Study on field detection and monitoring of slope instability by measuring tilting motion on the slope surface

Détection et surveillance in situ des phénomènes d'instabilités de pente par mesure locale des mouvements de surface

Wang L., Nishie S., Seko I.
Chuo Kaihatsu Corporation, Tokyo, Japan

Uchimura T.
University of Tokyo, Japan

ABSTRACT: Monitoring and early warning is one of the most effective methods toward reduction of disasters induced by landslides and slope instabilities, but the traditional methods such as multiple borehole inclinometers or extensometer are expensive and unsuitable to zoning monitoring. To overcome the above weaknesses, a simple and low-cost early warning system was developed for slope failure and landslide (Uchimura et al. 2009). The developed tilt sensor is easy to install and it can monitor slope deformation by means of a tilting MEMS module angle which embedded in the sensor, and transfers real time data via wireless network. The warning system with its developed equipments has been deployed in several actual slopes for validation of field performance in Japan and China. In this paper, the authors will show that the developed system and sensor can successfully detect the situation of slope and landslide, and issue useful information that allows residents to avoid slope failure or landslide disasters. Based on the results of field case studies, the developed low-cost sensor unit and real-time warning system are considered particularly effective against rainfall-induced slope failure or landslides and its general use is recommended.

RÉSUMÉ : Une surveillance constante associée à un dispositif rapide d'avertissement est une solution efficace pour lutter contre les désastres et les pertes humaines liés aux glissements de terrain ou aux ruptures de pentes. Cependant, les équipements traditionnels tels que les inclinomètres ou extensomètres installés par forage sont généralement d'un coût prohibitif et sont peu adaptés à une surveillance plus généralisée du territoire. Un nouveau système plus flexible et de coût plus réduit a été proposé par Uchimura et al. (2009). Il incorpore des micro-inclinomètres de type MEMS faciles d'installation qui permettent d'estimer les mouvements de surface. Les données peuvent être transmises en temps réel via réseau sans fil. Ce système a été déployé sur plusieurs sites en Chine et au Japon. A partir des données recoltées sur ces sites, il est démontré que ce système est efficace et fiable dans l'estimation et la détection précoce des glissements de terrain, et qu'il permet d'obtenir des renseignements cruciaux pour prévenir leur poursuite ou pour réduire les dégâts occassionés.

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

1 INTRODUCTION.

Typical measures to prevent slope failure are retaining walls and ground anchors which improve safety factor against failure. These measures have been widely used everywhere in the world and its effectiveness has been confirmed. However, the traditional methods take a lot of cost, as a result that a limited application can be used only for large scale slopes. In fact, most of landslide occurs at small scale slopes, but with a large number. It is not realistic to apply mechanical reinforcement measures for these slopes with potential risk.

Rainfall-induced slope failures are one kind of the most destructive natural hazards. Many slope failures have been observed to occur during or immediately after rainfall. For a wide range slope safety monitoring, a problem in the first was that the equipments were high-cost; this is a problem that disaster prevention measures was difficult for implementation into developing countries. The cost issues should be overcome for a purpose of widespread use; another is that a simple and effective real-time monitoring becomes necessary.

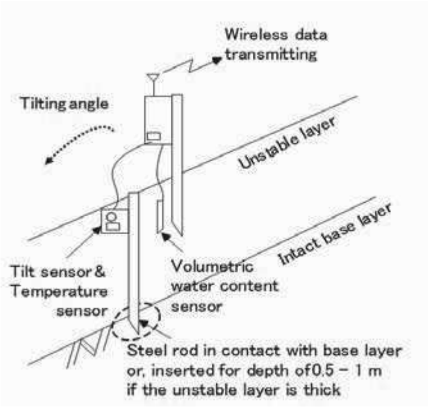

Figure 1. Wireless tilt sensor unit with water content sensor.

The authors have proposed an early warning system for sediment disasters, as one of more feasible countermeasures for small-scale slope failures. The system measures minimum number of items by using the developed smart sensor units; the measured data is transferred through wireless network. Thus, the system is low-cost and simple enough so that the residents in risk areas can handle it to protect themselves from slope disasters (Uchimura et al. 2009).

2 A LOW-COST AND SIMPLE WARNING SYSTEM.

A simple and low-cost early warning sensor unit was developed that only two parameters of the volumetric water content of soil and the inclination of slope or landslide were focused, and its applicability and effectiveness were tested on model slopes under artificial heavy rainfall (Uchimura et al. 2009). The senor unit works with batteries, and transfers real time data via wireless network, and installation is simple and easily to control so that non-expert residents in risk area can handle it by themselves, even in developing countries. Figure 1 shows the basic concept of the wireless monitoring unit using for early warning system.

2.1 RF (Radio Frequency) wireless data transmit method

Figure 2 shows the outline of wireless monitoring and early warning system for slope failure. The system is designed to be wireless, that is, each unit works autonomously with microcomputer with independent power supply by batteries or

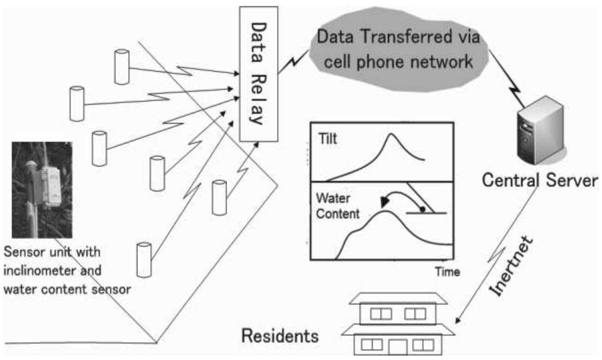

Figure 2.Outline of wireless monitoring units and early warning system for slope failure.

solar cells. Radio modems operated in the 429 MHz ISM band for Japan, 434 MHz ISM band for E.U. counties and China.

The sensor units measure the condition of the slope periodically every 10 minutes for example. The data is transferred to a gateway unit, which is also placed near the slope, by using low power radio communication modules. The data transmitting distance is 300-600 meters under typical conditions in the field. The gateway unit collects the data from all the sensor units, and sends them to a data server on internet through a mobile phone network. Thus, the data can be browsed anywhere and anytime on web site. The data is processed by the server, and any abnormal phenomena of the slope can be detected and used for a precaution of failure, and then issue an evacuation warning.

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.

2.3 Saving power designed based on 16-bit ultra-low-power MCU

In order to reach the purpose of a low-cost and simple warning system, the choice of CPU controller become very important. 16-bit Ultra-Low-Power MCU with ultralow power consumption being very suitable to no commercial power supply region was selected.

A long-term sensor unit power consumption test (not include Micro SD) was started on July 7, 2008, the interval time of data sampling and transmit was 10 minutes. 4 cells alkaline batteries were installed in the test senor unit. Figure 3 shows the relation of battery voltage and elapsed time, the test unit has been worked for 3.5 years.

3 FIELD VALIDATION FOR SIMPLE SLOPE MONITORING AND LANDSLIDE IN JAPAN AND CHINA.

3.1 A case of detection on Three Gorge Dam landslide failure in China

Prototype of the developed monitoring system has been established on a side slope of Three Gorge Dam region, the

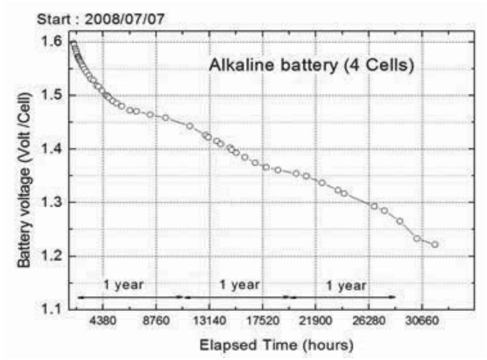

Figure 3. Sensor unit long-term power consumption test.

world largest dam in China, since 2008. The site named Sai-Wan-Ba is located on the right side of the dam lake, near Wenzhou Ward, 80 km eastward from Chongqing City (Figure 4). Several landslide blocks were found by geological investigations.

The time histories of the tilting angles in X-axis and Y-axis, the volumetric water content at a depth of 30 cm on the ground surface, and the record of precipitation are shown in Figure 5 and Figure 6 respectively.

A consecutive movement of a sliding block shown in Figure 5 was observed for a long period. A quick movement of tilt sensor was detected at a heavy rainfall event on June 6-7. 2009; a large scale of landslide disaster nearby observation point 2

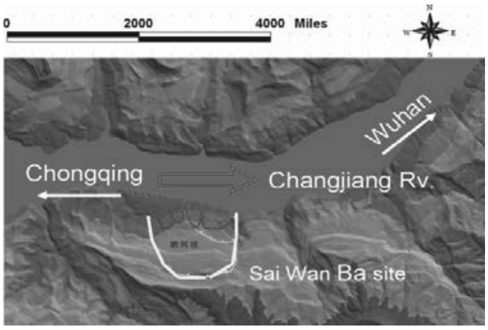

Figure 4. Location of Sai Wan Ba landslide site.

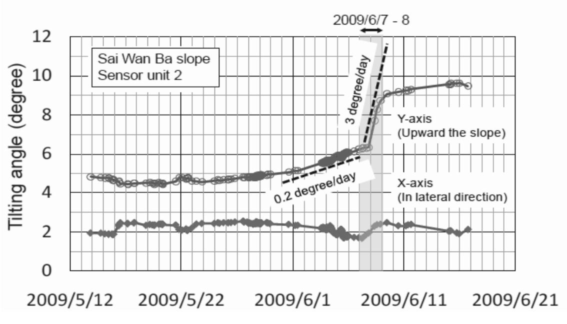

Figure 5. Time history of tilting angle & precipitation by sensor unit 2.

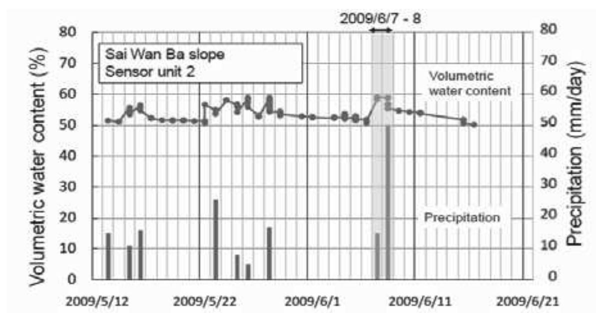

Figure 6. Time history of volumetric water content & precipitation by sensor unit 2.

was happened on 8 June shown in Figure 7, and this landslide disaster caused the slope of observation point 2 inclined gradually at the same time. As a result, there was almost two day for taking refuge before the landslide happened.

Figure 7. New landslide on June 7, 2009.

1.1 *Monitoring of a slope failure site for secondary disaster prevention in Japan*

Another field detection result of a slope failure site along a national road in Kyushu of Japan is shown in Figure 8. This slope consists of strongly weathered granite, and it was failed due to a heavy rainfall in July of 2009. The slope was excavated to have a gradient of 45 degrees for disaster relief work, and was monitored with three sensor units. Heavy rainfall caused a second failure, and a local part of slope including the sensor unit fallen down. Figure 9 shows the records of tilt sensor of the unit, in directions toward and laterals to the slope, respectively. Specially, the tilting in Y-axis (lateral direction) showed

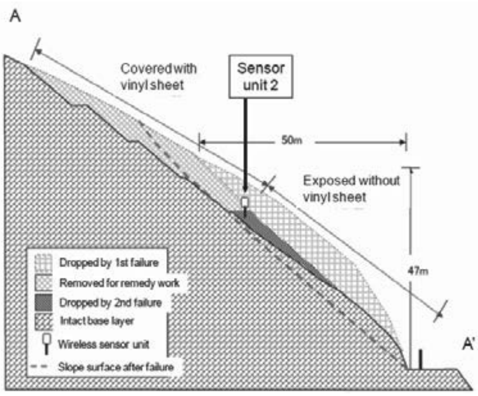

Figure 8. Sketch of failed slope along highway

a)

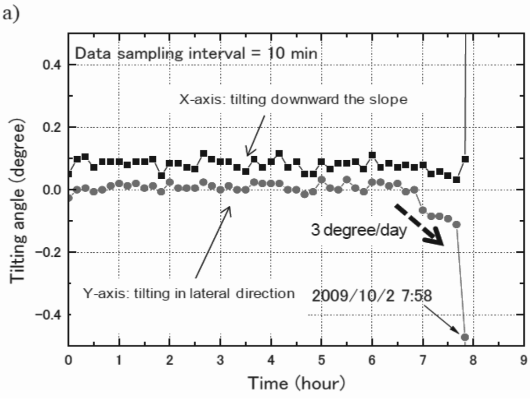

Figure 9. Tilt angle change just before the second failure.

extraordinary behaviors 50 minutes before the second failure.

Its tilting rate was around 3 degrees per day (0.12 degrees per hour). As this second failure took place adjacent to the location of the sensor unit 2, the behaviors of the slope before and after the failure was detected by the monitoring system. The site manager got aware of the extraordinary behaviors of the data from sensor unit 2, and he stopped the disaster relief work and the road service to avoid large loss successfully.

1.2 *Field evaluation for developed tilt sensors to traditional extensometers based on in-site measuring*

Another in-site measurement results were showed in Figure 10 to Figure 11a-e, a heavy rainfall on July 2011 caused a slope failure alone local national road in Kyushu of Japan.

For the road earthwork construction, an emergency monitoring system using multiple borehole inclinometers, extensometers, tilt sensors and rain gauge has been set up at

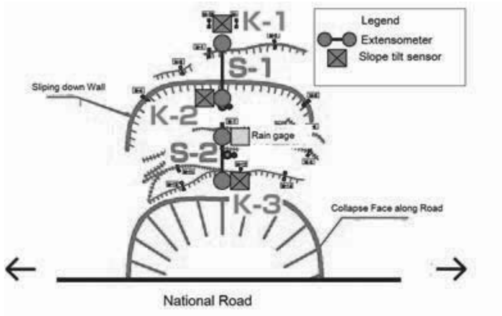

Figure 10. A field site of failed slope along national road in Japan

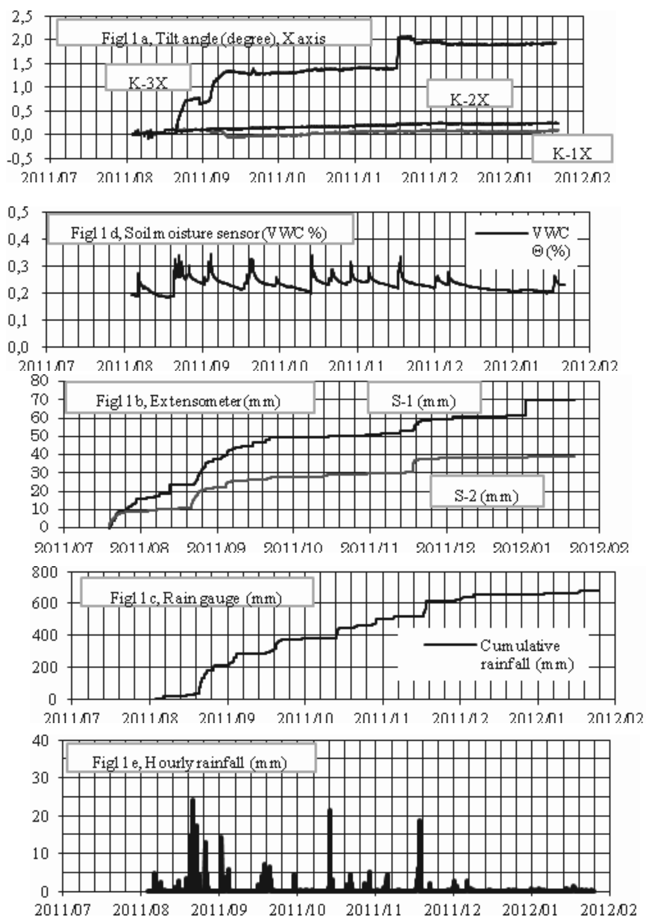

Figure 11, Time histories vs. measuring values.

slope failure site. For validating developed tilt sensor with field extensometers data, the three tilt sensors were installed nearby fixed pole of extensometers moving point shown in Figure 10. In this field site, other 4 boring surveys have been carried out and multiple borehole inclinometers were installed, two of the tilt sensors (K-2, 3) were just set up nearby the survey boring holes. According to the result of boring survey, a landslide slip surface, which depth was 17m, was found shown in Figure 12.

Figure 10a-b show the time histories of tilt sensor inclination alone extensometer wire direction (tilt sensor x axis) and the extensometer movement(S-1, S-2), Figure 10c shows the result of cumulative rainfall value by rain gauge. Figure 10d shows the result of volume water content bv ECH2O water content sensor.

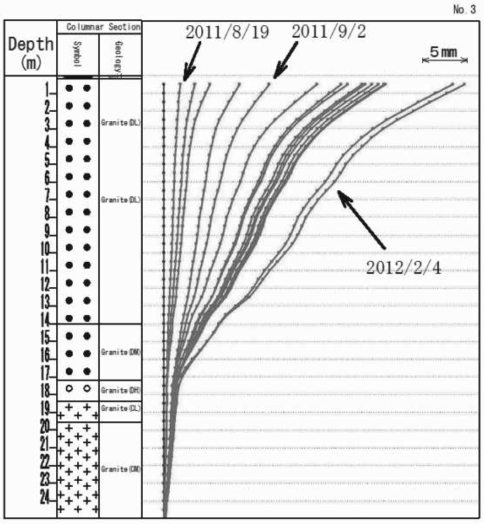

Figure 12. The result of multiple borehole inclinometers.

The normal case, the fix pole of tilt sensor was inserted into earth of slope surface at the depth of 1.0 meter, so that the inclination of tilt sensor means average movement of the slope surface. The inclinations of tilt sensors especially tilt sensor K-3, and movement of extensometers were increased with rainfall and showed a strong correlation each other based on the results of Figure 10a-e.

Figure 13 shows the relation of slope movement (mm) by extensometer(S-1) vs. inclination (degree) by tilt sensor (K-3). Based on the result, the almost linear relationship between extensometer and tilt sensor was obtained except for the storms period of August, October and November, 2011.

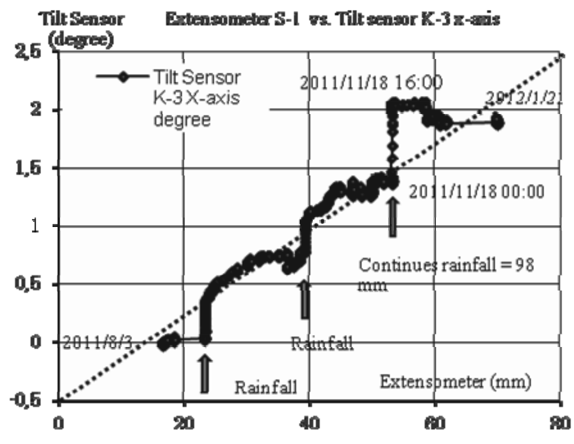

Figure 13. The relation of slope movement vs. tilt angle.

Another important result is that between heavy rainfall start and landslide initiation, the value of extensometer seems no any change but the tilt sensor inclination has reacted quickly, for example, the heavy rainfall on 18 November 2011, that hourly rainfall reached 20mm and continues rainfall reached 96mm, run continuously for 16 hours, during this period, the inclination of tilt sensor was increased but the value of extensometer showed no any change (Figure 13). The tilt sensor measures a local change of slope surface, and the extensometer measures a whole movement of slope failure or landslide. The failure of slope starts from local and enlarges to whole area usually, so that this result should be considered as an important slope pre-failure phenomenon, which can let warning system to issue useful information to residents to avoid slope failure or landslide disaster in advance.

2 CONCLUSION

Based on above case histories and field validation result, a low-cost and simple monitoring method of measuring tilting motion on these slope surface is effective and proposed for precaution of rainfall-induced slope failure and landslides; The tilt sensor unit with MEMS inclinometer module and wireless module is very save power and installed easily. At a side slope of Three Gorge Dam in China, consecutive movement of a sliding block was observed for a long period.

A quick movement was detected at a heavy rainfall event, in which a tilting rate of about 3 degrees per day was continued for 2 days. This event includes a slope failure and significant displacement in a wide area including the position of the sensor unit.

At a slope failure site along a national road in Japan, the slope surface showed abnormal tilting behaviors 30 to 50 minutes before failure. The tilting rate was around 3 degrees per day, although it continued for only 50 minutes before failure. Such behaviors could be used as a signal for early warning.

Furthermore, between heavy rainfall and landslide initiation, the tilt sensor inclination has reacted quickly than extensometer value; it can be considered that the tilt sensor unit is effective tool for early warning system.

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