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Validation and Interpretation of Monitored Behavior of Slopes Vulnerable to Failure

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Abstract Monitoring and early warning is one of the most promising ways toward reduction of disasters induced by landslides and slope instabilities. Although less costly than construction of retaining walls and other structural measures, early warning has several problems to be overcome. First, it is often the case that the exact location of an unstable soil mass is not defined and hence the location of monitoring sensors cannot be decided. This problem can be solved by installing many low-cost sensors within a possibly unstable slope. The second problem concerns what information of slope should be monitored. The present study has developed a low-cost MEM sensor unit that can monitor slope deformation during heavy rainfall. A wireless network collects signals from the sensors periodically and helps the local government issuing an alert signal or emergency evacuation order, depending upon the progress of tilting. It is further important that the low cost of the sensors allow individuals to purchase personally and install them in order to protect themselves from slope disasters. The developed equipments have been deployed in several slopes in the recent times for validation of their field performances. The present text reviews the obtained records and discusses their use for practice.

Keywords Slope failure, Monitoring, Early warning, Tilt sensors

Proposed wireless monitoring system

The authors have proposed an early warning system for slope disasters, as one of feasible countermeasures for small-scale slope disasters (Towhata, et. al. 2005 and Uchimura et. al. 2010). The system watches the behaviours of subsoil at minimum number of points on a slope with inexpensive and sophisticated sensors, and the data is transferred through wireless network. Thus, the system is low-cost and simple enough so that the residents in hazardous areas can use it to protect themselves from slope disasters.

It is reported from model tests that gradual displacement and high saturation ratio (80 to 90 %) are observed at the toe of model slopes before failure (Orense R.P. et. al. 2003 and 2004). Ochiai et. al. (2004) also reported gradual and accelerating displacement on a slope surface observed before failure in an artificial rainfall-induced landslide test conducted at Mt. Kaba-san, Tsukuba City, Japan. Thus, it is useful to monitor the displacement and the water contents on the slope for early warning of landslides.

Figure 1 shows the basic concept of the wireless monitoring and early warning system proposed by the authors. A group of low-cost and simple sensor units (Figure 2) are placed on the slope. The system is designed to be wireless, that is, each unit works autonomously

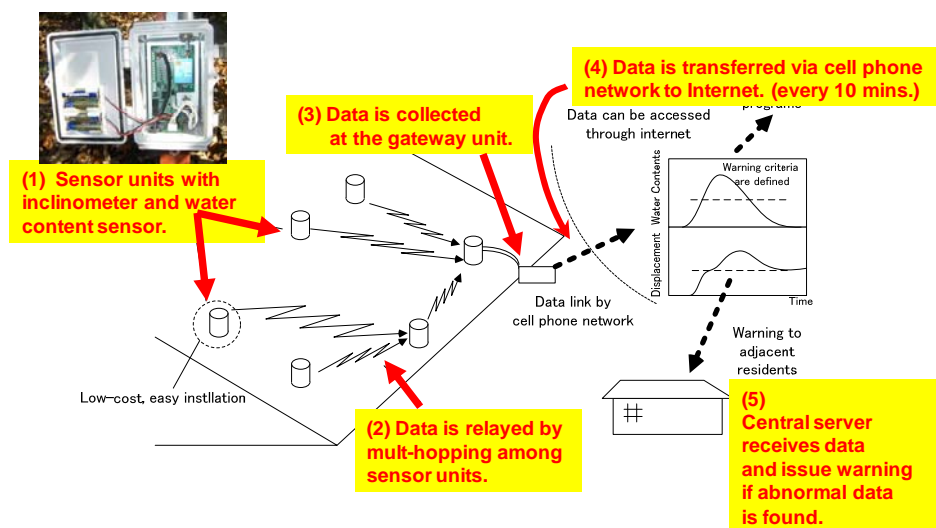


Figure 1. Outline of wireless monitoring and early warning system for slope failure

with micro computer with independent power supply by batteries or solar cells. 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. Its communication distance is 300 m 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 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 behaviour of the slope can be detected as a precaution of failure, and then warning is issued. Each sensor unit works for duration of more than 1 year with 4 AA Alkaline batteries.

The proposed system watches the rotation on the slope surface and the volumetric water content in the slope. A MEMS tilt sensor (nominal resolution = $0.04 \text{ mm/m} = 0.0025 \text{ degree}$) is installed in each sensor unit. At each monitored point, a steel rod is installed through the thickness of unstable soil layer on the slope surface. 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. Extensometer is commonly used for monitoring the displacement of slopes, but the advantage of using tilt sensor is that a long wire of an extensometer is not required, and therefore, the installation and maintenance is simple and inexpensive.

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 careful maintenance of the sensors is required. Therefore, use of volumetric water content sensors is more suitable for low-cost monitoring.

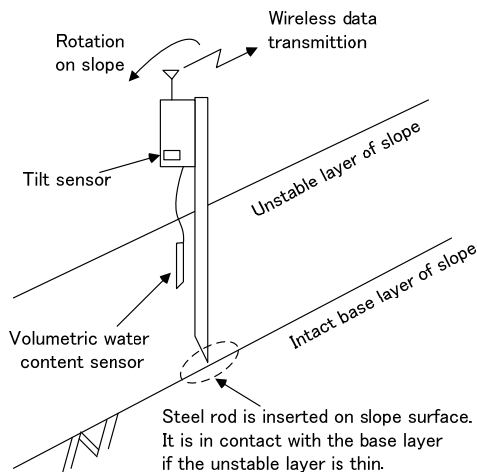


Figure 2. Wireless sensor unit with tilt and water content sensors on a slope.

Monitoring of a slope failure site during remedy work

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 Figure 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. As this second failure took place adjacent to the location of the sensor unit 2, the behaviours of the slope before and after the failure was detected by the monitoring system. The site manager got aware of the extraordinary behaviours of the data from sensor unit 2, and he stopped the remedy work and the highway service successfully.

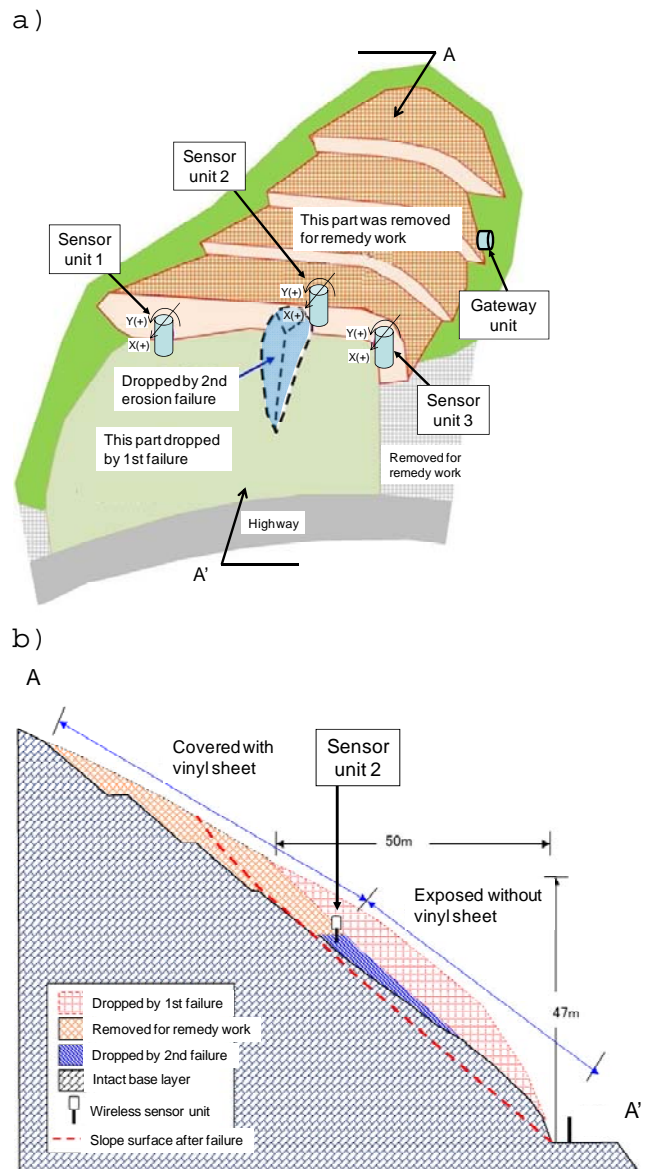


Figure 3. a) Sketch of failed slope along highway and arrangement of deployed sensor unit; and b) cross-section of the slope including the second failure part.

Figure 4a shows the records of tilt sensor of the unit, in directions toward and lateral to the slope, respectively. Specially, the tilting in Y-axis (lateral direction) showed extraordinary behaviours 50 minutes before the second failure. Its tilting rate was around 3 degrees per day (0.12 degrees per hour). Figure 3a also shows the directions of the sensor units. The negative changes in Y-axis mean that the sensor unit 2 tilted in the backward direction to the second failure part. It suggests a failure mode with a slip surface in the slope.

Figure 4b shows the behaviours of volumetric water contents at the unit. The slope did not failed when the water content recorded its peak value, but it failed after 2 hours of drainage stage. This may be because the distribution of water in a slope is quite non-uniform, and the measured value of volumetric water content depends on the position of the sensor. Thus, it is difficult to detect a precaution of slope failure only watching the water content.

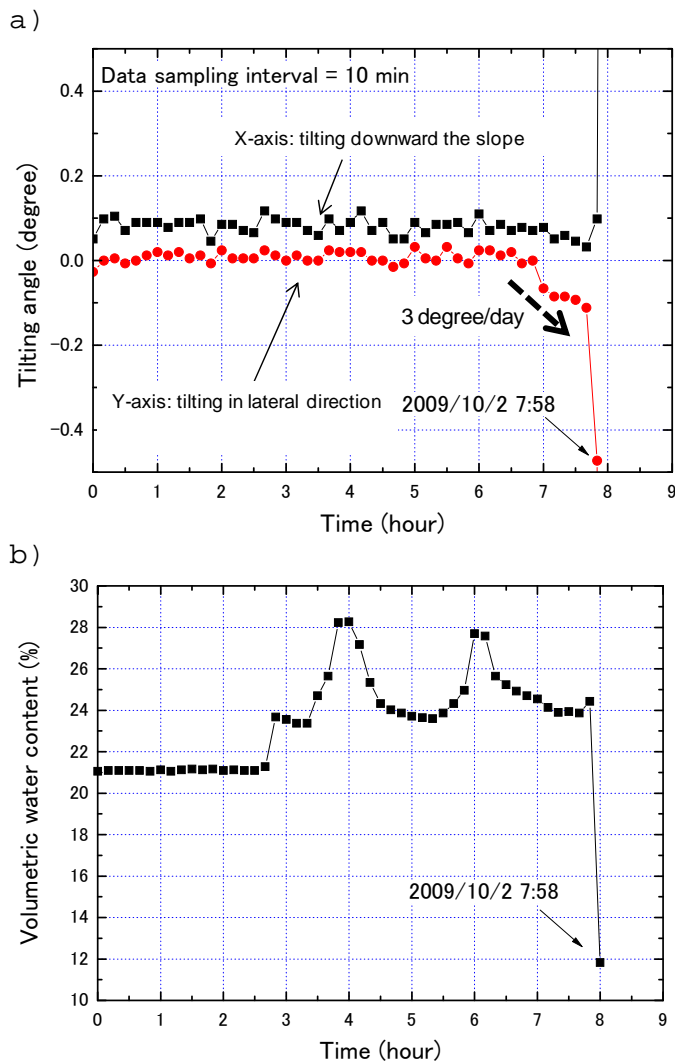


Figure 4. a) Tilting angle and b) volumetric water content obtained by sensor unit 2 on the slope site along highway just before the second failure.

Considering the data obtained from the slope mentioned herein, the followings issues are concluded:

- a) Monitoring of tilting (rotation) on slope surface is effective to detect the precaution of failure preceding by 30 minutes or more;
- b) It is difficult to detect a precaution of slope failure only by watching the water content; and
- c) Record of water content is very sensitive to rainfall events. It can be used to detect heavy rainfall which may cause slope failure.

Monitoring of a slope by Three Gorges 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 Wanzhou Ward, 80 km eastward from Chongqing City (Figure 5). Several landslide bodies, are found by geological investigations as shown in Figure 6 and 7. The locations of three sensor units deployed by the authors are also shown in Figure 7. They are responsible for each recent landslide bodies respectively.

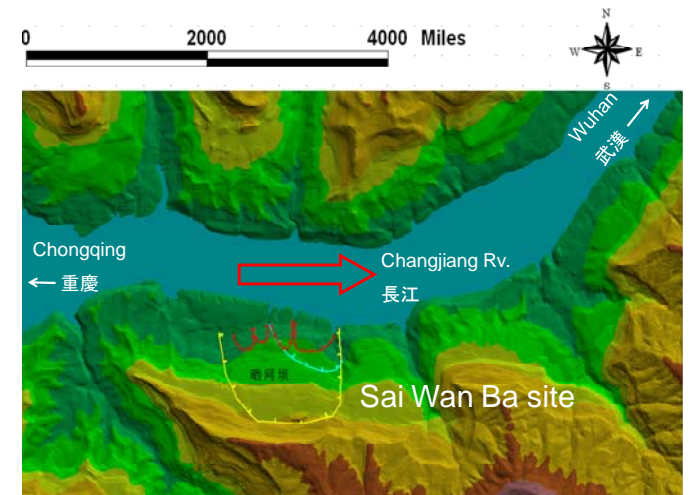


Figure 5. Location of Sai Wan Ba landslide site.

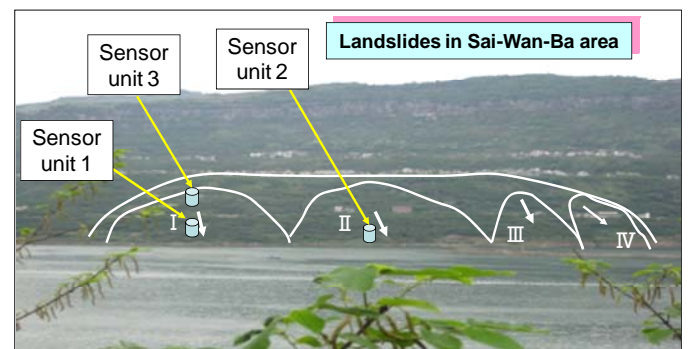


Figure 6. Panoramic view of Sai Wan Ba landslide site.

Figure 8 show the cross-section of slope passing the position of “sensor unit 2” shown in Figure 7. The slope mainly consists of mad stone or sandy mad stone layers, and a deposit layer of clayey soil with some crushed mad stone covers the slope surface with an average depth of 15 m. The length of the recent landslide body is around 350 m, with slope angle of 5 to 15 degrees.

The dam has been in service since 2008, and 30 m of periodical changes in the water level of dam-lake

(Changjiang River) are scheduled every year for dam operation. Besides, the site is located in a subtropical region where heavy rainfall events are expected, and some displacement on the slope surface was reported in summer of 2008. Therefore, the government also observes this area continuously by using borehole inclinometers, ground water level sensors, and a rain gage.

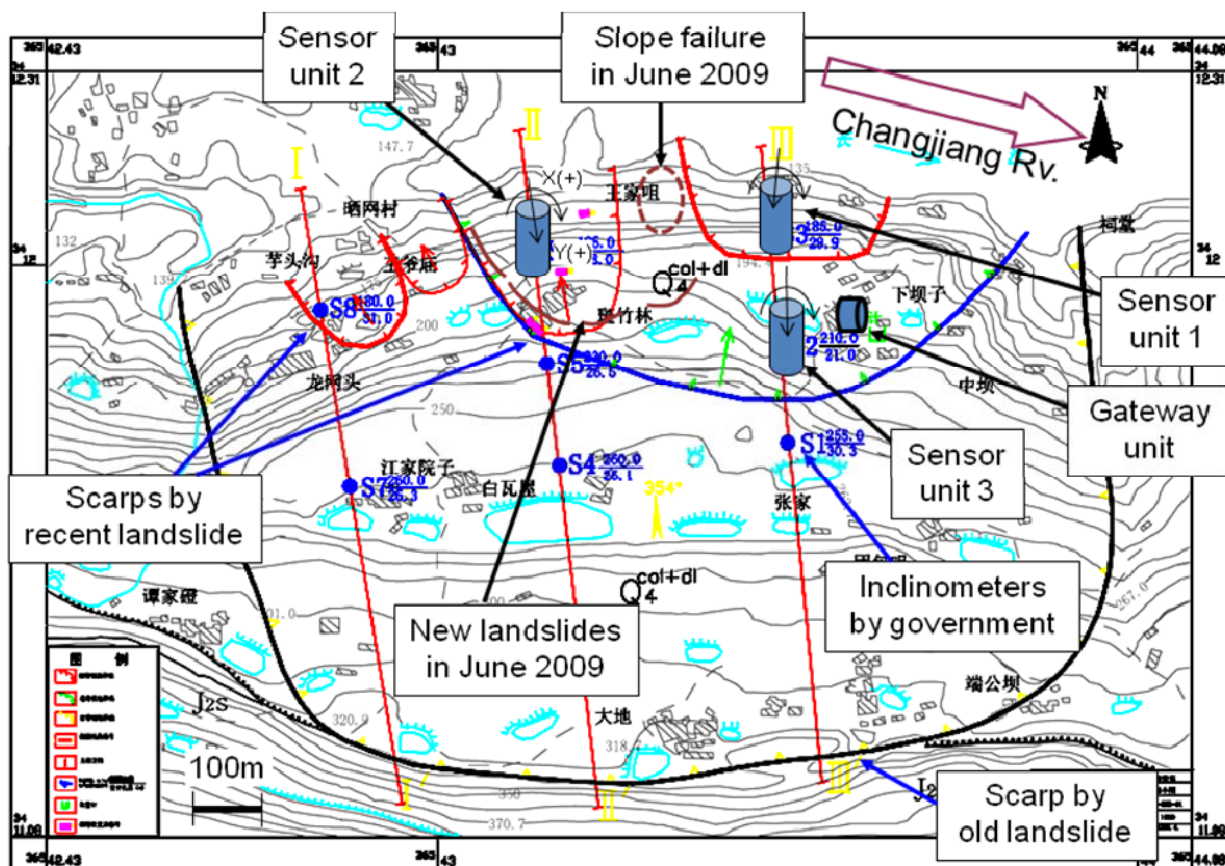


Figure 7. Plan view of Sai Wan Ba landslide site and locations of sensor units.

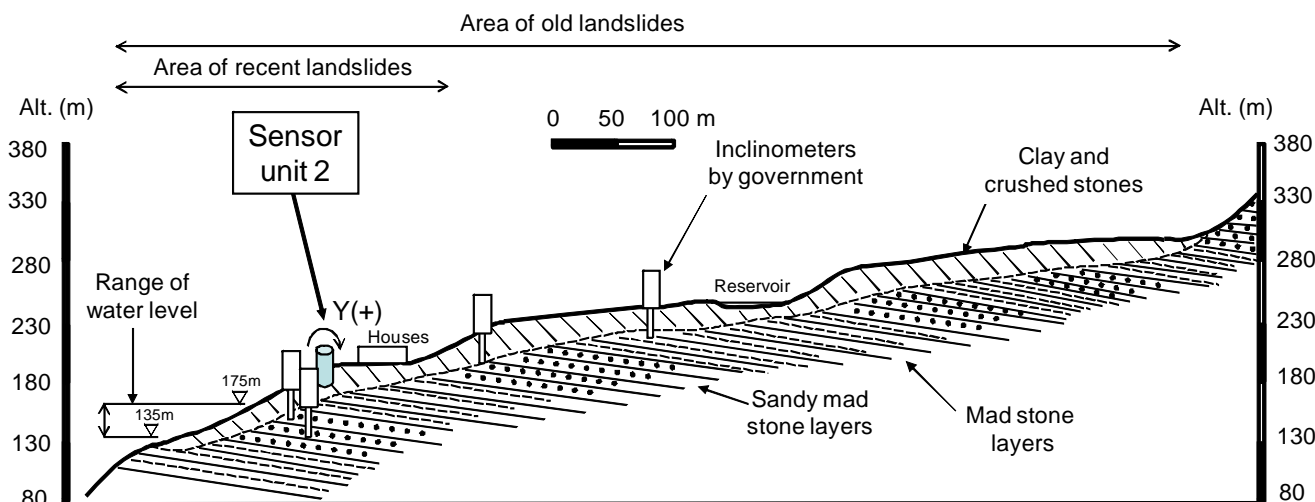


Figure 8. Cross sectional view of Sai Wan Ba landslide site passing the position of sensor unit 2.

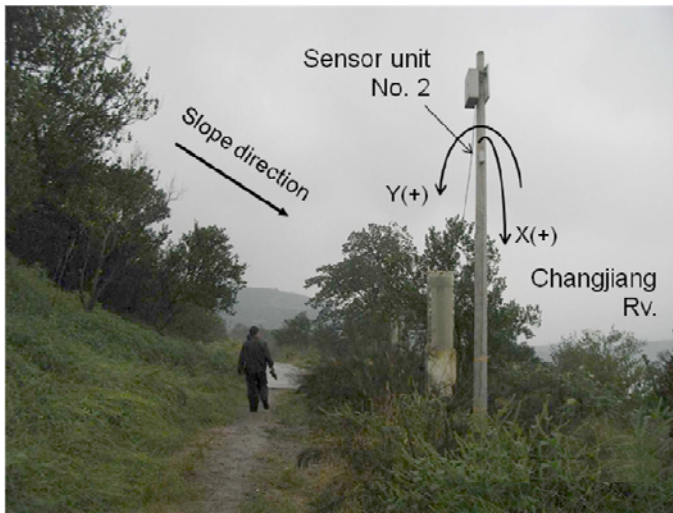


Figure 9. Installation of a sensor unit.



Figure 10. Installation of a gateway unit.



Figure 11. New landslide on June 7, 2009.

The sensor unit by authors are attached to a pole installed on the slope (Figure 9). Each sensor unit has a MEMS tilt sensor attached on the pole and a volumetric water content sensor buried into the ground at a depth of around 30 cm. The data was obtained every 10 minutes, and transferred to a gateway unit (Figure 10), which is placed on a roof of a private house nearby, 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.

The monitoring system has been in practice since October of 2008. Meanwhile, a heavy rainfall event on June 7 and 8, 2009, caused significant displacements in landslide bodies including the position of the sensor unit 2. The locations of the landslides are shown in Figure 7. It includes a slope failure at 150 m eastward of the sensor unit 2 as shown in Figure 11, where more than 10 m of displacement was observed in the sliding body.

The time histories of the tilting angles of the pole 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 12 and 13 respectively. 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. As shown in Figure 9, positive values of tilting angle in Y-axis means that the pole tilted upward the slope. Correspondingly, the tilting angle in X-axis in lateral direction on the slope, showed relatively smaller values.

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 behaviour should be corresponding to the landslide event in this period. According to village people in this area, the slope failure near the sensor unit 2 took place at noon of June 8, while the quick increase in Y-axis started in late night of June 7. Therefore, there was a time margin sufficient for issuing early warning in this area.

As the slope surface consists of clayey soil deposit, the volumetric water contents showed high values between 50 and 60 % throughout the monitoring period. It responded to every rainfall events, but no extraordinary response was recorded at the time of the landslide on June 7 and 8. As the volumetric water contents sensor was buried at a shallow part of the slope, only 30 cm from the ground surface, the obtained values are not corresponding to the conditions at the depth of slip surfaces. So it is not relevant to define the criteria of early warning based on use these values only.

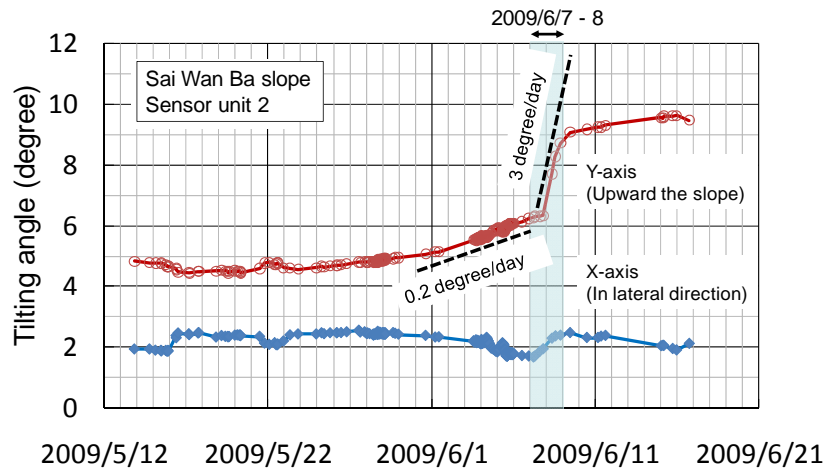


Figure 12. Time histories of tilting angle obtained by Sensor unit 2.

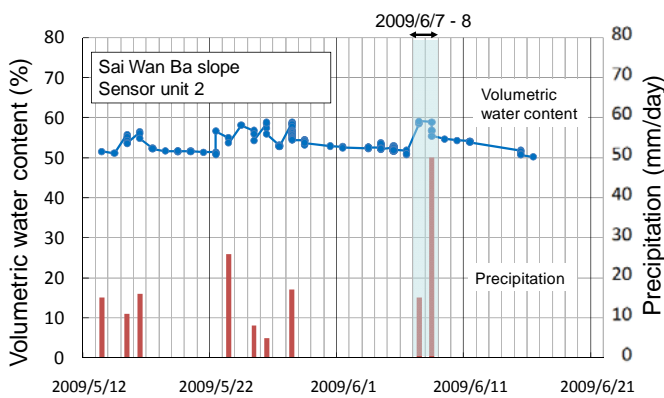


Figure 13. Time history of volumetric water content transducer at Sensor unit 2, and records of rainfall intensity.

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. A wireless sensor unit with a MEMS tilt sensor and a volumetric water content sensor was developed and installed on several real slopes in Japan and China, and a long-term monitoring was attempted.

At a slope failure site along a highway, the slope surface showed abnormal tilting behaviours 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 behaviours could be used as a signal for early warning.

At a side slope of Three Gorge Dam in China, consecutive movement of a sliding body 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.

Considering the behaviours of tilting monitored on the surfaces of these two slopes, a tilting rate of 3 degrees

per day, or 1 degree per day for conservative decision, could be a criteria to presume a significant sliding or failure of slopes.

It is difficult to evaluate the probability of slope failure quantitatively based on the values of water content. Conversely, it is easy to detect rainfall events from the water content data.

Acknowledgments

These researches are supported by Grants-in-Aid for Scientific Research of Japan Society for the Promotion of Science (JSPS), Construction Technology Research and Development Subsidy Program of Ministry of Land, Infrastructure, Transport and Tourism of Japan, Joint Research Projects/Seminars by JSPS, and International Cooperate Project of Chinese Ministry of Science and Technology (projects #: 07((2007DFA21150) and 09(2009DFB20190)).

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