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Technical developments for slope monitoring and mitigation of rainfall-induced landslide disaster

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Abstract

Rainfall-induced landslide is one of the most important natural disasters that has been threatening the safety of human communities in many parts of the world and will be more serious because of the possible change of global climate. Since the financial restriction hardly allows installation of structural safety measures such as retaining walls, slope monitoring and early warning is a preferred safety measure. A special requirement stems from the fact that rainfall-induced landslides occur in apparently stable slopes, not preceded by a long-term slip. Once initiated, the landslides develop rapidly within a few hours towards the ultimate failure. The present paper compares two types of slope monitoring and early warning (rainfall threshold and displacement/velocity threshold) from the viewpoints of the rate of development as well as the financial restrictions, which are often the case in practice. Of particular importance is that the so-called 'scientific' approach often hinders the early warning program for those who cannot afford the cost for scientific design and instrumentation. In this regard, the authors have been developing a tiltmeter technology that is based on the inexpensive MEMS sensors and employs the velocity threshold which is partially scientific but substantially relies on empiricism as well. To date, this technology has been installed at more than 1,200 points without false-negative trouble. Nevertheless, it is still necessary to further improve this technology and a novel acceleration sensor is added to it. This sensor is substantially less expensive than but as accurate as the conventional field acceleration sensors. This novel acceleration sensor can be applied to many new purposes beyond the conventional scope of slope monitoring.

Keywords: Landslide, Rainfall, Monitoring, Early warning, Empiricism, Tiltmeter, Accelerometer

1. Introduction

This paper addresses the mitigation of rainfall-induced landslides that are still frequent in the world today and are feared to be more serious in the coming decades because of the possibility of global climate change. Given that financial restrictions do not allow construction and installation of slope stabilizing structures, the second choice for safety is slope monitoring and early warning.

Monitoring of unstable slopes has a long history and many instruments have been utilized, including extensometer and inclinometer together with many photogrammetric instruments. Noteworthy is that the rainfall-induced landslides are different from the gravity-induced landslides in that the former occurs abruptly and quickly during heavy rain, often in midnight when visibility is poor. Moreover, it is difficult to identify in advance which part of a slope will fall down during the next rainfall.

The regional early warning of rainfall-induced landslide is a popular and effective measure to mitigate the related disasters. Herein, a warning is issued on the basis of the observed rainfall record (Ali, 2011; Baum & Godt, 2010; Brunetti et al., 2010; Caine, 1980; Endo, 1969; Keefer et al., 1987; Onodera et al., 1974; Soralump, 2010), and is called rainfall-threshold warning. The cost for this is low and the method is applicable to many regions. On the contrary, its limitation is that it does not consider the local geology and topography. Thus, the effects of shear strength, slope angle and ground water condition are out of scope. Accordingly, the rainfall-threshold is good only for regional warning for provinces or states but not valid for an individual slope. In this regard, there is a need to develop a supplementary technology that is slope monitoring and warning. The present paper introduces the characteristics and difficulties in the current practice of slope monitoring and proposes a novel technology for better future.

2. Philosophy of slope monitoring and early warning

Prior to addressing the details of the authors' early warning technology, it is crucial to touch upon the basic strategy of slope monitoring and early warning. The choice for practice is whether scientific principles should be pursued or empiricism should be accepted. From the soil-mechanic viewpoints, slope failure is a consequence of underground shear stress exceeding the shear strength that is governed by the weight of slope (total stress), pore water pressure, and material properties (friction angle and cohesion, if any). Strictly speaking, the scientific approach of early warning has to capture and monitor all of them and assess the likelihood of slope failure. In principle, this scientific approach is possible if and only if sufficient funding is available for field investigation on material properties and ground water conditions. Among many difficulties, the most serious problem is the monitoring of underground water flow during heavy rain as well as capturing the shear strength parameters in heterogeneous subsurface media. Thus, a scientific approach needs substantial financial supports.

The funding as mentioned above may be available in scientific research projects but is not so in practice of disaster mitigation for local community. Big landslides such as shown in Fig. 1 may be a good subject of scientific approach but small landslides as illustrated in Fig. 2 cannot be scientifically interested in. As long as a scientific approach is insisted on, early warning of rainfall-induced landslide cannot be practiced for small events. In reality, the majority of landslides disasters is small in size (called 'fall' in Fig. 3) and people living in front of such small but vulnerable slopes are undergoing the risk. Then a question arises; should we give up early warning for disaster-prone people? The answer is certainly 'no' and the engineers/researchers have to develop alternative (less scientific) methods of early warning that do not require much fund.

Figure 1: Azue landslide, Shikoku, SW Japan, triggered by heavy rainfall in 2005.

Figure 2: Rainfall-induced small but fatal landslide behind a village in 2005, Tochio, Central Japan.

The most common less-scientific approach is called the rainfall-threshold approach that monitors the rainfall intensity and its duration, and then compares the measured data with an empirical dataset that suggests the high likelihood of landslide disaster. Because measurement is made only of rainfall at available meteorological observatories, the needed cost is low. This is the reason why the rainfall-threshold approach is widely practiced. On the contrary, there are several basic issues that deserve attention. First, the rainfall record at specified observatories may not account for the situation at any particular slope. It is often the case that heavy rainfall may be concentrated in a small area. Second, the rainfall threshold does not account for any slope conditions that are slope gradient, material properties and ground water flow. Accordingly, the rainfall-threshold approach suits regional early warning by which the regional disaster likelihood in provinces, states or countries is assessed.

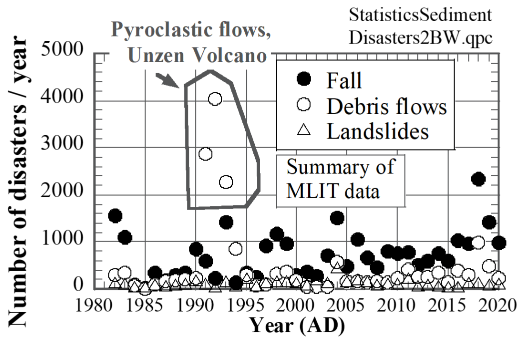


Figure 3: Frequency of landslide disasters in Japan; summary of many data provided by Ministry of Land, Infrastructure, Transport and Tourism; abbreviated as MLIT in what follows.

There are always people who are concerned with the instability of slopes behind their own places. Because instability of an individual slope is out of scope of the rainfall-threshold approach, the authors have been engaged in a different technology that is called displacement/velocity threshold. This approach installs sensors in a slope of interest and captures any precursor displacement/velocity of the slope that occurs several hours prior to the ultimate landslide during heavy rain. Note that this approach monitors the surface movement only due to financial limitation and the threshold level of movement is empirical. The aforementioned financial limitation does not allow scientific investigation of the subsurface condition that may affect the threshold. It is stressed that the disaster mitigation technology makes efforts to save people from landslide disasters even when scientific approach is not possible due to financial restriction.

Table 1 compares the two approaches, which are the rainfall threshold and displacement/velocity threshold, respectively. The authors personally prefer the 'velocity' threshold and feel that the 'displacement' threshold cannot be easily determined. This is because any designated threshold, e.g., 2 cm at surface, can occur rapidly after six hours of heavy rain or can be attained by stages; 1.5 cm yesterday and then 0.51 cm today. This stage-by-stage development of displacement may not mean the imminent risk of slope failure and the displacement threshold cannot discriminate its difference from the rapid development of displacement (2.01 cm in one day).

	Rainfall threshold	**Displacement/velocity threshold**
Sensor	Rain gauge	Extensometer, tiltmeter, soil moisture
Cost	Lower	Higher but not too high
Target	Regional warning	Individual slope failure
Empiricism	Threshold rainfall is empirically determined	Threshold displacement/velocity is empirically determined
Applicability to rapid slope failure; location and size not foreseen	Yes	Yes, if many inexpensive sensors are installed. Photogrammetry or satellite imagery not good at dark night
Consideration of local geology/soil condition	Little or no because of financial restriction	Little or no subsurface investigation but detected precursor of landslide implicitly accounts for the effects of local geology/soil condition
Consideration of local topography/slope angle	No, because regional warning is aimed	Detected onset of slope movement implicitly accounts for the effects of slope angle
Shortcoming	Topography or slope angle being out of scope	Location of sensors is engineering judgment

Table 1: Comparison of two thresholds for early warning of rainfall-induced landslides.

The method of displacement/velocity monitoring is another issue to be discussed. The use of photogrammetry or satellite imagery is attractive in the sense of cost saving. The imageries can capture the slope behaviour over a wide range and this is its advantage over the installation of sensors on a slope. Cost of image interpretation is absolutely less expensive than installation of sensors. The problem is the resolution of the images. As will be presented later, it has been found that the precursor displacement of a slope is of the order of mm or less. Obviously, it is very difficult to detect this small displacement in aerial or satellite photographs. The second important point is that the rainfall-induced landslides occur within a few hours. Those photogrammetric methods that compare the imageries before and during heavy rain cannot repeat surface observation and quickly detect the ground displacement within such a short period. The third point is the fact that the ground surface is covered by cloud during rain and that satellite photographs cannot be taken. Heavy rain is likely to occur in midnight when the air temperature at high altitude (stratosphere) is lower than in daytime. Obviously, taking photos in midnight is not easy. The visibility is even worse during heavy rainfall. Therefore, taking pictures at surface is difficult as well.

3. Slope monitoring by tiltmeter and early warning on the basis of the rate of tilting angle

Displacement/velocity threshold is a tradition in monitoring and early warning of gravity-induced landslides. Extensometers are installed across a surface manifestation of shear failure or head scarp and progress of landslide is recorded. Inclinometers are installed in drilled boreholes and the changing of the tilting angle along the bore hole reveals the location of a slip plane. They are, however, the practice in slow gravity-driven landslides and a rainfall-induced landslide requires a different principle of monitoring. The major difference comes from the sudden and rapid development of rainfall-induced landslides within slopes where there was no sign of landslide prior to rain. There is no time to install precise and expensive scientific instruments in such a slope.

Fig. 4 illustrates the authors' tiltmeter. This MEMS sensor is attached to the top of a steel rod that is driven down to the bottom of the surface unstable soil layer. When the surface layer becomes unstable during heavy rain, the earth pressure is exerted from the soil layer to the rod and the rod rotates around its tip that has been driven into a stable base layer. This tilting angle is monitored to the accuracy of the order of 0.02 degree and the record is sent through wireless and internet to the headquarter for real-time interpretation. In other words, the accuracy of monitored slope displacement is given by *tan(0.02 degree)* ×*(Length of rod*). Because the typical depth of the stable base in Fig. 4 is 1–1.5 m and the length of the rod is same, the accuracy is 0.3-0.5 mm. Through installation at about 1200 points internationally, this tiltmeter has proved that it can work for one year with four batteries (without expensive solar battery) and can remain intact after snow burial for several months.

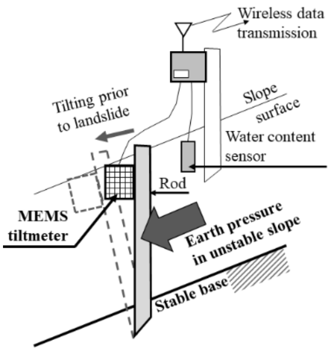


Figure 4: Conceptual sketch of slope monitoring by MEMS tiltmeter.

Figure 5: Artificial rainfall test in the field for validation of the MEMS tiltmeter technology (Sichuan Province, China).

The threshold for early warning by the tiltmeter has been decided empirically by field verification tests (Fig. 5) as well as engineering practice (Uchimura et al., 2015; Towhata et al., 2015). Fig. 6 presents the time history of monitored tilting angle at several locations in the tested natural slope (Fig. 5). The intensity of the artificial rainfall was 20 – 40 mm per 10 minutes and lasted for two days (only day time; Fig. 6a). It is found in Fig. 6b that the rate of tilting in three parts of the slope was 0.15, 0.40 and 0.24 degree/hour prior to the failure. Hence, it is reasonable that the warning is issued when the rate of tilting exceeds 0.1 degree/hour and this threshold value gives people several hours before failure so that they can safely evacuate into a shelter. Obviously, '0.1 degree/hour' was decided empirically without 'scientific' investigation.

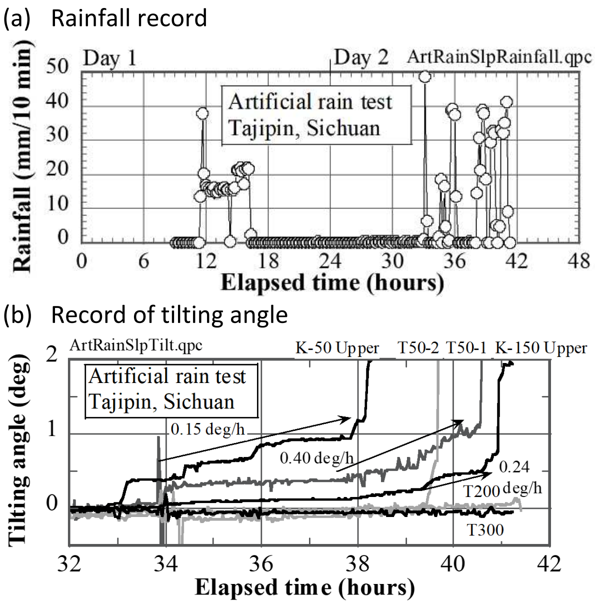


Figure 6: Time history of tilting angles recorded during the artificial rain tests.

The threshold of '0.1 degree/hour' has been validated through more experiences of real rainfall-induced landslides. Fig. 7 shows one of the monitored rainfall-induced landslides at Soeda, Japan. While the failure occurred at 12:30 PM, the rate of tilting parallel to the slope was 0.17 degree/hour about 6 hours in advance. Hence, the early warning at 0.1 degree/hour gives people more than six hours for safe evacuation. Note that this landslide happened when the rainfall intensity had been very low. In other words, the slope monitoring can mitigate slope disaster even after the end of heavy rain. This helps those officers in charge of disaster management who face high pressure from the public and the railway passengers insisting strongly on withdrawing the alert and resuming the normal train operation because heavy rain has already finished.

Fig. 8 presents the time history of tilting angles in the slopes along the Three Gorge Reservoir, China. As is often the case during the first impounding of a reservoir, the monitored slope fell down and this record was obtained. Although this was not a fully rainfall-induced event, one can recognize that the ultimate failure was preceded by the rate of tilting greater than 0.1 degree/hour, and that issuing an alert at 0.1 degree/hour provides people with more than several hours for evacuation.

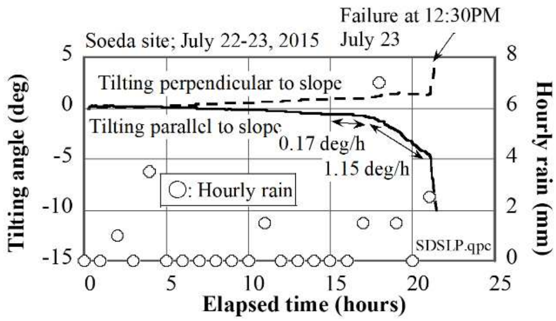


Figure 7: Time history of tilting angles during real rainfall-induced landslide in Soeda, Japan.

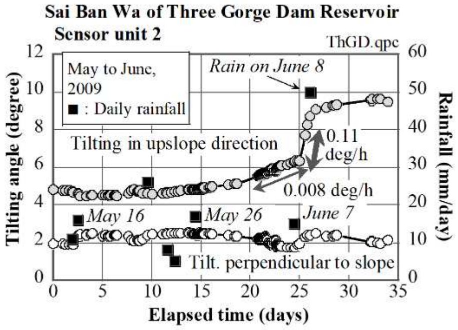


Figure 8: Tilting angles prior to slope failure during impounding Three Gorge Reservoir, China.

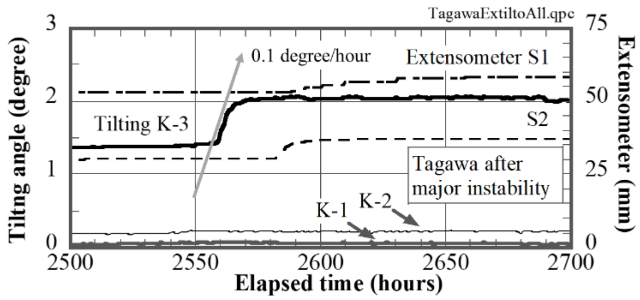


Figure 9: Tilting angles recorded at Tagawa after the major slope failure.

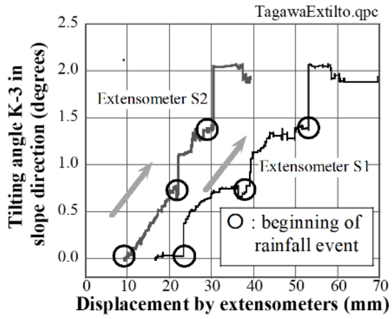


Figure 10: Comparison of tiltmeter output and extensometer records at Tagawa site.

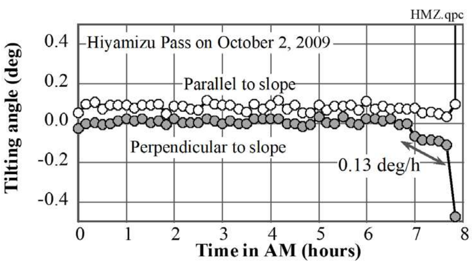
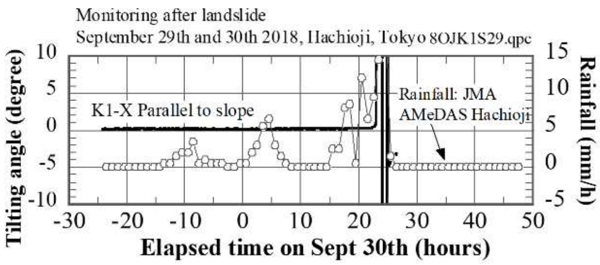


Figure 11: Tilting angles at Hiyamizu Pass after the major rainfall-induced slope failure and prior to the secondary failure.

(a) September 29th and 30th, 2018



(b) Evening of September 30th, 2018

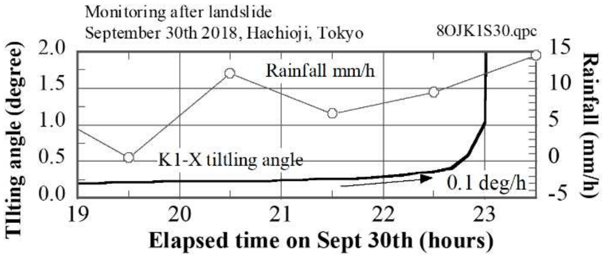


Figure 12: Monitoring in Hachioji, Tokyo, during restoration of rainfall-induced landslide.

Fig. 9 indicates the data obtained at Tagawa, Japan, where post-failure behaviour of a slope was monitored in order to avoid the secondary disaster during restoration works. It is interesting here that the maximum rate of tilting was 0.1 degree/hour, equal to the proposed threshold, and that the slope was stabilized without repeating failure as indicated by the extensometer record. Therefore, it is reasonable to say that 0.1 degree/hour is something marginal between stabilization and likelihood of failure within hours. Furthermore, Fig. 10 compares the records of tiltmeter and extensometers at the same Tagawa site. Upon three minor precipitations, the record of the tiltmeter increased first, followed by the extensometers. Although further consideration is needed on the optimum location of sensors, it is possible that a tiltmeter captures the beginning of slope deformation earlier than an extensometer, providing more time for evacuation.

Fig. 11 illustrates the tilting angle records at Hiyamizu Pass, Japan, where an unstable slope was monitored after its rainfall-induced failure in order to avoid the secondary disaster during repair. It is evident that the secondary failure was preceded by the rate of tilting = 0.13 degree/hour and the people at this site were able to evacuate safely in advance. Fig. 12 shows the tilting angle at Hachioji site in Tokyo in 2018. After the previous landslide three months ago, an emergency remedial work was going on here while monitoring the slope for safety of workers. Landslide occurred on September 30th as shown in this figure. About one hour before the landslide, the tilting angle measured just behind the head scarp reached 0.1 degree/hour and small mud flow occurred.

In summary, the reliability of the proposed threshold of 0.1 degree/hour has been validated empirically by reviewing the demonstrated case histories. It is important that, to date, no 'false negative' has occurred in which slope fails although the rate of tilting did not exceed the threshold. Because the number of the monitored slope failure is few, it is not possible to do any statistical analysis. Probably, local geology is not very important because the failed slope surface consisted of disintegrated soil only.

4. Assessment of remaining time until landslide

The data in the previous section demonstrated that the rate of tilting is a good measure of an imminent landslide risk. Probably, the higher the rate of tilting is, the shorter is the time until landslide. This point is illustrated in Fig. 13 where the data from landslides are plotted by solid symbols (●). Moreover, there have been many cases in which no landslide happened. For them, the time until stabilization was plotted by hollow symbols (○), indicating the time until the slope was verified to be landslide-free. It is shown in this figure that the proposed threshold of 0.1 degree/hour gives the remaining time of at least one hour and likely more than three hours. Thus, the proposed tiltmeter technology is able to assess the time that is available for evacuation. This is the unique and important advantage of the tiltmeter technology of slope monitoring.

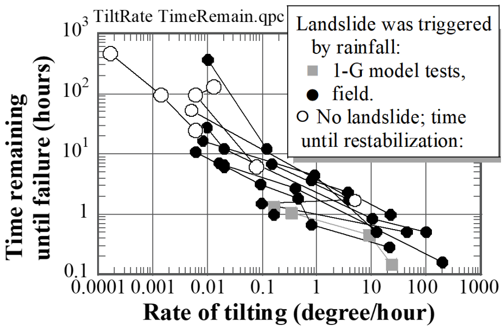


Figure 13: Empirical relationship between the observed rate of tilting and the time that remains until the ultimate slope failure.

4. Newly developed inexpensive accelerometer

To widen the scope of field monitoring, an inexpensive but still good-quality acceleration sensor was developed (Wang et al., 2022). The price of this sensor is approximately 20% of the price of conventional field accelerometers but its accuracy has been verified to be equivalent (Fig. 14).

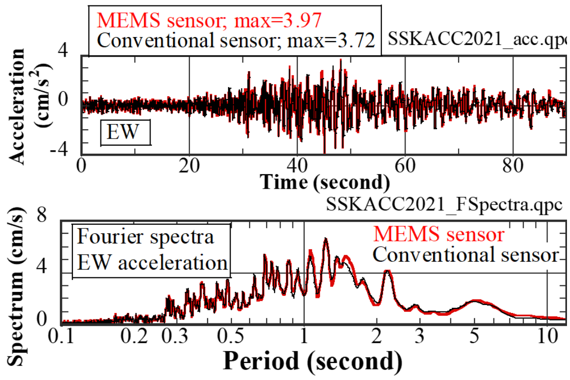


Figure 14: Acceleration time histories recorded by the novel inexpensive MEMS and conventional sensors.

The notable advantage of the novel acceleration sensor stems from the low price that enables multi-point monitoring of ground tremor. This advantage is important in a hilly terrain where subsoil conditions and slope angles are highly heterogeneous, making the ground motion different from place to place. It is very possible to capture the landslide-induced ground vibration at multiple points and quickly assess the location and the size of the source landslide. This idea helps issue landslide alert over a vast area which cannot be fully covered by the tiltmeter network. Note that the quick assessment of landslide onset by monitoring ground tremor is very promising (NIED, 2013). The authors' novel acceleration sensor improves its accuracy and coverage by increasing the number of deployed sensors.

The second idea is the multi-point monitoring of volcanic earthquakes that is triggered by the underground magma movement. By using the similar algorithm as supposed for landslide assessment, it will be possible to assess the location of magma movement and its size; finally leading to eruption alert.

Moreover, from the viewpoint of deterioration of infrastructures, the acceleration sensors can evaluate the softening of earth fill in which poor materials (such as crushed mudstone) is affected by water (hydration, slaking) and becomes softer. It is expected that the measured acceleration records exhibit the natural period of fills and that significant deterioration can be detected in case that the natural period is getting longer with time.

4. Conclusions

This paper reviews the basic principle and background experiences of the early warning of rainfall-induced landslides that was developed by the authors and has been in practice internationally in the past decade. The major points therein are summarized in what follows.

1. Although technology should preferably have scientific background, there are real situations in which budget limitation does not allow scientific approaches. The hazard of small but many rainfall-induced landslides is its typical example. Therein, the vulnerable people cannot afford the cost of scientific analysis and design. Then, it is a mission of engineers to propose an alternative that can be practiced within the budget limitation.
2. The authors' proposal is the slope monitoring by tiltmeters. The interpretation and logic for issuing landslide alert during rainfall rely on empiricism. This technology has been used at 1,200 points internationally without false-negative problem.
3. Note that early warning and evacuation can save human life only; properties and working places not saved.
4. To widen the scope of the authors' method, a novel inexpensive accelerometer was developed. It is promising not only in the field of slope monitoring but also in monitoring other kinds of natural disaster and deteriorating infrastructures.

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