Monitoring of unstable slopes by MEMS tilting sensors and its application to early warning

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Abstract. The present paper addresses the newly developed early warning technology that can help mitigate the slope failure disasters during heavy rains. Many studies have been carried out in the recent times on early warning that is based on rainfall records. Although those rainfall criteria of slope failure tells the probability of disaster on a regional scale, it is difficult for them to judge the risk of particular slopes. This is because the rainfall intensity is spatially too variable to forecast and the early warning based on rainfall alone cannot take into account the effects of local geology, hydrology and topography that vary spatially as well. In this regard, the authors developed an alternative technology in which the slope displacement/deformation is monitored and early warning is issued when a new criterion is satisfied. The new MEMS-based sensor monitors the tilting angle of an instrument that is embedded at a very shallow depth and the record of the tilting angle corresponds to the lateral displacement at the slope surface. Thus, the rate of tilting angle that exceeds a new criterion value implies an imminent slope failure. This technology has been validated against several events of slope failures as well as against a field rainfall test. Those validations have made it possible to determine the criterion value of the rate of tilting angle to be 0.1 degree/hour. The advantage of the MEMS tilting sensor lies in its low cost. Hence, it is possible to install many low-cost sensors over a suspected slope in which the precise range of what is going to fall down during the next rainfall is unknown. In addition to the past validations, this paper also introduces a recent application to a failed slope in the Izu Oshima Island where a heavy rainfall-induced slope failure occurred in October, 2013.

1. Introduction

People’s concern for safety from natural disasters are increasing significantly in the recent decades and this trend is even more intensified internationally under the initiative of the United Nations conducting many projects. One of the target natural disasters is the slope failure that is induced by heavy rainfall and it is the main theme of the present study.

It is often argued that the probability of extraordinary heavy rain is increasing recently due to the global climate change. Although the authors are not able to judge whether or not this idea is correct, it is certainly true that people are more concerned than before with safety of their lives and properties.
during heavy rains. Nevertheless, the current situation is very difficult. For example, photo 1 illustrates the post-disaster situation in Hiroshima, Japan, where a residential land at a foot of hill was attacked by slope failure and induced debris flow during a midnight heavy rain on August 20th in 2014. The residents were living on an alluvial fan that was formed by repeated debris flows in the past, but they were not experts of geology and did not appreciate the hazard information issued by public sectors. It is important here that, although people are concerned with safety, they on the other hand decide their places to live on the basis of the convenience in daily life, good landscape, business chance and so on only. Hence, an advice for relocation to safer places is not effective.

Early warning and evacuation to shelters are popular in the recent times. Generally, evacuation order and/or alert is issued by public sectors on the basis of a rainfall criterion which assumes that the possibility of slope disaster is controlled by the intensity of rain. This idea is basically correct and hence rainfall-based early warning is practiced today in many parts of the world.

A possible drawback of this practice is that the rainfall criterion does not take into account the effects of local geology, topography and human actions in a sloping ground. Moreover, the rainfall forecast cannot capture the local variation of rain in a small spatial scale such as hundreds of meters. Therefore, the rainfall-based early warning is not sufficient when a family wants to be prepared for the failure of a particular slope behind its house. To foresee failure of a particular slope that cannot be captured by the regional rainfall-based warning, a supplementary warning system is necessary.

![Photo 1](image)

**Photo 1 Rainfall-induced disaster in a residential land on an alluvial fan (Hiroshima, August 2014)**

2. **Principles of slope monitoring by MEMS tiltmeter**

It has been empirically known that slope failure during heavy rain is preceded by such phenomenon as ground “roaring”, muddy water ejection, cracking in the ground surface, smell of methane gas and so on. Although installation of video, sound and smell sensors would capture those precursors in principle, their reliability is too low during heavy rain with possible thunders in dark midnight. The authors, therefore, understand that those precursors are caused by or closely related with minor slope deformation and decided to develop a displacement sensor [1 and 2]. Moreover, an artificial rainfall test to trigger slope failure reported that minor slope deformation started around 2000 seconds prior to the ultimate failure [3].

Another important point is the cost of a sensor. Although an extensometer has a long and good tradition in landslide monitoring, its price is too high and installation is not very easy for individual citizens who are not engineers but wish to help themselves from natural disaster. The cost is even more important because a rainfall-induced slope failure may occur everywhere and it is difficult to foresee which part of a slope will fall down during the next heavy rain. Thus, many sensors have to be installed in a slope and hence the cost per sensor has to be reduced.

Figure 1 illustrates the MEMS (Micro Electro Mechanical Systems) tiltmeter and its operation principle that were developed by the authors. A MEMS tiltmeter is stored in a protection box. After punching a rod into a stable base layer that do not fail during heavy rain, this box is attached to the top
of the rod. During rain, the surface soft soil may move downwards and push the rod. Because the bottom tip of the rod is penetrated into a stable base layer, the rod starts to rotate or tilt. The tiltometer captures this minor change of the angle prior to the final failure and transmits the signal to the Internet through wireless (figure 2). Because of the use of MEMS sensor, the price per sensor is reduced. Although the precise cost varies with the mass production, it is of the order of hundreds of US Dollars at this moment. Note that this kind of monitoring is mainly interested in shallow failures which are small in scale but significantly more in numbers than more dramatic deep-seated gigantic slope failures.

Figure 1 Schematic illustration of MEMS tiltometer sensor for early warning (volumetric water content sensor is optional)

Figure 2 Idea of slope monitoring by multi-displacement sensors connected to internet

To reduce the cost, the following efforts were made so far;

- Water content sensor is optional. Although water content and pore water pressure play major roles in shear failure of soil as soil mechanics states, the use of water information in early warning of slope failure needs to know the exact location of a failure plane. To know this, soil investigation and analysis are required and increase drastically the cost which people cannot afford any more. Consequently, it was decided to issue early warning on the basis of minor displacement precursor.
The sensor is driven by electricity. This power is provided by dry cells that are substantially cheaper than solar batteries. To reduce the energy consumption, the MEMS sensor works once every 10 minutes, sends the signal through wireless and sleeps again. Accordingly, it has been proven in the field that four batteries can maintain operation for more than one year.

3. Validation of developed technology by artificial rain test

The developed sensor has been installed in many slopes in Japan and China in order to decide the new displacement-based criterion of early warning. To date, the authors propose that an evacuation order should be issued if the rate of the tilting angle exceeds 0.1 deg/hour during rainfall. This deformation criterion was derived by interpreting many field studies during real slope failures and an artificial rainfall test. To begin with, this chapter presents data from an artificial rainfall test that triggered failure in a natural slope.

The artificial rainfall test was conducted in Sichuan Province of China as a joint research project between authors and the Institute of Mountain Hazards and Environment in Chengdu, China. The test slope consists of debris flow deposits that are basically cohesionless, including gravels. Photo 2 illustrates ongoing artificial rain. An unstable cut face was prepared by excavating a part of the slope and water seeped into the upslope side of the face, thus increasing the weight of soil as well as pore water pressure and reducing the factor of safety. The affected cut face, which is of 40 degrees in slope, is shown in photo 3.

Figure 3 shows the locations of installed sensors in the slope. Many tiltometers were embedded both near and at far distance from the cut face and slope failure started from the vicinity of the face and proceeded inwards with time. The intensity of rainfall was 40mm/10 minutes (240 mm/hour) prior to the failure. Figure 4 indicates the time histories of the recorded tilting angles. It may be evident that the rates of tilting angle were 0.15, 0.40 and 0.24 degrees/hour respectively at three sensor locations and then slope failed progressively. Thus, the criterion of 0.1 deg/hour for issuing an evacuation order is reasonable.

It is of common concern whether or not the new tiltometer is equivalent with the conventional extensometer monitoring. To shed light on this, the surface displacement was assessed at a tiltometer location by (length of vertical rod)*tan(tilting angle) and compared with the displacement obtained by an extensometer. Figure 5 reveals that the two kinds of displacement are similar with minor difference. Thus, it is very possible that more expensive extensometer is replaced by multi-point monitoring by less expensive tiltometers.

(a)  
(b)  

Photo 2 Ongoing artificial rain to de-stabilize a slope  
Photo 3 Cut face to fail during artificial rain
Figure 3 Locations of installed sensors

Figure 4 Time history of recorded tilting angles

Figure 5 Comparison of extensometer and tiltometer records
4. Validation in failure of natural slope

After the completion of the Three Gorge Dam in China, many slopes along its reservoir, which had been potentially unstable, started to move due to water submergence effects. Photo 4 illustrates one of such sites and, because of this situation, tiltometers were installed for validation of the technology. Photo 5 shows the situation after the slope failure as expectedly happened.

Figure 6 shows the time history of the tilting angle that was recorded by a sensor inside the failed soil mass. No heavy rain happened in this period and the slope failed due to the gravity and water submergence. More than several days before the final failure, the rate of tilting was only 0.008 deg/hour and did not suggest incipient failure. However, precipitations of 15mm and 50mm occurred on June 7th and 8th, respectively, and consequently the rate of tilting was accelerated. As figure 6 shows, the rate became 0.13 deg/hour, exceeding 0.1 deg/hour, and the final failure occurred. Thus, the proposed criterion of 0.1 deg/hour was validated.

It is important that evacuation order is issued well in advance so that people has sufficient time to do so. From this viewpoint, the time histories in figures 4 and 6 are examined to show that the rate of tilting greater than 0.1 deg/hour lasted for hours or even for one day that are sufficiently long for evacuation.

5. Rainfall-induced slope disaster in Izu-Oshima volcanic island in Tokyo

On October 16th, 2013, a strong typhoon made as much as 800 mm of precipitation in one night in a volcanic island of Izu Oshima, south of Tokyo (figure 7). This rain induced a huge slope failure that
claimed 39 lives. The failed slope is shown in photo 6. This slope has been stable for the past 600 years. It was even stable when another typhoon in 1958 produced precipitation of more than 400mm in one day. However, the heavy rain in 2013 exceeded the past record (figure 8) and the disaster was induced. It is noteworthy that the failure in 2013 happened at around 2AM when the accumulated rainfall exceeded the previous record of 400mm. It was very unfortunate that the size of the affected area of was smaller than the target size of the rainfall-criterion strategy of warning. Hence, people were attacked by the disaster without precaution in mid midnight.

Figure 7 Location of Izu Oshima Island  Photo 6 Failed volcanic slope and soil deposition

Figure 8 Rainfall record during the disaster in 2013  Photo 7 Piping holes in the failed slope

Failure of a volcanic slope has an interesting characteristic that does not occur in other kind of slopes. It come from the stratified structure which consists of interbedding of more pervious ash deposits and less pervious fine materials as well as lava. Obviously this stratified structure was produced by the history of repeated eruptions in the past. Photo 7 demonstrates one of the most impressive features of the slope failure, which is the occurrence of many piping holes from which ground water was ejected. Certainly, the pervious layers introduced ground water towards the failed slope and the high ground water pressure affected the stability of the surface soil (figure 9). Another important issue is that the failed soil was very thin at the top (photo 7) but the flow of soil thus initiated eroded soils in the middle of the slope to be huge and devastating finally (photo 6).
The fact that the failure occurred in midnight posed several problems in the early-warning and evacuation strategy. Going out of home for evacuation during heavy rain in midnight may be a dangerous action unless good transportation is provided. It is certainly difficult, however, for a driver to visit families and collect people from every house. It may be an alternative idea to designate some streets as evacuation routes and install good illumination. Vertical evacuation, which finds a shelter in the upper floors in the same house or apartment building, can improve the safety. This issue needs further study.

After the disaster, the local administration started to issue evacuation advices well in advance during the daytime, even if heavy rain is expected after midnight. From the safety viewpoint this is a reasonable idea. However, people may not understand the reason why they have to go evacuation when rain has not yet started. Because slopes do not always fail in spite of evacuation advices, people would feel more reluctant to evacuate and spend inconvenient time in a shelter. It is hence being discussed that evacuation should be made more enjoyable by providing light entertainments.

![Figure 9 Mechanism of slope failure associated with piping holes](image1)

![Photo 8 Location of tiltometers in head scarp](image2)
6. Slope monitoring in Izu Oshima

After the disaster, tiltometers were installed at several head scarps of the failed slope in Izu Oshima where further failure appeared likely (photo 8). It was intended therein to validate the operation of the MEMS tiltometer system through internet. Figure 10 shows a successful example of the record as obtained through internet. Very fortunately no failure occurred during the monitoring period of 2014. Although the issuing of evacuation order can be automatic and computerized, the authors still rely on the judgement of experienced engineers who are watching the record. If the rate of tilting becomes high, a notice is sent to a local government who decides whether or not people should evacuate. Administrators have a dilemma between safety and unnecessary panic of people.

7. Comparison of extensometer and tiltometer

Figure 11 illustrates another monitoring site in Japan where road construction was conducted under the safety control by means of slope monitoring. During rainfalls, the monitored slope developed a certain extent of deformation and they were recorded by tiltometers and extensometers. What is importance is that many sensors were installed here so that different records from different locations and sensors might be compared.
Figure 12 shows time histories of the records during several rainfall events. It is first noticed that the tilting angle at K-3 near the bottom of the moving soil mass increased faster and more profoundly than those in the upper part of the soil mass. This implies that the soil conditions in the lower part was worse than in the upper part and/or the stress concentration in the lower part played a significant role. In other words, this moving soil mass was pulled down by its bottom. Second, the extensometer record S-1 across the head scarp was greater than the S-2 record within the moving soil mass. This may be consistent with the traditional idea of landslide monitoring by extensometers. However, the S-2 deformation is not negligible and the soil mass was subject to deformation. This finding supports the principle of tiltometer monitoring in which soil deformation induces tilting of the device.

Figure 13 compares the extensometer and tiltometer records in more detail. Herein, records of two extensometers, S-1 across the head of the moving soil mass and S-2 within the middle part of the soil mass, are compared with the tilting angle at K-3 near the bottom. S-1 is always greater than S-2 as stated above. It is noteworthy that each rainfall increases the K-3 record first and then S-1 and S-2 follow. This implies that early warning is more facilitated by a tiltometer than an extensometer because the former responds to the soil mass movement more quickly.
8. Conclusion
The authors have been developing an inexpensive early-warning technology that monitors the deformation of unstable slopes undergoing heavy rain. The developed instruments monitor the tilting angle prior to the final failure and, if the rate of tilting exceeds the criterion of 0.1 degree/hour, an evacuation warning is issued. This technology has been validated by several case histories and a field
rainfall test, some of which were referred to in this paper. The major conclusions drawn from this study are as what follows.

1. An artificial rainfall test on an unstable slope successfully induced failure.
2. There is a minor slope deformation well in advance of the final failure.
3. A tiltometer sensor was developed and further cost reduction is going on so that early warning may be issued prior to the final failure.
4. The criterion of 0.1 degree/hour is reasonable and there are plenty of time for evacuation after the occurrence of this rate of tilting.
5. Slope monitoring by the newly-developed tiltometer is equivalent with that of the conventional extensometer but much less expensive.
6. Multi-point monitoring, which intends not to miss the slope movement in any part of the moving soil mass, becomes feasible by the use of inexpensive tiltometers.
7. A tiltometer can capture the onset of precursory deformation of a slope earlier than a conventional extensometer.
8. A volcanic slope that failed recently was monitored but no further failure happened in the next year.
9. Rainfall-induced failure of this volcanic slope is characterized by the profound occurrence of water piping that reduced the safety factor of the slope during heavy rain.
10. Evacuation during midnight is not advisable and hence more strategy needs to be studied for successful early warning.

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