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Precaution and early warning of surface failure of slopes using tilt sensors

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Abstract

A simple monitoring method for the early warning of rainfall-induced landslides is proposed. Tilting angles in the surface layer of the slope are mainly monitored in this method. In the first stage of this study with a scaled model slope, distinct behaviors were observed in the tilt angles monitored on the surface of the slope prior to failure. Hence, a set of equipment has been developed for practical use, which is equipped with a Micro Electro Mechanical Systems (MEMS) tilt sensor and a volumetric water content sensor. An optional arrangement of tilt sensors has also been developed in order to investigate the deformation of the deeper layers. These sets of equipment have been deployed at several slope sites in Japan and China, and their performances have been recorded. Slope failure tests were also conducted on a natural slope by applying artificial heavy rainfall. The developed system detected distinct behaviors in the tilting angles at these sites in the pre-failure stages. Considering the behaviors of tilting monitored on the surfaces of these slopes, it is proposed that a precaution be issued at a tilting rate of 0.01° per hour and a warning be issued at a tilting rate of 0.1° per hour, to be on the conservative side.

Keywords: Slope failure; Monitoring; Early warning; Tilt angle; Sensor network

1. Introduction

There is a long history involved in the prevention and mitigation of landslides. Most landslide disasters are caused by heavy rainfall or strong earthquakes. As for rainfall, there has been some discussion that the intensity and frequency of heavy rainfall events are increasing in many countries in Asia and other regions. Meanwhile, economical growth and urbanization impel the extension of land use to areas with a high risk of landslide disasters. Therefore, the demand for mitigation measures against landslide disasters is on the rise in every country.

Typical measures to prevent slope failure are retaining walls and ground anchors which improve the factor of safety against failure by means of mechanical reinforcement. These measures have been widely adopted around the world and have been effective. They are costly, however, which results in a limited number of applications.

It is noteworthy that the size of most slope disasters is not significantly large. Osanai et al. (2009) conducted s statistical study on 19,035 cases of landslides between 1972 and 2007 in Japan. They reported that 93% of those landslides were caused by heavy rainfall, and most of them were shallow surface landslides. The average thickness of the failed surface layer was 1.2 m, and 90% of them were less than 2.5 m-deep. The average height of scarp was 12.7 m. On the other hand, the number of high-risk

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areas is huge. The Japanese government lists around 520,000 of such areas in Japan. Therefore, it is not feasible, from a financial viewpoint, to reinforce all of these high-risk slopes by means of mechanical methods. In addition, mechanical methods often damage the eco-system and the landscape around the slopes.

Longstanding effort has been made to understand the mechanism of landslides based on soil mechanics. The concept of "stability analysis" suggests that a landslide takes place when the shear stress exceeds the shear strength of the soil along the slip surface. Many engineers have attempted to analyze the individual cases of landslides using quantitative numerical methods. However, such methods give us exact conclusions in limited situations only when the geological, strength, and hydraulic properties of the slopes are well-known. Costly investigations are needed to satisfy these requirements, and this brings back the difficulty from a financial viewpoint again.

In the above context, monitoring and early warning comprise one of the most promising ways to reduce disasters induced by landslides and slope instabilities. A time history of rainfall intensity is widely used for warning. There are many applications of early warning based on real-time rainfall records (Keefer et al., 1987; Baum and Godt, 2010, among others). The criteria of issuing warnings are defined based on the current rainfall intensity and/or the cumulative rainfall during a recent period of several hours in advance. The Japan Meteorological Agency has developed a Soil Moisture Index (SMI) as a more appropriate index to represent the virtual moisture content in slope grounds. It is calculated by assuming a three-tank model for the infiltration and drainage process of rain water (Ishihara and Kobatake, 1979; Okada, 2001). SMI has been adopted as a standard reference for early warning by Japanese local governments since 2008. There are also many studies on the validity and new applications of SMI (Osanai et al., 2010, for example). However, this index is calculated with a spatial resolution of 5 km and provided for local governments who are responsible for disaster mitigation.

These early warning methods based on rainfall records are advantageous in that the amount of rain can be measured easily and at a low cost. By assuming the uniform distribution of rainfall intensity, only one rain gage can monitor the time history of rainfall in each zone with an area of several square kilometers. However, such a sparse arrangement of rain gages cannot properly detect cloudbursts, in which extremely heavy rainfalls occur in limited areas. In addition, the criteria of warning are decided for every area based on local areal records of past slope failure events. Therefore, the monitoring of rainfall solely is not enough to evaluate the risk of landslide disasters for individual slopes. It is recommended that the behaviors of individual slopes be monitored in combination with the areal monitoring of rainfall. They complement each other.

Displacement, or deformation, is one of the items to be monitored for individual slopes. Extensometers are the most widely-used equipment for monitoring the displacement along a slope surface. Recently, GPS and remote sensing with radar technology are also being examined for use in monitoring the long-term displacement of wide areas on slope surfaces (Casagli et al., 2010; Yin et al., 2010). However, their typical resolutions are 5–10 mm; this level is insufficient for detecting the displacement of slopes in the very early stages.

In most cases of landslides, the displacement is observed continuously for several hours or days before the catastrophic failure. For example, Kuroki et al. (1995) reported a case study of failure in a cut slope whose pre-failure deformation was observed. Ochiai et al. (2004) also reported gradual and accelerating displacement on a slope surface before failure in an artificial rainfall-induced landslide test conducted at Mt. Kaba in Tsukuba, Japan.

In addition to the total amount of displacement from the beginning of monitoring, the rate of displacement is often used as an index to define the threshold of warning. The thresholds of the displacement rate are determined based on the conditions of each slope, but values of several mm/day for caution and several mm/hours for evacuation are usually adopted in Japan (Maruyama and Kozima, 1994). Saito (1965), Fukuzono (1985), and Saito (1987) proposed a more advanced technique to predict the timing of catastrophic failures based on the monitored time history of the displacement on the slope surface.

Although being less costly than the construction of retaining walls or other structural measures, monitoring and early warning methods have several problems that must be overcome. The first problem is that the exact locations of unstable soil masses often cannot be defined; and hence, the locations of the monitoring sensors cannot be decided distinctly. This problem can be solved by installing many simple and low-cost sensors within a possibly unstable slope. The second problem concerns what items of the slope should be monitored. The observed items should precisely represent the instability of the slopes.

Most conventional sensors, including extensometers, require skilled engineers for their installation and operation, resulting in considerable costs and limited locations of monitoring. The authors suppose that the equipment should have high serviceability so that their installation and operation are easier and less time-consuming.

In recent decades, sensing, computing, and communication technologies have developed rapidly. Flexible and innovative designs for monitoring and early warning systems for landslide disasters have been realized by providing accurate, low-cost, and low-power-consumption wireless equipment. Nowadays, many attempts are being made to develop new applications for these technologies, like Azzam et al. (2011), Sawada et al. (2012), Nishiyama et al. (2012), etc.

The present study proposes a simple monitoring system with Micro Electro Mechanical Systems (MEMS) technology that can measure the tilt angles (rotations) in the unstable surface layer of slopes. Therefore, the proposed system is primarily suitable to detecting the pre-failure stages of surface failures with shallow slip surfaces.

However, in case of a slope deformation with a deeper slip surface, which is also investigated in this study as "Site C", the tilt sensors also detected pre-failure behaviors corresponding to the progressive deformation of the sliding mass. The sensors are also useful for detecting the instability of slopes under such conditions.

The authors observed the pre-failure tilting behaviors in slope surfaces of a laboratory model slope, artificial rainfall tests on a