Prefailure deformation monitoring of landslide and slope by using tilt sensors

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ABSTRACT

Monitoring and early warning is one of the most effective methods toward reduction of accident induced by landslide and slope failure during rainfall. The traditional methods such as extensometers and borehole inclinometers are common monitoring ways, but the traditional equipment is expensive and not easy to install in field site. The authors have developed a tilt sensor unit and proposed an early warning system as one of more feasible countermeasures to avoid slope failure accident. The warning system including developed tilt sensor unit, has been deployed in several actual slopes for validation and verification of field performance in Japan.

Key words: Monitoring, Early warning, Rainfall induced slope failure, Inclinometer Sensor

1. INTRODUCTION

Rainfall induced slope failures and landslides are one of the most destructive natural disasters, it is also the same dangerous situation during construction of a road and civil engineering structure nearby slope. Many slope failures have been observed to occur during or immediately after rainfall. The conditions leading to these failures have been described as the reason caused by a rise in pore water pressure (soil moisture) and slope deformation. It was found that the water contents of soil and the inclination (tilting) angle of slope are important factors to judge the stability of slope based on a series of laboratory experiments (Orense, et. al. 2004). For wide range slope safety monitoring, the first problem is that the equipment are high-cost, which causes difficulty for implementation into developing countries. The cost issues should be overcome and solved for a purpose of widespread use; another is that a simple and effective real time monitoring becomes necessary. To overcome the above weaknesses, a simple and low-cost early warning system was developed for slope failure and landslide (Uchimura et al. 2009).

2. PRE-WARNING SYSTEM USING TILT SENSORS

A simple pre-warning system was developed that only two parameters of the water content of soil and the inclination of slope or landslide were focused, and its applicability and effectiveness was verified by model slopes under artificial heavy rainfall. The system works with batteries, and transfer real time data via wireless network, and it is simple so that non-expert can also handle easily even in the developing countries. The basic concept of the wireless monitoring and early warning system is shown in Fig. 1.

Fig.1. Outline of wireless monitoring units and early warning system for slope failure.

A group of low-cost and simple sensor units are placed on the slope. 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 radio communication. The gateway unit collects the data from all the sensor units, and sends them to a data server on internet through a cell phone network. Thus, the data can be browsed anywhere and anytime on Web site. The data is processed by the server, and any abnormal behavior of the slope can be detected as a precaution of failure, and then warning is issued.
MONITORING OF A SLOPE FAILURE SITE FOR SECONDARY DISASTER PREVENTION

Prototypes of slope safety monitoring system have been deployed at various sites by the authors. One of them was set up for slope failure safety monitoring along a national road in Japan (Fig. 3). This slope 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 tilt sensor units. Fig. 4 shows the directions of the sensor units. The negative value changes in Y-axis mean that the sensor unit 2 was tilted in the backward direction to the second failure part. It suggests a failure mode with a slip surface in the slope. After 2 months during the remedy work, another heavy rainfall caused a second failure, and a local part of slope including the tilt sensor unit fallen down. 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 were detected by the monitoring system. Fig. 4 shows the records of tilt sensor 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 was around 3 degrees per day (0.12 degrees per hour), the monitoring of tilting (rotation) on slope surface can be considered as an effective method to detect the precaution of failure.

4 SAFETY MONITORING OF CUT SLOPE STABILITY DURING A NATIONAL ROAD CONSTRUCTION

The following case (Fig. 5) introduces a success early warning example of the year 2010 in Japan. In this case, the slope consists of the neogene sandstone, the cut construction was started from top of the slope to

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designed level, and a consecutive movement (tilting angle change) of slope was observed at a speed of 0.004 degree per day during slope cut construction, but in the period of following two days (from the 18th to 19th of October), a quick movement (tilting angle change) was detected by developed tilt sensor monitoring system at the speed of 0.034 degree per day, as a result a large slope crack was found, and the field management engineer stopped the construction work based on the above information, a counterweight fill work was carried out as an emergency measures from the 19th to 20th of October, nevertheless, the speed of tilting angle change enlarged to 0.142 degree per day. After finished the countermeasures on the 20th October, the slope movement (tilting angle change) was stopped, and a slope failure accident was finally avoided successfully. As a result, the developed low-cost and simple monitoring method for precaution of slope failure is effective and proposed for cutting slope construction.

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

Another in-site measurement results were showed in Figure 6, 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 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 6. In this field site, other 4 boring surveys have been carried out and multiple borehole inclinometers were installed, three of the tilt sensors (K-1,K-2,K-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.

Fig. 7 shows the relationship of extensometers, tilt sensors, multi inclinometers and rainfall vs. date time based on the observed data. During the whole monitoring period the four times warning issues were send such as A to D period, according to the monitoring result we can conclude as

![Fig 6. a field site of failed slope along national road](image-url)

![Fig 7. The relationship of extensometers, tilt sensors, multi inclinometers and rainfall vs. date time](image-url)
following:
1) At the first stage of ‘A’ period, the behavior of each type of instruments showed the same movement (except top side tilt sensor).
2) The extensometer of S-1 installed at top of slope position showed a large movement compared with the extensometer S-2 which installed at bottom of slope.
3) The movement of top of slope showed a parallel motion. Tilt sensor (K-1) which installed in the top of slope didn’t show an obvious effective, but tilt sensor (K-2) showed a same change tendency like extensometer (S-1) which installed at top of slope.
4) The movement of bottom side showed a good effect compared with top side during whole period. For the purpose of early warning, monitoring of slope bottom will be further effective.
5) Deformation at bottom of slope starts earlier than top of slope. The movement of a extensometer is also the same with tilt sensor at bottom of slope.

To summarize the results of the above-mentioned, extensometer was suitable to install at top of slope, on the other hand, tilt sensor is able to get better effective at bottom of slope. Deformation at bottom of slope starts earlier than top of slope and the movement of an extensometer is also the same with tilt sensor at bottom of slope.

Fig. 8 compares the tilting behaviors at K-3 with the displacement obtained by extensometers S-1 and S-2 respectively. They show linear relationships in a large sense. However, when their responses to each rainfall events are investigated in details, the tilt angle of K-3 starts to respond nearly together with the rainfall, while the displacement at S-1 and S-2 start to increase later. For the case of the rainfall event on November 18, the extensometer S-1 responded 16 hours later than the tilt sensor K-3. This suggests that the movement of this slope starts from the bottom of slope, and then propagate upward. In such cases, it is effective for early warning to use tilt sensor at the lower part of slope.

6. CONCLUSIONS

A wireless sensor unit with a MEMS tilt sensor and a volumetric water content sensor was developed by the authors, and it has been applied to several actual slope fields in Japan. Based on the above field site test results, the proposed simple monitoring method is not only suitable to the precaution of rainfall-induced slope failure but also effective to construction safety monitoring. The second case of road cut slope stability monitoring proofed that the safety monitoring system can transmit the slope information quickly to management engineer to avoid a slope failure accident during the cutting slope period. By the final case, the tilt sensor at bottom of slope showed a good effect compared with tilt sensor in top of slope. For the purpose of early warning, monitoring of bottom of slope will be more effective.

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