Study on Early Warning of Slope Failure by Using Tilt Sensors Installed at Slope Surface

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ABSTRACT: Monitoring and early warning is one of the most effective ways toward reduction of disasters induced by landslides and slope instabilities comparing to some traditional methods of early warning, which based on monitoring of displacement or deformation of slope such as extensometer or multi-segment inclinometers. The tilt sensors developed by authors are easily to install and they can capture a small change caused by slope deformation by using means of tilting MEMS module which embedded in the sensor unit; at same time volumetric water content can be measured by moisture sensor. The developed equipment has been deployed in several slopes sites for validation of field performance in Japan and China. Based on some results of field sites, the developed system detected distinct behaviors in the tilting angles in the pre-failure stages. According to some case histories listed in the paper, the results show that a low cost and simple monitoring method for precaution of rainfall-induced slope failure and landslides is effective and proposed.

1 INTRODUCTION

Rainfall induced slope failure is one of the most destructive natural hazards. Many slope failures have been observed to occur during or immediately after rainfall. The conditions resulting in these failures have been described as the reason caused by a rise in pore-water pressure as a result of rainwater infiltration, it is an important factor that influence the initiation of slope failures, and widely known by previous studies. It was found that water contents of soil and inclination angle of slope are important factors to judge the stability of slope based on a series of laboratory experiments (Orense, et. al. 2004). For a wide range of slope safety monitoring, the first problem is that the equipment price is too high that causes difficulty for widespread support in 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. A simple and low cost early warning system was developed that only two parameters of the water content of soil and the inclination of slope or Shallow landslide were focused, the system works with batteries, and transfer real time data via wireless network, and is low-cost and simple so that non-expert residents in risk area can handle it easily by themselves, even in developing countries. Fig. 1 show the basic concept of the wireless monitoring and early warning system.

Actual operation in the field at each monitored point is that a steel rod is installed through the thickness of unstable soil layer on the slope surface (Fig. 2). If the unstable layer is too thick, the rod is installed for 50 to 100 cm-deep. Then, the wireless sensor unit is attached at the top of the rod. Consequently, the tilt sensor detects the average shear deformation of the slope surface layer as the deformation of the slope, the installation and maintenance is simple and inexpensive.

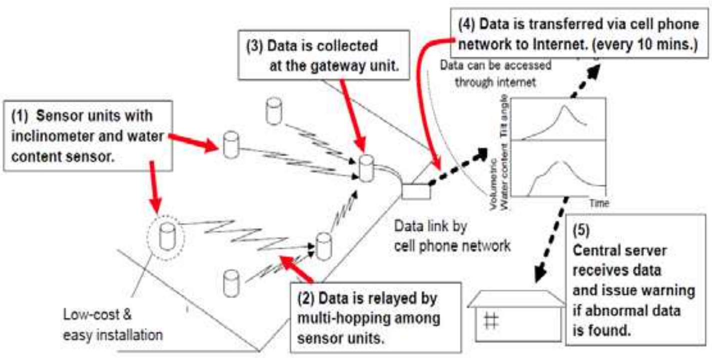

Fig. 1 Outline of wireless monitoring and early warning system

The water content is measured at a shallow position (typically 30 cm-deep) of slope by using a volumetric water contents sensor. This sensor measures the dielectric constant of the surrounding soil, which corresponds to the water contents. The soil mechanics theories say that the slope stability directly depends on the suction, or pore water pressure, rather than water content. But, measurement of suction of unsaturated soils is usually difficult, and the sensors require careful maintenance. Therefore, use of volumetric water content sensors is more suitable for low-cost monitoring.

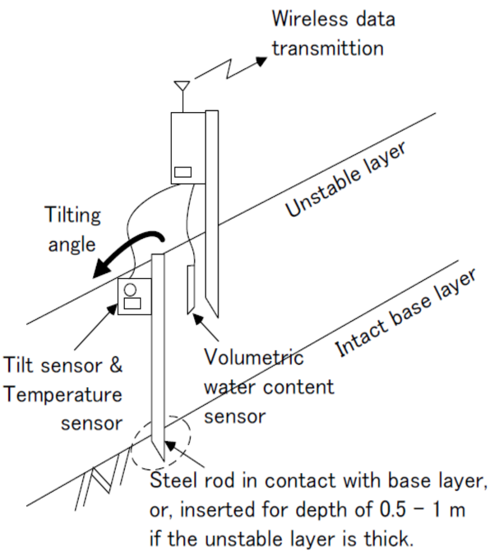

Fig. 2 Wireless sensor unit with tilt and water content sensor on a slope

2 MONITORING OF A SLOPE FAILURE SITE FOR SECONDARY DISASTER PREVENTION

Prototypes of the developed monitoring system have been deployed at various sites by the authors. One of them, a slope failure site along a highway, is shown in Fig. 3. 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 remedy work, and was monitored with three sensor units. After 2 months during the remedy work, another heavy rainfall caused a second failure, and a local part of slope including the sensor unit fallen down, the behaviors of the slope before and after the failure was detected by the monitoring system, and remedy work and the highway service was stopped successfully.

Fig. 4 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 extraordinary behaviors 50 minutes before the second failure. Its tilting rate

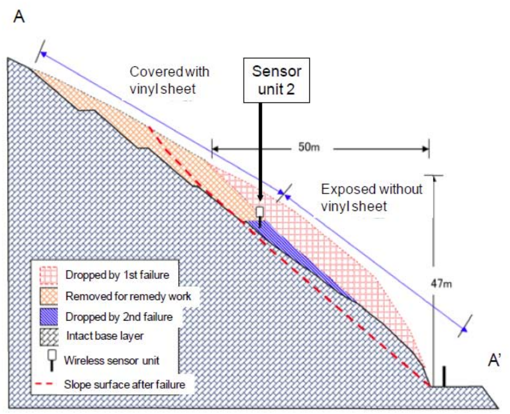

Fig. 3 Cross-section of the slope including the second failure part.

was around 3 degrees per day (0.12 degrees per hour).

3 MONITORING OF A LANDSLIDE FAILURE BY THREE GORGE DAM

Prototype of the developed monitoring system has been installed on a side slope by Three Gorge Dam, the world largest dam in China, since 2008. The site, Sai-Wan-Ba area, is located on the right side of the dam lake, near Wenzhou Ward, 80 km eastward from Chongqing city. Several landslide blocks, are found by geological investigations as shown in Fig. 5. The locations of three sensor units deployed by the authors are responsible for each recent landslide blocks respectively. The dam has been in service since 2008, and periodical changes of the water level of dam-lake (Chang Jiang River) by 30 m are scheduled every year by dam operation. Besides, the site is located in a subtropical region where heavy rainfall events are

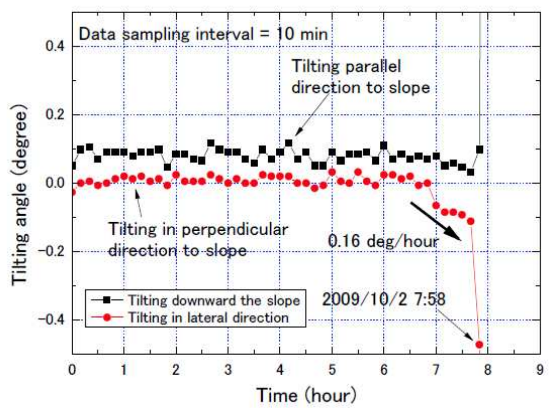

Fig. 4 Tilting angle deformation on the slope site

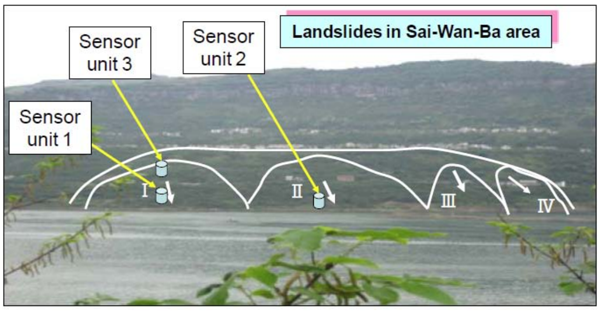

Fig. 5 Panoramic view of Sai Wan Ba landslide site

Fig. 6, new landslide on June 7, 2009

expected, and some displacement on the slope surface was reported in summer of 2008.

The time histories of the tilting angles of the pole

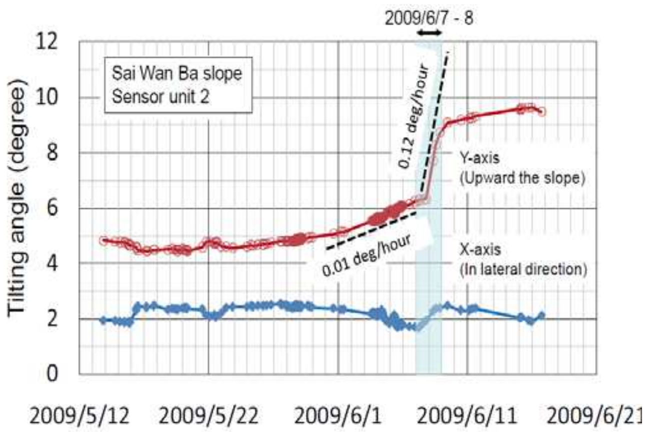

Fig. 7 Time histories of tilting angle obtained by Sensor unit 2

in X-axis and Y-axis, the volumetric water content at a depth of 30 cm on the ground surface. While receiving frequent rainfall events, the tilting angles showed gradual progress, and the tilting angle in Y-axis reached around 5 degrees at the beginning of June 2009. A quick increase in the tilting angle in Y-axis, and a small increase in the X-axis are recorded on June 7 and 8. The precipitation for these 2 days was 65 mm, while the criteria for heavy rain warning was decided to be 30 mm per day in this area. The increasing rate of the tilting angle in Y-axis was 3 degrees per day during this event, while the rate just before this event was around 0.2 degrees per day. This quick behavior should be corresponding to the landslide event in this period. The slope failure near the sensor unit 2 took place at noon of June 8 shown in Fig. 7.

4 FIELD EVALUATION FOR DEVELOPED TILT SENSORS TO TRADITIONAL EXTENSOMETERS BASED ON IN-SITE MEASURING

Another in site measurement results were showed in Fig. 8, 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 **i**nclinometers, extensometers, tilt sensors and rain gauge has been set up at slope failure site. For validating developed tilt sensor with field extensometers data, the three (K-1, K-2 and K-3) tilt sensors were installed nearby fixed pole of extensometers moving point. In this field site, other 4 boring surveys have been carried out

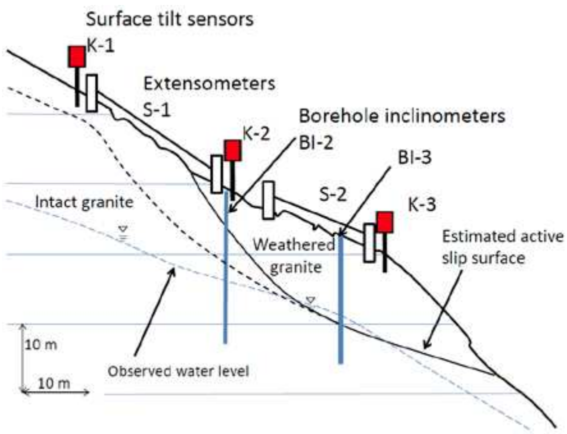

Fig. 8 A field site of failed slope along national road

and multiple borehole inclinometers were installed.

Fig. 9 shows the relationship of extensometers, tilt sensors, multi inclinometers and rainfall vs. time. During the monitoring, the four times warning issues were send out for a period of time A to D, the results could be concluded as following:

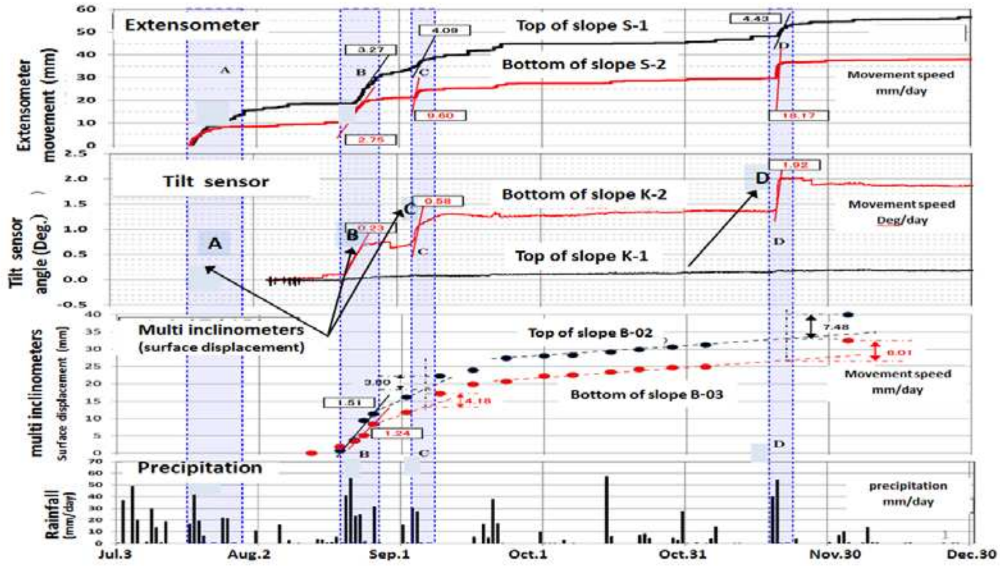

Fig. 9, the relationship of extensometers, tilt sensors, multi inclinometers and rainfall vs. time

(1) At the first stage of 'A' period, the behavior of each type of instruments showed the same movement, the warning issue was send out based on rainfall value what the threshold was exceeded only. (2)The extensometer of S-1 installed at top of slope position showed a large movement compared with the extensometer S-2 at bottom of slope in whole period, it is means that the installation of extensometer is better effective at top of surface. (3) For tilt sensors, because of parallel motion, the sensor (K-1) installed in the top of slope was not reasonable to catch the phenomenon of slope failure. But, the tilting degree change of sensor (K-2) was very clearly and the result of K-2 showed a same change tendency like extensometer (S-1) installed at top of slope.

5 CONCLUSIONS

A low cost and simple monitoring method for precaution of rainfall induced landslides is proposed, which uses tilt sensors on the slope surface to detect abnormal deformation.

At a slope failure site along a highway, 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. 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 around 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.

Based on the above field site test results, the proposed monitoring method is not only suitable to the precaution of rainfall induced slope failure but also effective to construction safety monitoring. The final case proofed that a tilt sensor at bottom of slope showed a good effect compared with tilt sensor in top of slope. For the purpose of early warning, the monitoring of bottom of slope will be better effective.

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