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Stability Monitoring of Earthquake-Induced Slope Failure and Landslides

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ABSTRACT

An early warning monitoring system is one of the most effective ways to reduce disasters induced by slope instabilities. The 2008 Ms 8.0 Wenchuan earthquake that occurred in Sichuan province, China, induced more than 197 000 slope failures and landslides. To reduce vulnerability to such slope and landslide hazards, an early warning system becomes important, and for this purpose, a newly developed simple and low-cost early warning system for slope failure and landslides is presented here. The new system is based on a tilt sensor that is easy to install. The sensor can monitor water content and slope deformation with a tilt Micro Electro Mechanical Systems (MEMS) module embedded in the sensor unit, and it can transfer real time data via a wireless network. Since 2010, the monitoring system has been used in seven actual large-scale slope failure and landslide sites to validate field performance. In this paper, we report on two monitoring cases to show that the early warning system adequately monitors the stability of slope and debris fields in China and Japan. Based on the field site test results, the monitoring method is proposed for regions of increased hazard of earthquake-induced slope failure.

Introduction

Slope failure is one of the most destructive natural hazards. Many slope failures have been observed to occur during or immediately after rainfall events. The conditions leading to these failures have been explained by anticipating a rise in pore–water pressure.

Rockfalls are another natural and dynamic geologic process involving the detachment and rapid downward movement of rock. Tectonic stresses and erosion cause rock to fracture. Rockfalls later occur along these fractures, which are referred to as sheeting joints, when they develop parallel to the surface. Over long periods, water flowing through fractures erodes the bedrock by weathering, which loosens the bonds that hold the rock in place. Triggering mechanisms like changes in water levels, earthquakes, and vegetation growth are among the final forces that cause unstable rocks to fall. If water enters fractures in the bedrock, it can build up pressure behind unstable rocks. Water also may seep into cracks in the rock causing those cracks to grow. This process can incrementally lever loose rocks away from cliff faces.

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Ground shaking during small- or large-scale earthquakes often triggers slope failure or rockfalls. In the area of the May 12, 2008 Ms 8.0 Wenchuan earthquake, landforms have resulted from tectonic stresses and sheeting joints. Due to its steep, glacially carved cliffs, the mountainous area of Sichuan province in China experienced many rockfalls during and following the Wenchuan earthquake. For example, on July 26, 2009, six people were killed and 12 injured when a rockfall hit a bridge in Wenchuan. The reasons for the rockfall included a number of seismic processes that set the stage, in addition to weathering and the bedrock configuration.

A Low-Cost, Simple Warning System

This simple low-cost early warning system focuses on only two parameters: the water content of the soil and the inclination of the slope or landslide. The applicability and effectiveness of the system was tested on model slopes under artificial heavy rainfall (Uchimura et al., 2004). The system is powered by batteries, and transfers real-time data via a wireless network. It is low-cost and simple so that non-expert local residents from the assessment area can maintain equipment independently, even in developing countries. Figure 1 shows the basic concepts behind the wireless monitoring and early warning system for slope failure. The system is designed to be wireless, i.e., each unit works autonomously with a microcomputer running on an independent battery or solar-cell power supply. Radio modems operated in the 429 MHz ISM band for Japan and the 434 MHz ISM band for European Union countries and China.

The sensor units measure the condition of the slope periodically, e.g., every 10 minutes. The data are transferred to a gateway unit, which is also placed near the slope, using low-power radio communication modules. The data transmitting distance is 300 to 600 m under typical field conditions. The gateway unit collects the data from all sensor units, and sends them to a data server on the Internet using a mobile phone network. In this way, the data can be searched anywhere and anytime on a website. The data were processed by the server, and any abnormal behavior of the slope can be detected as a precaution of failure. A warning can then be issued.

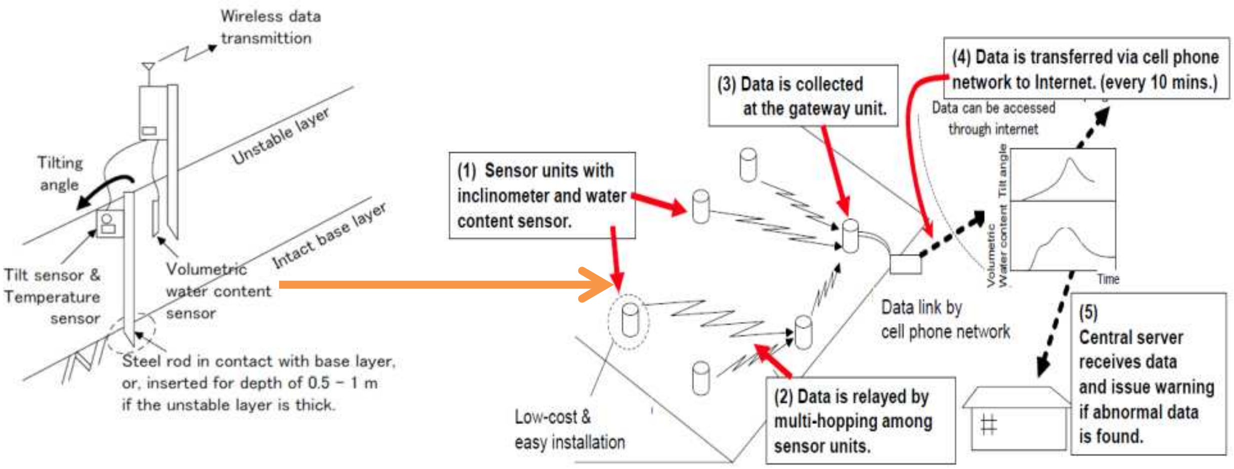

Figure 1. Outline of wireless monitoring and early warning system for slope failure.

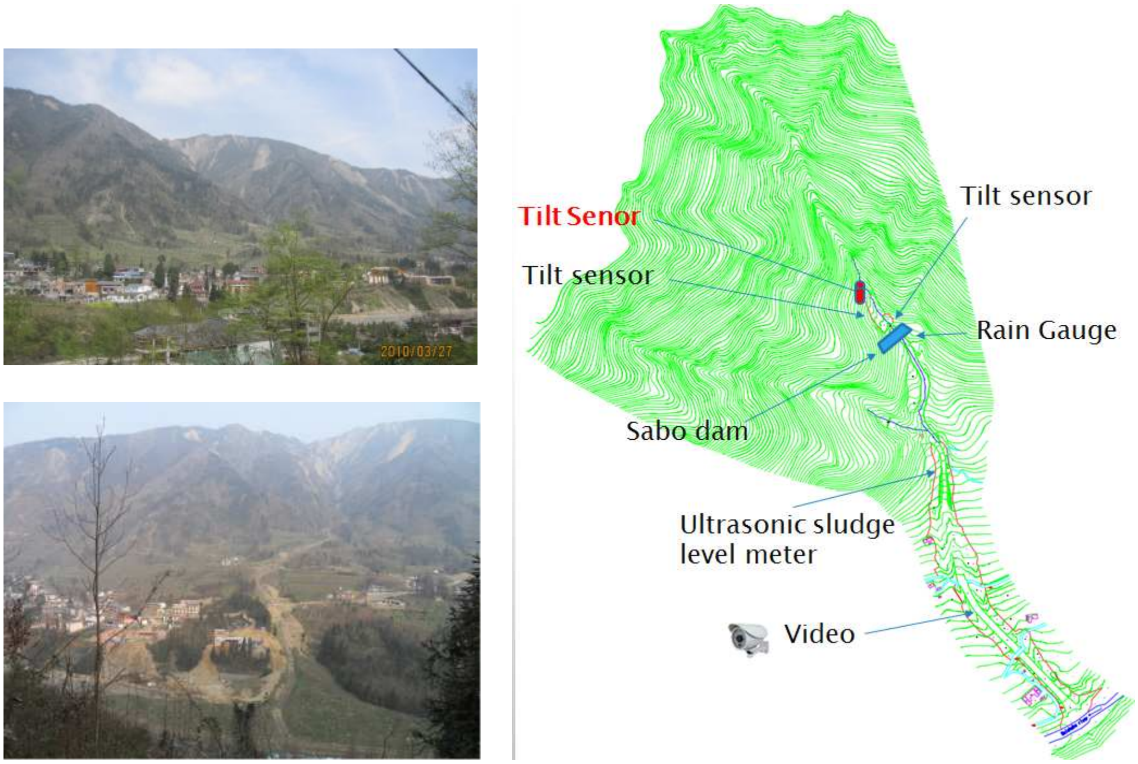

Figure 2. The monitored debris flow site relative to nearby settlements following the Wenchuan earthquake.

MEMS Inclinometer Technology Embedded in a Sensor Unit

The proposed system measures rotation on the slope surface and the volumetric water content within slope sediments. A MEMS tilt module (nominal resolution = 0.04 mm/m = 0.0025°) 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. The robust sensing element design features low temperature dependency, high resolution, economic power consumption and low noise. These MEMS type inclinometers are an ideal choice for slope failure sensors.

Field Evaluation of the Tilt Sensor Early Warning System – Chinese Example

Seismically-induced slope displacements or failures triggered by changes in environmental conditions have a long record in China. On May 12, 2008, the Ms 8.0 Wenchuan earthquake induced more than 197 000 slope failures and landslides in Sichuan province (Xu et al., 2013). To reduce the human vulnerability to such hazards and improve management of such events, an early warning system should be implemented. The development of an early warning system has been undertaken using real-time data monitoring of tilt angles, water content and rainfall. Prototypes of the monitoring system have been developed and deployed at various sites by the authors. One prototype, at a debris flow site that occurred near a group of settlements following the Wenchuan earthquake, is shown in Figure 2.

Study Area - Debris Flow Site Induced by the Wenchuan Earthquake

The study area is located north of the city of Dujiangyan in the Sichuan Basin where the annual average precipitation was 1134.8 mm from 1987 to 2006 (Table 1).

Table 1. The average monthly rainfall for 10 years (1987–2006)

Month	1	2	3	4	5	6	7	8	9	10	11	12	Annual
Precipitation (mm)	18.0	24.4	43.2	64.2	85.7	126.3	241.1	250.6	170.4	63.9	35.8	11.2	1134.8

A large debris flow occurred in the early morning of July 17, 2009, triggered by 6 hours of precipitation totaling 219 mm; two people died in the event. The elevation of this area is 920 to 1773 m, with a relative elevation difference of 853 m. The mountains trend in roughly an E–W direction, with general slope gradients of 35° to 55°. The total volume of sedimentary material involved in the slide is approximately 352 400 m^3 (Figure 2, 3). The slope consists of weathered granite with fractured rock joints, and with the surface rock being broken. Three wireless sensor units with tilt sensors were installed at high-risk positions as shown in Figures 2 and 3.

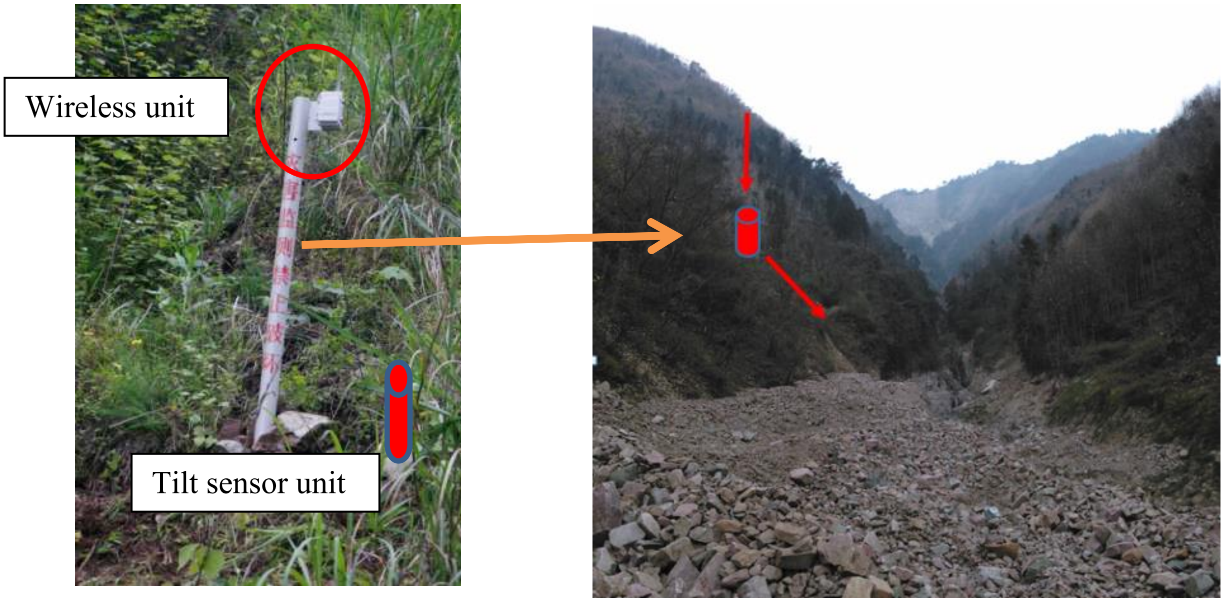

Figure 3. Wireless sensor unit with tilt and water content sensor on a mountainous slope

A small-scale slope failure suddenly occurred at the position of wireless sensor unit K-1 on July 6, 2013, without an accompanying increase in rainfall. Another two wireless sensor units maintained normal operations. The site manager became aware of the abnormal behavior from the wireless sensor, and traveled to the field site. He found that the wireless tilt sensor of unit K-1 was completely buried (Figure 4).

Figure 4. Wireless sensor unit destroyed by suddenly slope failure or rockfall flow

Figure 5 a) shows how the inclination of the 2D MEMS embedded in the separated tilt sensor unit changed over time, and Figure 5b) shows the relationship between the 3D MEMS inclination and time. On this slope, the real-time monitoring system started with three sensor units (Figure 1) 3 months earlier. No rain fell during the collapse of the slope. At 9:00 on July 6, the system showed that the tilt angles of the X and Y axes had notable changes. The output voltages of the 2D MEMS tilt sensor unit reached their limited, which means that the cable that connected the sensor and wireless units had become disconnected or broken, i.e., the separated 2D MEMS tilt sensor unit was destroyed by the first stage of slope failure or rock flow. At this time, the wireless unit continuously transferred the 3D MEMS tilt data, as is normal, to the remote data center. In other words, the system gave us a lot of time, more than 5 hours, to send out warnings.

Figure 5. Real time data for sensor unit K-1 around the time of slope failure.

After 5 hours, another trigger event caused a second slope failure, meaning that an additional large amount of rockfall flow happened. The wireless unit was buried in the slope and the data transfer stopped. Because the first slope failure and second rockfall were located at sensor unit K-1, the deformation of the slope at the time of failure was detected successfully by the monitoring system.

Slope movement can be generally classified into the type of material involved (e.g., rock, soil, debris) and the dominant type of movement (e.g., falling, sliding, toppling, flowing, or a combination thereof); the type of slope movement can be considered with the latter group. Based on the field site results, the new monitoring method is considered to provide suitable precautions for assessing seismically induced slope displacements and failure hazards.

Field Evaluation of the New Tilt Sensor Method Compared with Traditional Extensometers – Japanese Example

Another set of in-situ measurements are shown in Figures 6 and 7. These concern a period of heavy rainfall in July 2011 that caused a slope failure along a local highway in Kyushu, Japan. During road construction involving substantial earthwork, 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, the three tilt sensors were collocated near the fixed pole of the extensometer moving points as shown in Figure 7. 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 set up near survey holes 2 and 3. The results of the boring surveys show that the depth of landslide slip surface is 6 m at one location and 14 m at the other, as shown in Figure 8. Figure 7 shows the time histories of the tilt sensor inclination in the direction of the extensometer wire (tilt sensor x axis) and the movement of the extensometer (S-1, S-2); Figure 7c shows cumulative rainfall values by rain gauge; Figure 7d shows the water content determined by the ECH2O water content sensor.

Normally, the fixed pole of a tilt sensor is inserted into a slope surface to a depth of 1.0 m, so 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 tilt sensor K-3) and the movement of extensometers increased with rainfall, and showed a strong correlation with each other (Figure 7a–e). Figure 9 shows the relation of slope movement (in mm) as measured by extensometer (S-1) plotted against the inclination (in degrees) as measured by the tilt sensor (K-3). An almost linear relationship was found between the extensometer and tilt sensor, except during storm periods such as those that occurred in August, October, and November 2011.

Another important result is that between the start of heavy rainfall and the initiation of a landslide, the extensometer values remain constant but the tilt sensor inclination changes quickly. For example, during the heavy rainfall on November 18, 2011, hourly rainfall was as high as 20 mm and continuous rainfall reached 96 mm in a 16-hour period. During this time, the inclination of the tilt sensor increased but the extensometer readings showed no change (Figure 9). The tilt sensor measures local changes in the slope surface, whereas the extensometer measures overall movement. Because the failure of a slope usually starts from a local region and enlarges to a wider area, the difference between the tilt meter and the extensometer result should be considered an important phenomenon that needs to be addressed in early warning systems.

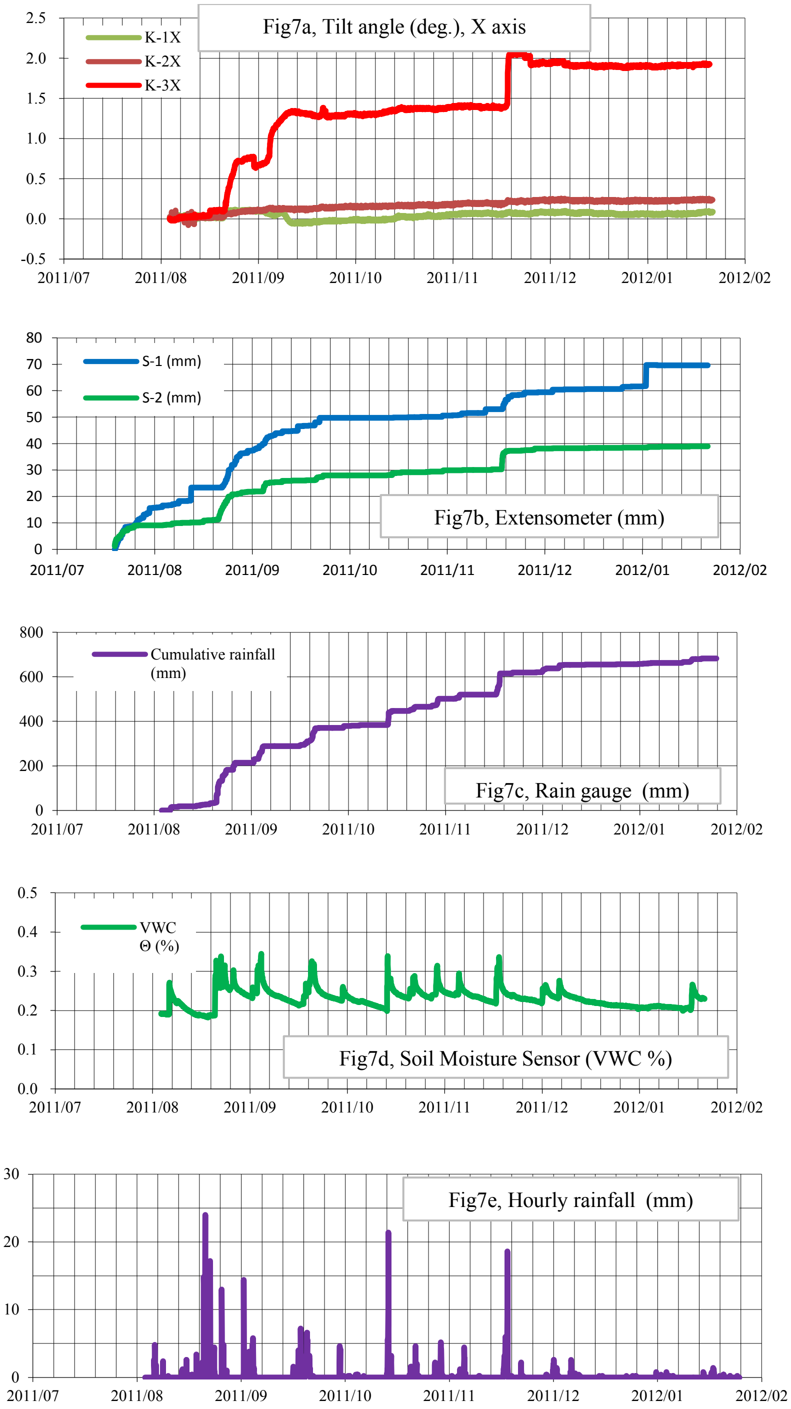

Figure 7 (a) Tilt angle (deg), X-axis, (b) Extensometer (mm), (c) Rain gauge, (d) Soil moisture sensor (VWC %) and (e) Hourly rainfall.

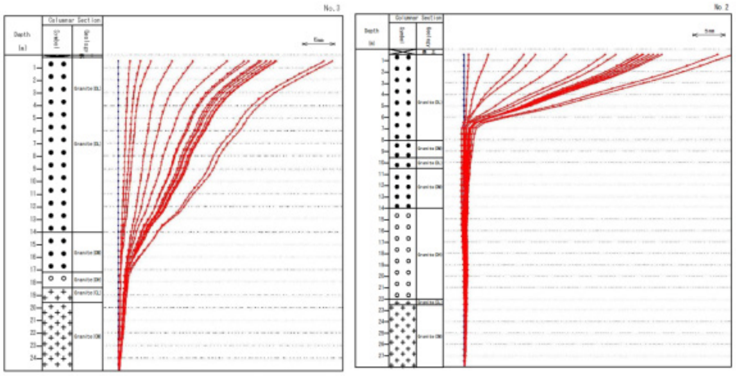

Figure 8. Multiple borehole inclinometers

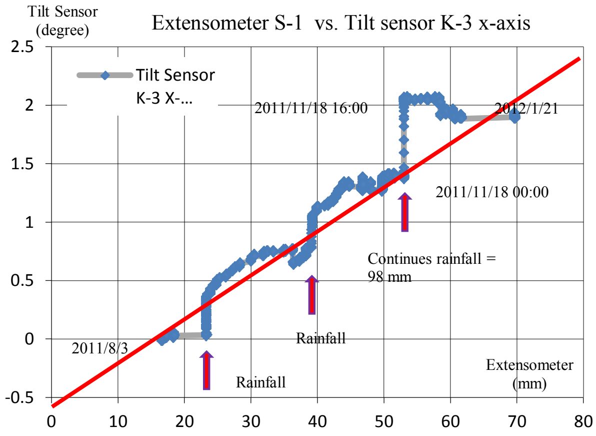

Figure 9. Relation of slope movement to tilt angle

Conclusions

In general, earthquakes generate seismic ground shaking that can result in inertial forces being applied to rock and soil masses. This causes the rock mass within a slope to loosen, and furthermore increase the possibility of a slope failure and an eventual rockfall. Earthquakes can also cause cyclic deterioration of the strength that initially keeps rock or soil masses stable. It is difficult to predict the events that cause slope failure or rockfall flow, but it is possible to observe and measure the movement of a sloping surface or changes in water level or water content. Based on the field results presented above, the outlined multi-measurement monitoring scheme is considered an effective choice for predicting slope failure or rockfall flow disasters.

To meet the project objectives, a simple and low-cost early warning system was developed for slope failure and landslides. The newly developed tilt sensor was easy to install and monitored slope deformation by means of tilting MEMS modules that transferred real-time data via a wireless network. Two successful monitoring case reports showed that the newly developed system can monitor slope movement adequately and issue useful information to nearby residents, enabling them to avoid slope failure disasters. The newly developed, low-cost, and simple monitoring method for earthquake-induced slope failure is effective and should be widely applied.

Acknowledgments

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