Stability monitoring of earthquake-induced rockfall

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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 197000 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 MEMS (Micro Electro Mechanical Systems) 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 one monitoring case to show that the early warning system adequately monitors the stability of slope and debris fields in China. Based on the field site test results, the monitoring method is proposed for regions of increased hazard of earthquake-induced slope failure.

Keywords: early warning, monitoring, landslide, slope failure

1 INTRODUCTION

Seismically induced slope failure is one of the most destructive natural hazards. Another type of earthquake-induced slope failure is rockfall. Rockfall is a natural and dynamic geologic process involving the detachment and rapid downward movement of rock. Due to its steep, glacially carved cliffs, the mountainous area of Sichuan province in China experienced many rockfalls during and following the May 12, 2008 Ms 8.0 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. 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. In the area of the Wenchuan earthquake, landforms have resulted from such processes. Over long periods, water flowing through fractures weathers the bedrock through chemical and physical processes that loosen the bonds holding 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. Ground shaking during small-scale earthquakes often triggers slope failure or rockfalls. Also, 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, which is an important factor influencing the initiation of slope failures. Laboratory experiments (Uchimura et al., 2009) show that soil water content and the inclination angle of the slope are two important factors that can be used to assess the stability of a slope. The development of such a system has the potential to provide simple and effective real-time monitoring of slopes that are close to failure. However, for a wide range of slope safety monitoring applications, a significant problem that needs to be considered is that measuring devices and equipment are expensive. High costs often hinder the implementation of a warning system in developing countries. Those cost issues could be overcome if effective methods used to determine soil water content and slope inclination angle were to gain widespread use.

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2 A LOW-COST AND SIMPLE WARNING SYSTEM

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 landslide were focused, and its applicability and effectiveness was tested on model slopes under artificial heavy rainfall. 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 (Uchimura, et. al. 2009). Figure 1 shows the basic concept of the wireless monitoring and early warning system.

2.1 RF (Radio Frequency) Wireless Data Transmit Method

A group of low-cost and simple sensor units (Figure 1) are installed on the slope. The system is designed to be wireless, that is, each unit works autonomously with microcomputer with independent power supply by batteries or solar cells. Radio modems operated in the 429 MHz ISM band for Japan, 434 MHz ISM band for E.U. counties and China, pre-programmed 127 channels 1mW/10mW power selectable which meets the requirements of the European R&TTE Directive and carries the CE mark is embedded in each sensor unit, so that the sensor units are provided for building a range of wireless data transmit system, from simple control systems to wide network systems.

### Wireless Feature

- (i) Narrow band FM for reliable long range communication
- (ii) 429 MHz/Japan, 434 MHz/EU and China ISM band Pre-programmed 127 channels
- (iii) 1 mW/10mW power selectable
- (iv) Error correction with Reed-Solomon code
- (v) Repeater and auto answer back function
- (vi) Low power operation 42mA at 3Volt

#### MEMS Inclinometer Feature

- (i) Dual axis inclination measurement (X and Y)
- (ii) Measuring ranges ±30°
- (iii) 0.0025° resolution (10 Hz BW, analog output)
- (iv) 12bit A/D analog data output or 11bit digital data output
- (v) Sensing element controlled over damped frequency response (-3dB 18Hz)
- (vi) Single +5 Volt supply
- (vii) Radiometric analog voltage outputs

Table 1. Maximum possible communication distance test results.

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>Receiver Unit Height (m)</th>
<th>Transmit Unit Height (0m)</th>
<th>Transmit Unit Height (0.5m)</th>
<th>Transmit Unit Height (1.0m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>0.5</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>400</td>
<td>0.5</td>
<td>X</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>X</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>500</td>
<td>0.5</td>
<td></td>
<td>X</td>
<td>O</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td></td>
<td>X</td>
<td>O</td>
</tr>
<tr>
<td>600</td>
<td>0.5</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>X</td>
<td>X</td>
<td>O</td>
</tr>
</tbody>
</table>

The result of Table 1 shows that the transmit distance is not less than 300m. If raising the height of the sensor units (RF module antenna), the communication distance can be extended to over 600m. Figure 1 shows the outline of wireless monitoring and early warning system for slope failure. 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 behavior of the slope can be detected as a precaution of failure, and then warning is issued.

2.2 MEMS Inclinometer Technology embedded to Sensor Unit

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 mm/m = 0.0025 degree) is installed 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 and low noise, together with a robust sensing element design, if we keep on leveling installation, this MEMS type Inclinometer is ideal choice for slope failure sensors.

MEMS Inclinometer Feature

- (i) Dual axis inclination measurement (X and Y)
- (ii) Measuring ranges ±30°
- (iii) 0.0025° resolution (10 Hz BW, analog output)
- (iv) 12bit A/D analog data output or 11bit digital data output
- (v) Sensing element controlled over damped frequency response (-3dB 18Hz)
- (vi) Single +5 Volt supply
- (vii) Radiometric analog voltage outputs

2.3 Saving Power Designed based on 16-bit Ultra-Low-Power MCU

For 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 (MSP430, the product of Texas Instruments), which include extensive performance of 7ch 12bit AD Converters with synchronization, 2 USART, I2C modules, were embedded to the sensor unit. The MCU is ultralow power consumption in standby mode=1.1 μA, and can run at low supply-voltage range: 1.8 Volt to 3.6 Volt, is very suitable to the no commercial power supply region.

A long-term sensor unit power consumption test (not include Micro SD) was started, the interval time of data sampling and transmit was 10 minute. 4 cells alkaline batteries were installed in the test sensor unit. Figure-1 shows the relation of battery voltage and elapsed time, the test unit works for duration of more than 3.5 years (Wang, et. al. 2012).

Actual operation in the field at each monitored point, a steel rod is installed through the thickness of unstable soil layer on the slope surface (Figure 1). 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 the sensors require careful maintenance. Therefore, use of volumetric water content sensors is more suitable for low-cost monitoring.

## 3 FIELD EVALUATION FOR DEVELOPED TILT SENSORS EARLY WARNING SYSTEM

Seismic slope displacements-induced slopes failure hazard triggered by environmental conditions changes have a long record in China. On May 12, 2008, the Wenchuan earthquake induced more than 197000 earthquake-induced slope failures and landslides in Sichuan province (Xu, et. al. 2013). In view of hazard reduction and management, the development of an early warning system for the landslide would be important. The developed early warning systems were designed using method of real time data transition of monitoring tilting angle, water contents or rain gauge. Prototypes of the developed monitoring system have been deployed at various sites by the authors. One of them, a debris flow site nearby settlements after Wenchuan earthquake, is shown in Figure 3.

## 4 STUDY AREA - DEBRIS FLOW SITE INDUCED BY WENCHUAN EARTHQUAKE NEAR SETTLEMENTS

Study Area is located at north of Dujiangyan city in Sichuan basin, the annual average precipitation is 1134.8mm from 1984 – 2006 years (Table 2).

![Fig. 1. Outline of wireless monitoring and early warning system for slope failure](image-url)
A large debris flow was occurred on July 17, 2009 early morning, the six hours precipitation reached to 219mm, 2 people dead. The elevation of this area is 920m - 1773m, and the relative elevation is 853m, the mountain trend is nearly in EW direction, general slope gradient is at 35 degree to 55 degree, the total amount of sediment material is approximately 352,400 cubic meters (Figure 3).

This slope consists of weathered granite with fractured rock joints, and its surface rock shows the broken situation; three wireless sensor units with tilt sensors are installed to a selected dangerous position shown in Figure 3 and Figure 4.

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 5 a) shows how the inclination of the 2D MEMS embedded in the separated tilt sensor unit, 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. 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.

Table 2. The average monthly rainfall for 10 years (1987-2006)

<table>
<thead>
<tr>
<th>Month</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>Annual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation (mm)</td>
<td>18.0</td>
<td>24.4</td>
<td>43.2</td>
<td>64.2</td>
<td>85.7</td>
<td>126.3</td>
<td>241.1</td>
<td>250.6</td>
<td>170.4</td>
<td>63.9</td>
<td>35.8</td>
<td>11.2</td>
<td>1134.8</td>
</tr>
</tbody>
</table>

Fig. 2. The monitoring site - debris flow site nearby settlements after Wenchuan earthquake
There was no any rainfall while the slope collapses.

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

Fig. 4. The destroyed wireless sensor unit by sudden slope failure or rockfall flow.

Fig. 5. The real time data information of sensor unit K-1 around time of slope failure.
On July 6, 9:00, the system showed that tilt angles of X axis and Y axis appear large changes, the output voltages of 2D MEMS tilt sensor unit reached limited values, it means that the cable connected sensor unit to wireless unit was disconnected or broken. In the other words, the separated 2D MEMS tilt sensor unit was destroyed by first stage of slope failure or rockfall flow. In this time, wireless unit transferred the 3D MEMS tilt data normally to remote data center. After that, the system gave us a lot of time, more than 5 hours, to send out warning issues.

Five hours after, another trigger event caused second slope failure, it means that large amount of rockfall flow happened, the wireless unit was also buried into slope and the data transfer was stopped finally. As the first and second failures took place adjacent to the location of the sensor unit K-1, the behaviors or deformation of the slope around the time of failure was detected successfully by the monitoring system.

The slope movement can be classified into the type of material involved in movement (rock, soil, or debris) and the dominant type of movement (falling, sliding, toppling, flowing, or a combination thereof), the slope movement type of our study area can be thought of as latter. Based on the field site test results, the proposed monitoring method is suitable to the precaution of seismic slope displacements-induced slopes failure hazard.

5 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.

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