, 6/3, and 8/13 caused relatively higher values of V_{alarm}, but without exceeding the precaution threshold of 0.01°/h.

4. Conclusions

A system of distributed tilt sensors for early warning monitoring of earthquake-induced landslides and slope failures has been proposed. Tilt angles in the surface layer of a slope were monitored using this method and, in several case studies, distinct behaviors in tilt angles in pre-failure stages were detected. Based on this behavior, it is recommended, from a regulatory perspective, a precaution be issued when the tilting rate of a slope is 0.01°/h, and a warning be issued when the tilting rate is 0.1°/h.

Acknowledgements

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