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

Taro Uchimura[a,*], Ikuo Towhata[a], Lin Wang[b], Shunsaku Nishie[b], Hiroshi Yamaguchi[b], Ichiro Seko[b], Jianping Qiao[c]

[a]*University of Tokyo, Department of Civil Engineering, 7-3-1, Hongo, Bunkyo-Ku, Tokyo 113-8656, Japan*
[b]*Chuo Kaihatsu Corporation, Tokyo, Japan*
[c]*Institute of Mountain Hazards and Environment, Chengdu, China*

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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

*Corresponding author.
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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 natural slope, and several practical cases of disaster prevention. Based on the obtained results, the authors propose that a precaution be issued at a tilting rate of 0.01° per hour and that a warning be issued at a tilting rate of 0.1° per hour, to be on the conservative side.

2. Proposed equipment for slope monitoring

Fig. 1 illustrates the basic concept of the wireless monitoring and early warning system proposed by the authors (Uchimura et al., 2009). A group of simple sensor units are placed on the slope. The system is designed to be wireless. The sensor units periodically measure the condition of the slope at an interval of 10 min, for example. The data is transferred to a gateway unit, which is also placed near the slope, by radio communication. The gateway unit collects the data from all the sensor units, and sends them to a data server on the Internet through a cell phone network. Thus, the data can be browsed anywhere and anytime on the Web site. The data is processed by the server and abnormal behavior of the slope can be detected as a precaution of failure; then a warning is issued.

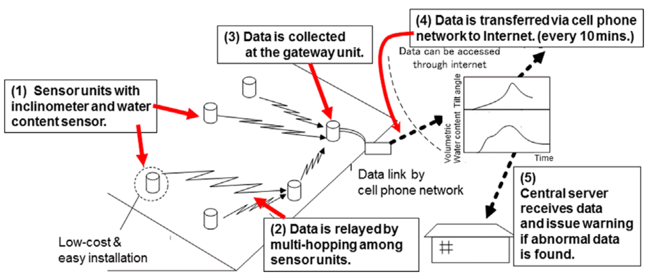

Fig. 1. Structure of the proposed wireless monitoring and early warning system.

The authors developed two types of sensor units, surface tilt sensor (Fig. 2(a)) and multi-segment inclinometer (Fig. 2(b)). They are equipped with a MEMS tilt sensor (nominal resolution = 0.0025° = 0.04 mm/m) as well as a volumetric water content sensor (nominal resolution = 0.1%) (Fig. 2(c)). An additional temperature sensor is also used for temperature compensation for the tile sensor. Each sensor unit is powered by 4 AA alkaline batteries and functions well in the field for a duration of more than 1 year. By attaching an optional solar battery, which costs around 5 USD, the sensor unit can work semi-permanently without having to worry about the batteries.

Orense et al. (2003, 2004) conducted model tests and observed the gradual displacement and high saturation ratio (80–90%) at the toe of model slopes before failure. Therefore, the authors decided to monitor the displacement and the water

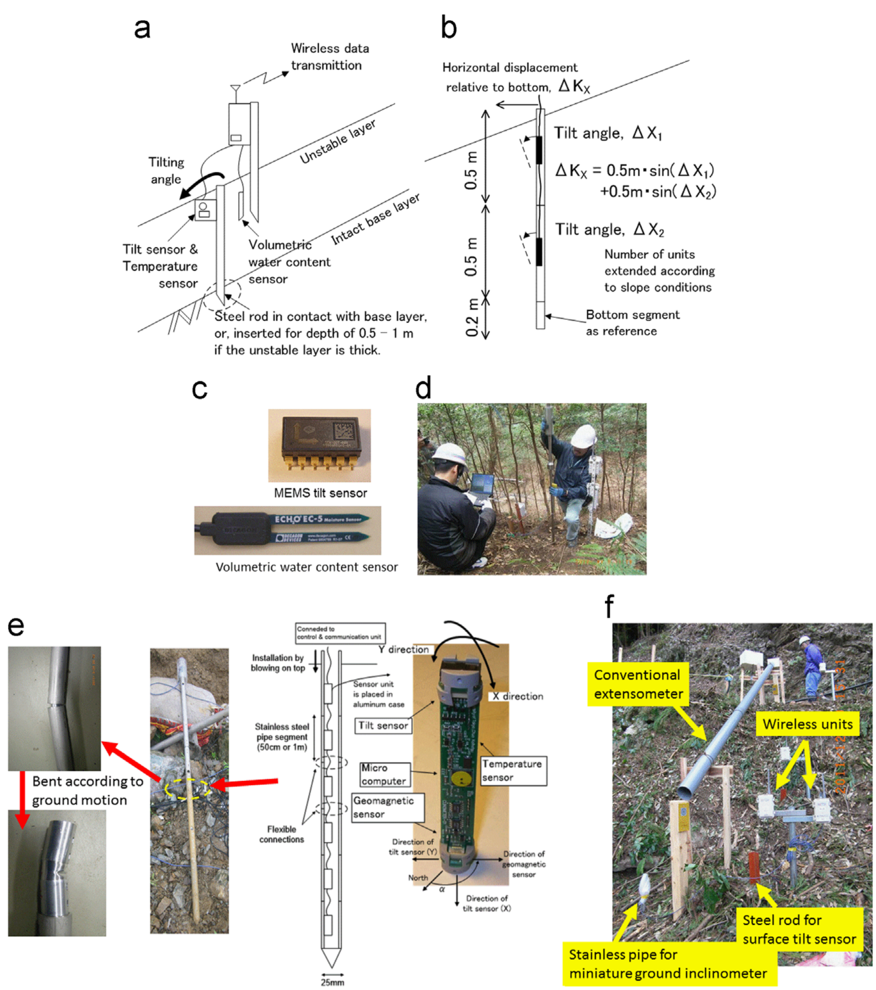

Fig. 2. Proposed sensors: (a) surface tilt sensor; (b) multi-segment inclinometer; (c) sensors used in the unit; (d) installation by using hammer; (e) details of segment, and aluminum hinge connection; and (f) example of installation.

content on the slope for the early warning of landslides. The surface tilt sensor (Fig. 2(a)) measures the tilt angle of a steel rod installed to a depth of around 1 m or more in the unstable soil layer on the slope surface. The depth will be shorter if the unstable layer is thinner, and the tilt sensor detects the average shear deformation of the slope surface layer in such cases. As mentioned previously, most landslides are shallow surface failures due to heavy rainfall, whose thickness is 1.2 m on average (Osanai et al., 2009). Therefore, deformation of the whole surface layer can be detected with this arrangement in most cases. The tilt sensor is embedded into the ground after being attached to a steel rod to avoid large changes in temperature which could cause measurement errors.

The volumetric water content sensor is placed at a shallow position (typically a depth of 30 cm) in the slope. This sensor measures the dielectric constant of the soil, which is a soil parameter sensitive to the water contents. Soil mechanics theories state that the slope stability directly depends on the suction, or pore water pressure, rather than the water content. However, it is usually difficult to measure the suction of unsaturated soils, and it requires careful maintenance of the sensors. Thus, use of volumetric water content sensors is more suitable for simple monitoring.

The authors also developed a new sensor device named “multi-segment inclinometer”, which is suitable for detecting the behaviors of the deep layers of slopes (Fig. 2(b)). This is a long stainless steel pipe consisting of short pipe segments. The diameter of the device is 25 mm, which is the same as that of the cone for portable dynamic cone penetration tests (JGS 1433-2003). Therefore, it can be directly inserted into the slope ground together with the sensor units inside it by using a small hammer (Fig. 2(d)). This provides simple and quick installation of the device at landslide sites. The segments are 0.5 m-long, and as many of these devices as needed can be connected.

Each segment is equipped with a sensor unit inside it, which contains a MEMS tilt sensor, a geomagnetic sensor, and a control circuit (Fig. 2(e)). The geomagnetic sensor is used to detect the direction of the tilt sensor, because the segment may rotate horizontally in the hole during the installation process. The segments are connected to each other by flexible aluminum joints which work as hinges. The device moves together with the ground displacement, and the tilt sensors detect it at respective depths. More details and an on-site evaluation of this device have been reported by Uchimura et al. (2011a).

Fig. 2(f) presents an example of the installation of the sensor units. A conventional extensometer is also installed for a comparative study, as seen in this figure. The advantage of the tilt sensor is that no long wire is required for the extensometer; and therefore, the installation and maintenance are simple and inexpensive.

3. Validation of monitoring tilt angles in surface layer

In 2006, the authors developed a prototype of the sensor unit with a tilt sensor and a volumetric water content sensor, and tested it on a 1-m-high model sandy slope under artificial heavy rainfall, conducted by Public Works Research Institute (PWRI), Tsukuba, Japan (Uchimura et al., 2010). The model slope had a gradient of $H=2$: $V=1$, and was made of a compacted sandy material ($D_{max}=4.57$ mm, $D_{50}=0.17$ mm, $Fc=14.3\%$, $Gs=2.69$, $\gamma_d=1.37$ g/cm^3, $Dr=80\%$) with an initial water content of 19%. After filling water on the back side of the slope to reproduce the situation of a river dike with a high water level, an artificial continuous rainfall of 15 mm/h was produced. Two sensor units, equipped with a MEMS tilt sensor and a volumetric water content sensor, were installed on the slope (Fig. 3). The installation procedure was simple, just embedding the units and the attached water content sensor into the slope at a depth of 20 cm, taking less than 30 min of working time for each unit.

Fig. 4(a) shows the tilting angle obtained by each sensor unit. The slope failure progressed starting from the toe, and the lower part with sensor unit 2 failed around 2 h after the rainfall started. The sensor tilted abnormally 30 min before failure. Such behavior could be considered as a signal of ongoing slope instability.

In contrast to sensor unit 2, the upper part of the slope around sensor unit 1 failed after 3 h of rainfall, but the development of the tilting angle was not as clear as in the lower part. The pre-failure tilting behavior is case-by-case. As mentioned above, the tilt sensor detects the average shear deformation of the slope surface layer. However, the depth of the tilt sensor units in this test was very short, only 200 mm. Therefore, the behavior in the very shallow part of the slope surface was observed, while the major deformation may have occurred in deeper part. This may be one of the possible reasons for these disunity behaviors. In the field monitoring cases, mentioned later in this paper, the tilting angles of the steel rods installed to a depth of 0.5–1 m showed more consistent behaviors.

Although the tilting behaviors varied drastically during the failure process, tilting rates exceeding 0.1°/h were observed for more than 1 h at both tilt sensors. From this, the idea of detecting abnormal conditions in slopes by monitoring the tilting rate on the surface can be suggested.

On the other hand, the records of volumetric water contents are presented in Fig. 4(b). As the void ratio of the slope ground is $e=0.935$, the volumetric water content will be 0.48 at full saturation. The measured water content increased after the rainfall started, but it did not indicate nearly saturated condition before the failure. Thus, it was found difficult to detect a precursor of failure based on the monitored water contents only. One of the reasons for this difficulty is that the water content varies very sensitively with the depth from the slope surface. In addition, it is hard to determine the depth of the failure surface.

4. Tilting behavior in artificial rainfall tests

An artificial rainfall test was conducted on a natural slope of weathered andesite deposit in order to observe its pre-failure behaviors (Uchimura et al., 2011b). The site is located on the Taziping landslide slope in Sichuan Province, China.

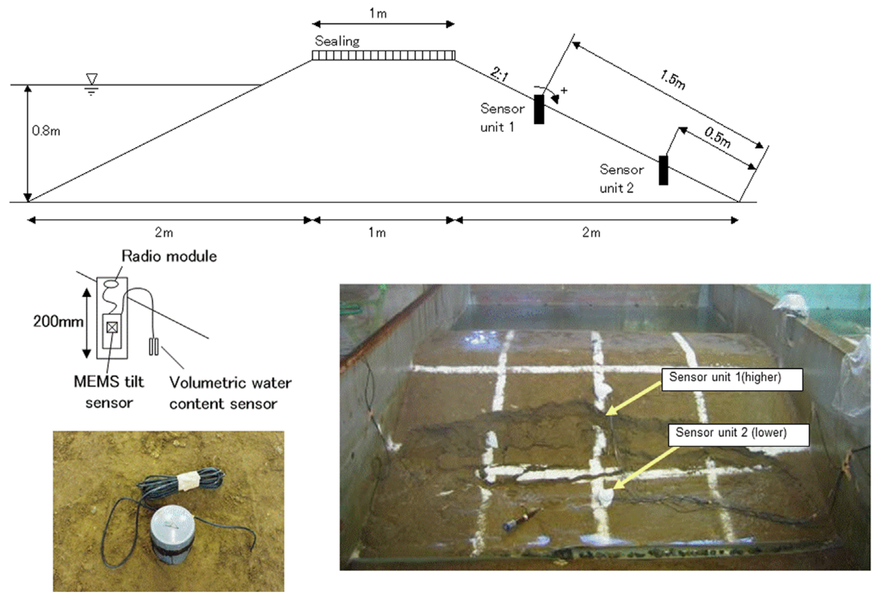

Fig. 3. Arrangement of slope model and sensor units for the model test 2006.

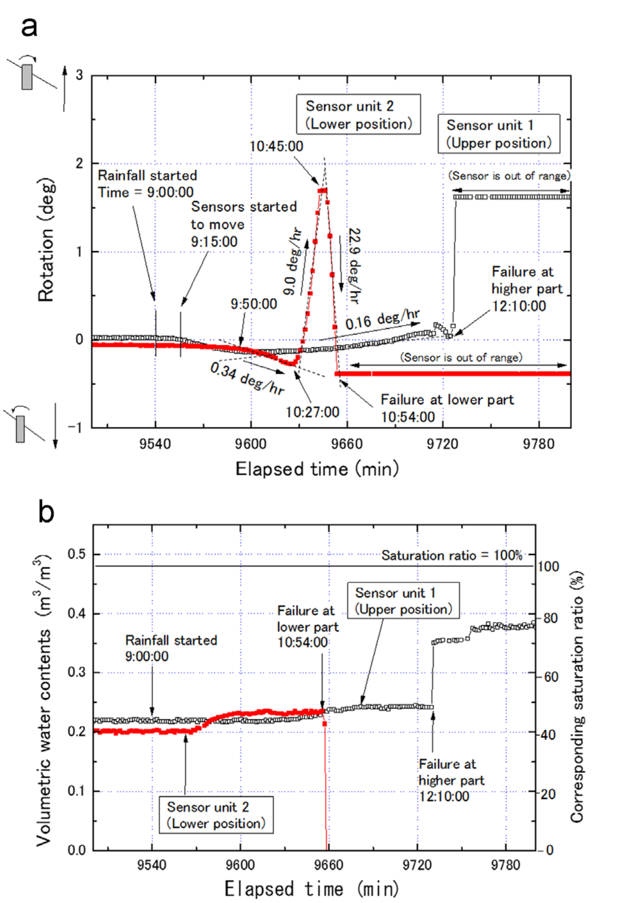

Fig. 4. (a) Behaviors of inclination for the model test 2006 and (b) behaviors of water contents for the model test 2006.

Fig. 5 provides the cross-section and photo of the site together with the instruments. The blow counts, N_d, by portable dynamic cone penetration tests (JGS 1433-2003) are less than 10 for 10 cm of penetration. This corresponds to $N=3$–4 by standard penetration tests. The slope angle is around 18°, and its lower end was excavated to a depth of 1.4 m with an angle of 40°. The slope consists of loose gravel and sand, but the soil contains many large stones.

A time history of the artificial heavy rainfall is recorded in Fig. 6. The rainfall intensity fluctuated due to the restricted water supply, but a total of around 500 mm of rain occurred on the first day, and an additional 700 mm fell on the second day. As the slope material is loose and highly permeable, rainfall of this amount was needed to cause failures.

Major deformation was observed on the second day, and the slope failed progressively from the bottom with a scarp angle of 40–50°. The final shape of the scarp is drawn with a thick broken line in Fig. 5. This figure also indicates the locations of the surface tilt sensors, T50-1, T50-2, T200, and T300, as well as the multi-segment inclinometers, K50 and K150 (see Fig. 2(a) and (b) for the respective types of the sensors). The number in the notation for each sensor represents the distance in cm from the bottom end of the slope. The steel rod of each surface tilt sensor was inserted into the ground at 0.75 m. Each multi-segment inclinometer consists of 2 segments with sensors and 1 short segment at the bottom.

Time histories of the tilting angle were recorded, as seen in Fig. 7, during the rainfall on the second day. Tilt angles of the upper segment are plotted in this figure for the multi-segment inclinometers (K50 and K150). At the beginning of failure at the bottom of slope, the tilt sensors (T50-1 and upper segment of K50) nearest to the bottom started to respond with a tilting rate of 0.15–0.4°/h. Meanwhile, another sensor, located at a more distant position from the bottom of slope (upper segment of K150), started to tilt slowly, and then accelerated to 0.24°/h when the failure became imminent. One of the tilt sensors near the bottom of slope (T50-2) suddenly responded to failure without showing prior slow tilting stages, because there was a big stone in front of it, which blocked the displacement of the slope ground around it.

In summary, the tilting rate of 0.15–0.4°/h was observed for 3–5 h just before the failure around the position of each sensor. In

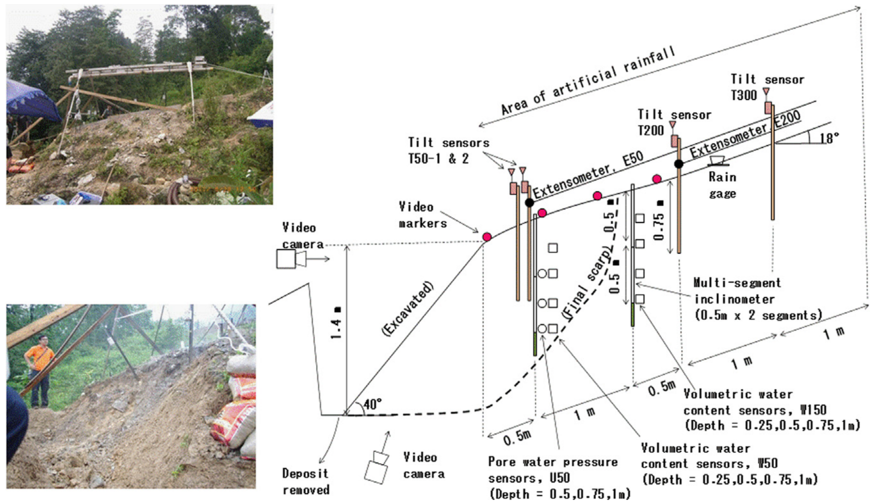

Fig. 5. Vertical cross-section of slope site for artificial rainfall test, and its photos before and after failure.

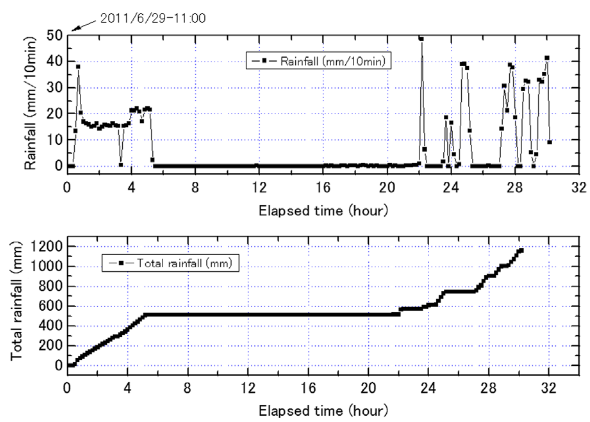

Fig. 6. Record of rain intensity given for artificial rainfall test.

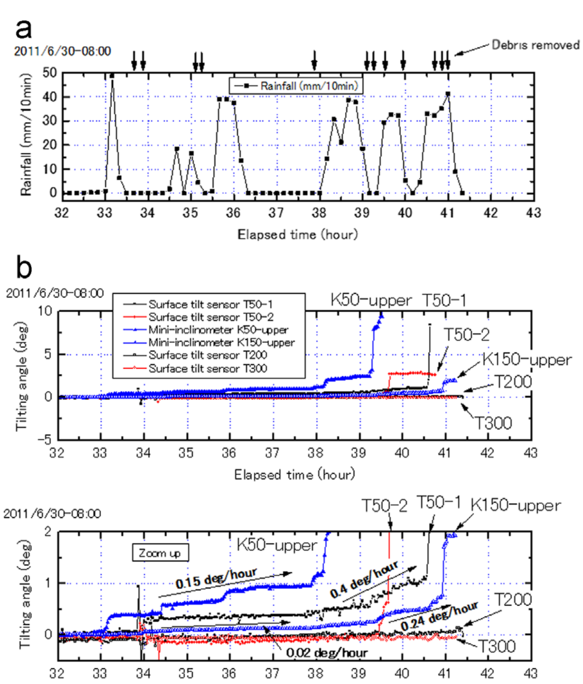

Fig. 7. Tilt angles observed in artificial rainfall test: (a) rainfall record and (b) tilt angles.

addition, the tilting was always directed downward. Unlike the model tests mentioned in the previous section (Figs. 3 and 4), in which the depth of the tilt sensor units was as short as only 200 mm, the pre-failure tilting behaviors observed in the field tests are consistent among the sensors which measure the tilting angles of the steel rods installed to a depth of 0.5 or 0.75 m.

It is also remarkable that the sensors set apart from the bottom of the slope started to tilt slowly in the early stage, when the failure was observed only at the bottom slope. This behavior is not visible to human eyes. For example, the tilting rate for K150-upper is only 0.02°/h. However, the sensors can detect such slight effects of the failure event at some distance.

Two extensometers, E50 and E200, were also installed at the test site (Fig. 5). Unlike the conventional use of extensometers, they were fixed on the rod of the surface tilt sensors, T50 and T200 respectively, at a height of 0.2 m from the slope surface (Fig. 8). Therefore, the displacements obtained by them include some effects of tilting of the steel rod. By assuming that the bottom of the steel rod at the depth of 0.75 m did not move, the relationship between the displacement (ΔE) by the extensometer and the tilting angle of the surface tilt sensor (ΔS) can be represented as follows:

$$\Delta E = (0.75\ \text{m} + 0.2\ \text{m}) \cdot \sin(\Delta X) \tag{1}$$

Time histories of the displacements (ΔE) obtained by the extensometers are plotted in Fig. 9. Fig. 10 compares displacement ΔE, calculated by Eq. (1) from the tilt angle (ΔX) of T50-2, with ΔE, obtained by extensometer E50. Although there are some fluctuation at the beginning, the difference in ΔE obtained by the two methods is around 10%. Therefore, monitoring the tilt angle in the surface layer with a depth of 0.75 m is a useful alternative to monitoring with an extensometer.

5. Tilting behavior observed in unstable slopes

The developed monitoring equipment has already been installed at many sites in Japan and China, and the instability and/or failure of slopes have been observed at some of them.

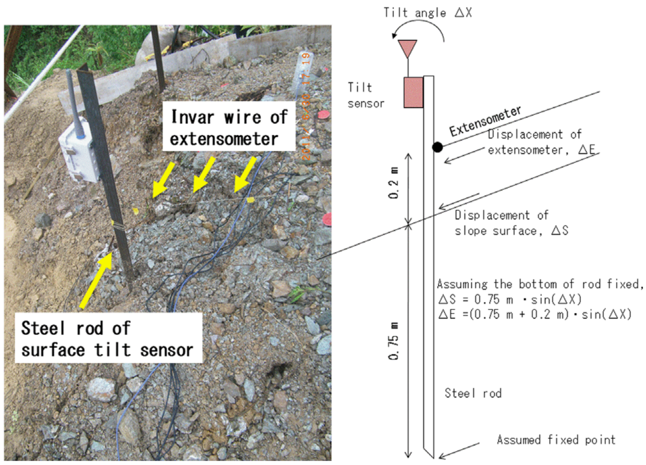

Fig. 8. Installation of extensometers in artificial rainfall test.

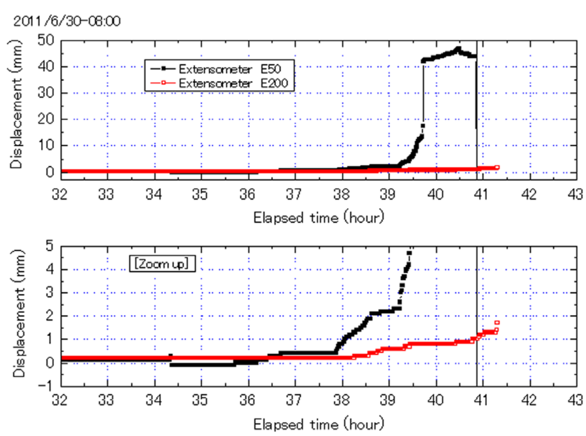

Fig. 9. Displacement obtained by extensometers in artificial rainfall test.

5.1. *Monitoring of a secondary slope failure during remedy work [Site A]*

A slope failure site along a highway in Fukuoka Prefecture, Japan, is presented in Fig. 11. This slope consists of strongly weathered granite; it failed due to a heavy rainfall in July of 2009 (Uchimura et al., 2011b; Wang et al., 2012). The slope was excavated to reduce the gradient to 45° for remedy work, and was monitored with three sensor units.

After 2 months of the remedy work, another heavy rainfall caused a second failure, and one part of slope, including sensor unit 2, fell down. Hence, the behavior of the slope before and after the failure was detected by the monitoring system. The site manager recognized the extraordinary behaviour of the data, and successfully stopped the remedial work and the highway service prior to the final failure.

The time histories of tilt angles in directions parallel and perpendicular to the slope are recorded in Fig. 12(a). In particular, the tilting in the direction parallel to the slope showed extraordinary behaviour with a tilting rate of 0.16°/h for a period of 50 min before the failure. The tilting motion occurred mainly in the direction parallel to the slope because the sensor had been placed next to the failure part, as illustrated in Fig. 11(a).

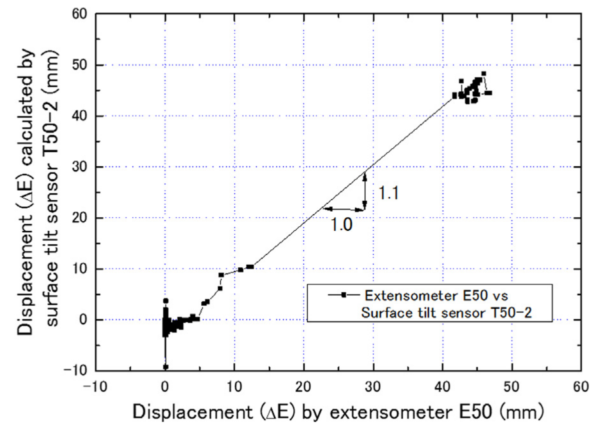

Fig. 10. Comparison between tilting angle and surface displacement in artificial rainfall test.

The volumetric water content was recorded as seen in Fig. 12(b). The slope did not fail when the water content recorded its peak value, but it failed 2 h after the second peak. It is difficult to detect a precursor of slope failure only by monitoring the water content.

5.2. *Monitoring of slope along Three-Gorges Dam Reservoir [Site B]*

The developed tilt sensor units have been installed on a side slope by Three Gorge Dam in China since 2008 (Uchimura et al., 2011b; Wang et al., 2012). The site, in the Sai-Wan-Ba area, is located on the right bank of the reservoir, near Wanzhou Ward, 80 km east of Chongqing City. Several landslide blocks have been found by geological investigations (Figs. 13 and 14). The locations of three sensor units deployed by the authors are also indicated in these figures.

Fig. 13 illustrates the cross-section of the slope passing the position of sensor unit 2. The slope mainly consists of mud stone or sandy mud stone layers, and a deposit layer of clayey soil with some crushed mud stone covers the slope surface with an average thickness of 15 m. The length of the recent landslide block is around 350 m, with a slope angle of 5–15°.

The dam has been in service since 2008, and periodical changes in the water level of the reservoir (Yangtze River) by 30 m are scheduled every year by dam operation. In addition, the site is located in a subtropical region where heavy rainfall events are expected, and some displacement on the slope surface was reported in the summer of 2008. Therefore, the government also monitors the deformation of this slope continuously by using borehole inclinometers, ground water level sensors, and a rain gage.

The sensor units were attached to an electric pole installed in the ground. The data was obtained every 10 min, and transferred by radio communication to a gateway unit, which was placed in a room of a nearby private house.

The monitoring system has been in use since October of 2008. In the meantime, a heavy rainfall event on June 7 and 8 of 2009 caused significant displacements in the landslide blocks, including the position of sensor unit 2 (Fig. 13), and a slope failure occurred 150 m east of sensor unit 2, where more than 10 m of displacement were observed in the sliding block.

The time histories of the tilting angles of the pole in X and Y directions are indicated in Fig. 15. The volumetric water content at a depth of 30 cm under the ground surface and the recorded precipitation are plotted in Fig. 16. While receiving frequent rainfall events, the tilting angles showed gradual progress, and the tilting angle in the Y direction reached around 5° at the beginning of June 2009.

A quick tilting in the Y direction and a small tilting in the X direction were recorded on June 7 and 8. The precipitation for these 2 days was 65 mm, while the criterion for heavy rain warning was set at 30 mm per day in this area. The increasing rate of the tilting angle in the Y-axis was 0.12°/h during this event. The slope did not fail at the position of this sensor unit, but the slope did finally fail at an adjacent place. Therefore, such quickly obtained behavior is considered as a sign of a high-risk condition in this area. According to the people in this village, the slope failure near sensor unit 2 took place at noon on June 8, while the quick increase in the Y direction started late at night on June 7. Therefore, there was a time margin of around 12 h, which is sufficient for issuing an early warning.

As the slope surface consists of clayey soil, the volumetric water content showed high values of between 50% and 60%

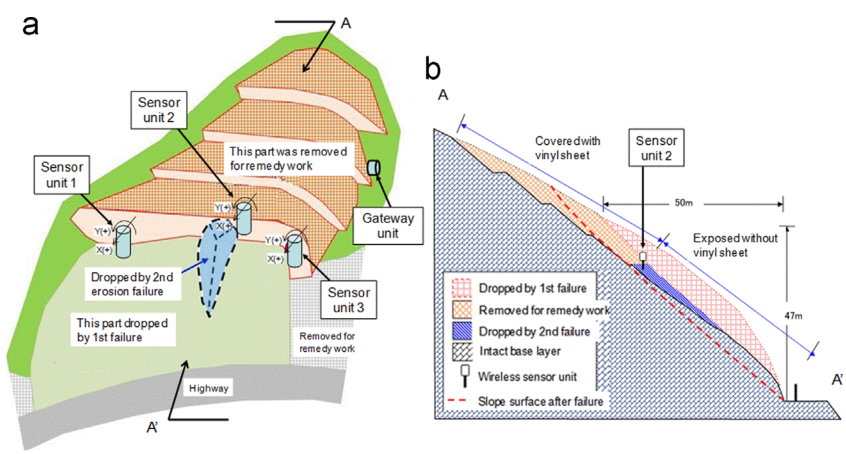

Fig. 11. (a) Sketch of failed slope along highway and arrangement of deployed sensor unit and (b) cross-section of the slope including the second failure part.

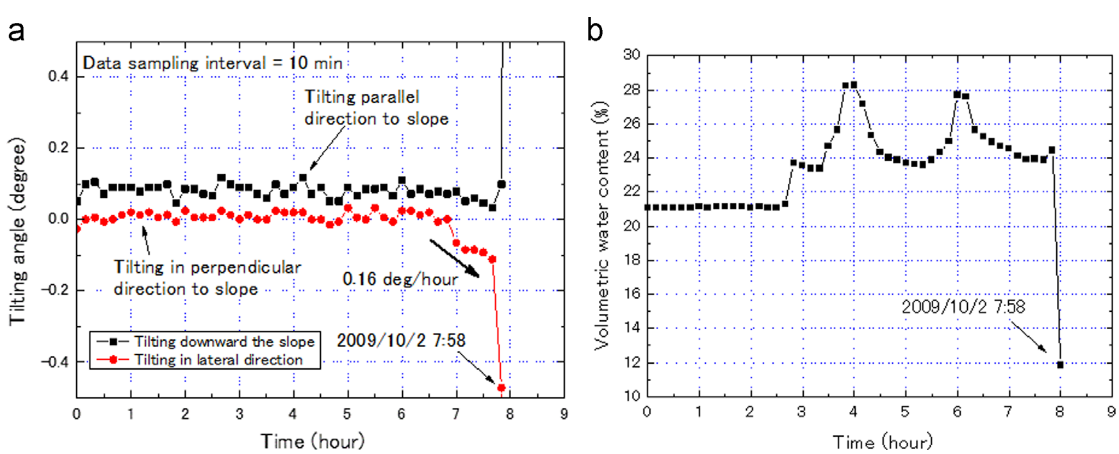

Fig. 12. Tilting angle and volumetric water content obtained by sensor unit 2 on the slope site along highway just before the second failure.

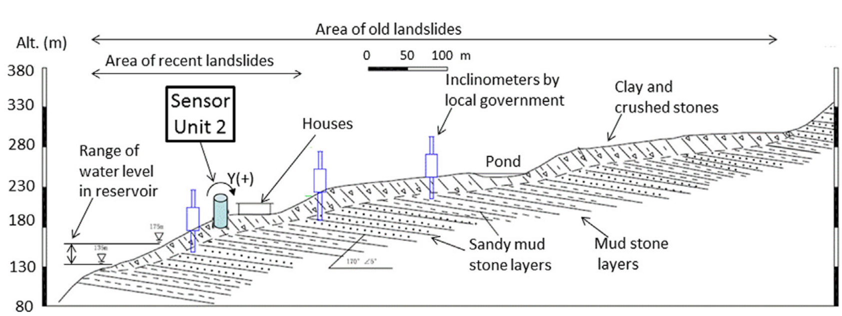

Fig. 13. Cross sectional view of Sai Wan Ba landslide site passing the position of sensor unit 2.

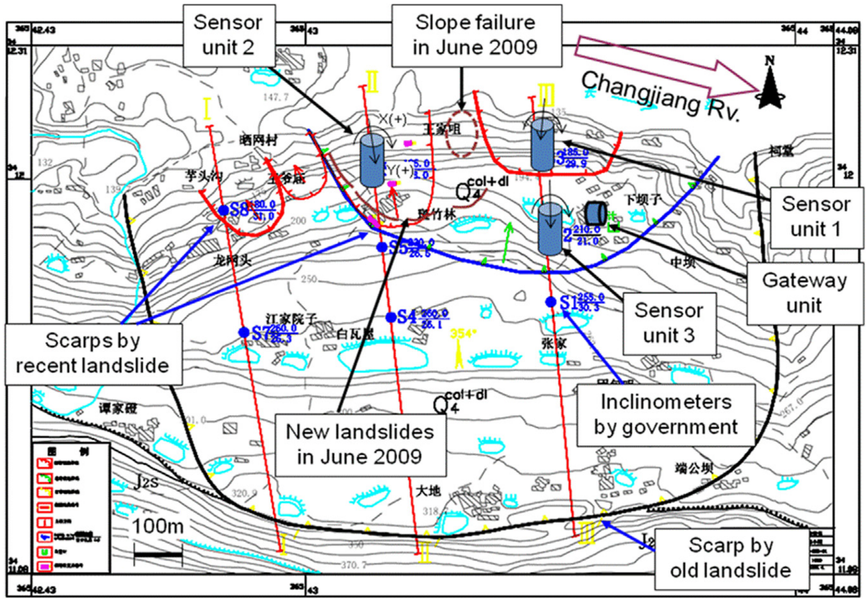

Fig. 14. Plan view of Sai Wan Ba landslide site and locations of sensor units.

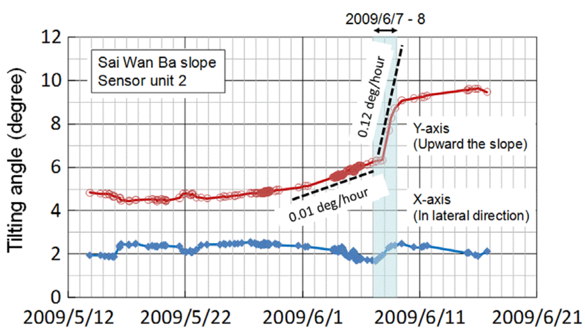

Fig. 15. Time histories of tilting angle obtained by Sensor unit 2.

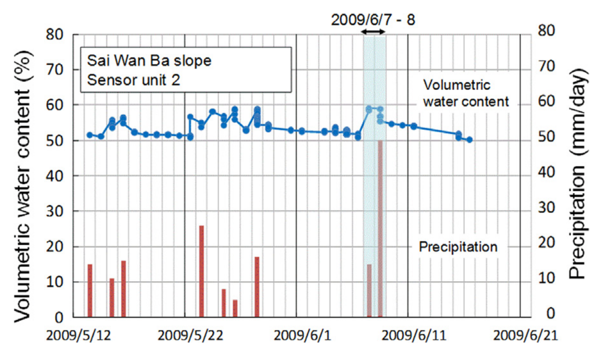

Fig. 16. Time history of volumetric water content transducer at Sensor unit 2, and records of rainfall.

throughout the monitoring period (Fig. 16). It responded to every rainfall event, but no extraordinary response was recorded at the time of the landslide on June 7 and 8. As the volumetric water content sensor was buried in a shallow part of the slope, only 30 cm from the ground surface, the obtained values did not correspond to the conditions at the depth of the slip surfaces. Thus, it is not relevant to define the criteria of early warning based only on the water content.

5.3. *Long-term deformation of slope damaged by heavy rainfall [Site C]*

Another slope failure site along a highway in Fukuoka Prefecture, Japan, is presented in Fig. 17. According to the borehole and geological surveys, this slope consists of granite, and its surface layer was highly weathered for a depth of more than 10 m. The location of the landslide slip surface drawn in this figure was estimated by using the data from borehole inclinometers (see also Fig. 20). It failed on July 2011 in the rainy season. As the highway is vital for the traffic network in this region, the remedy work was done without closing down road service. In order to assure its safety, monitoring and the early warning systems were installed.

The monitoring equipment was arranged as seen in Fig. 17. There are 3 surface tilt sensors, 2 extensometers, 2 borehole multiple inclinometers, and a rain gage. The time histories of the obtained data are presented in Fig. 18. Although this slope did not have catastrophic failure, both the tilt sensors and the extensometers were sensitive to the repeated rainfall events. The surface tilt sensor, K-3, which was placed at the lowest part of the slope, showed the largest tilting behaviour among the tilt sensors. Extensometer S-1, which was placed over the top scarf of the failure, showed larger displacement than extensometer S-2 at the lower position. Tilt sensor K-3 tilted with rates of 0.006–0.079°/h corresponding to the 3 major rainfall events.

Fig. 18(e)–(h) also indicates time delays among the responses of the sensors. Moreover, Fig. 19 compares the tilting behaviour at K-3 with the displacement obtained by extensometers S-1 and S-2, respectively. When their responses to each rainfall event are investigated in detail, it can be noted that the sensors at the lower part of slope, tilt sensor K-3 and extensometer S-1, were the first to start to respond. However, the extensometer at the upper part, S-1, responded later by 10–27 h. This suggests that the movement of this slope starts from the bottom, and then propagates upward. In such a case, it is effective to use the tilt sensor at the lower part of the slope for early warning.

Fig. 20 provides a profile of deformation along the multiple borehole inclinometers at BI-2 and BI-3. The upper part, BI-2, showed progressive deformation over the depth of around 7 m, while the lower part, BI-3, deformed at the depth of around 20 m. These data were utilized to estimate the location of the active slip surface in Fig. 17. Fig. 21(a) shows time histories of the lateral displacements on the slope surface obtained by BI-2 and 3. In addition, Fig. 21(b) plots them against the tile angles from the nearest tilt sensors, K-2 and 3, respectively. The obtained tilt angles have clear co-relations with the displacement on the slope surface.

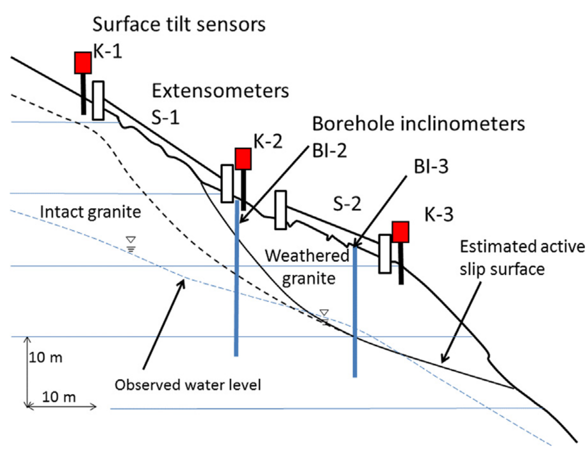

Fig. 17. Site of long-term monitoring along national road.

5.4. *Long-term deformation of slope due to cutting work [Site D]*

A cut slope for a new highway with a height of around 20 m was monitored with a surface tilt sensor during the excavation (Fig. 22). The slope consists of neogene sandstone, and the cut slope was designed and constructed with a standard slope angle. Only one surface tilt sensor was installed at the top of the slope to detect the undesirable behavior caused by the excavation.

The excavation was completed within 2 months, but the tilt angle at the sensor started to increase at the end of the excavation period (Fig. 23). It was very small and slow (0.00017°/h = 0.004°/day) at the beginning. However, it did not stop, but accelerated to 0.0014°/h (= 0.034°/day) after the excavation was finished. Therefore, a careful investigation was conducted on the slope, and a crack was found on the top of the slope. Additional counter weight fill was constructed to stabilize the slope, and then the tilting was stopped successfully. However, the maximum tilting rate of 0.006°/h (= 0.142°/day) was recorded meanwhile.

Compared to the sites described in the former sections, the tilting rates observed at this site were lower by 10 times or more. This suggests that the very beginning of the deformation and failure process of the slope was successfully detected at this site. If the slope had not been monitored and had been left without any additional stabilization works, its deformation might have accelerated more and more, leading to ultimate failure.

6. Discussions on tilting rate and duration before failure

In this paper, tilting behaviors in the unstable surface of natural slopes are observed for artificial rainfall tests on a natural slope and 4 unstable slopes (Site A: secondary failure of a slope along a highway during remedy work; Site B: slope

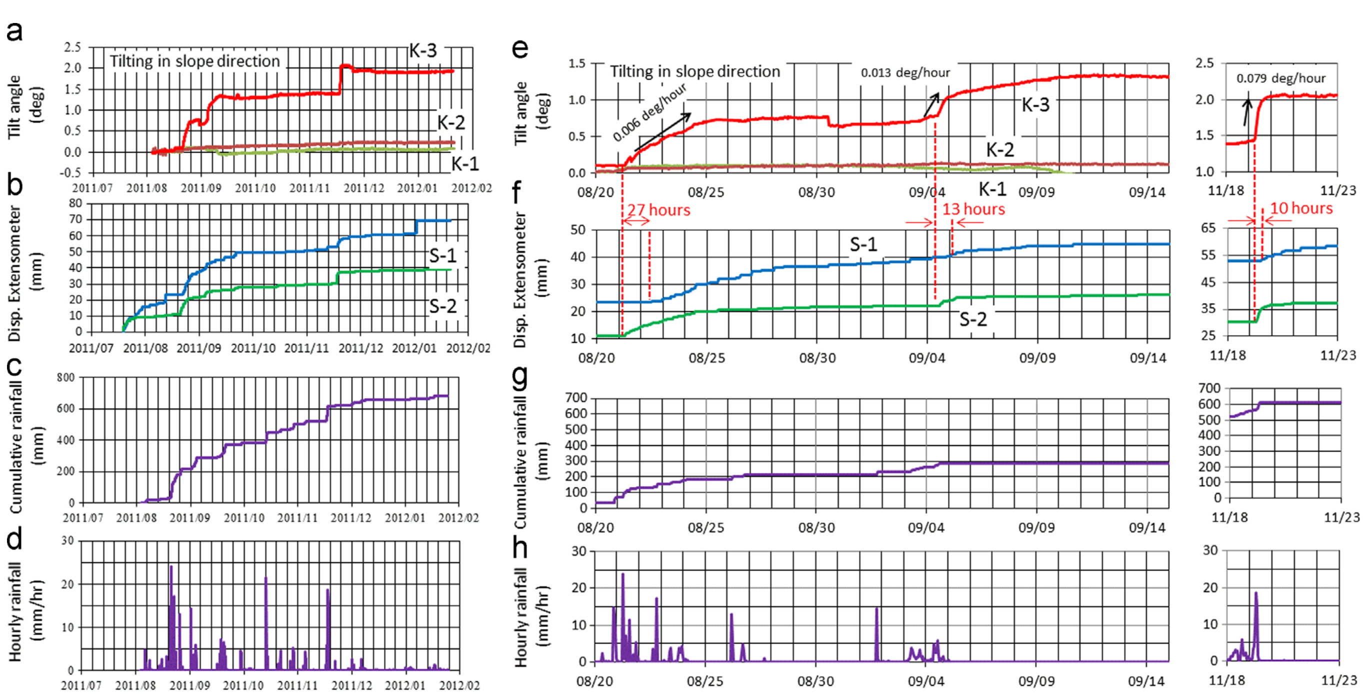

Fig. 18. Time histories of monitored items: (a) tilt angles by surface tilt sensors; (b) displacements by extensometers; (c) accumulated amount of rain; (d) rainfall intensity; and (e)–(h) Zoom up for heavy rainfall events.

along Three Gorges Dam reservoir; Site C: long-term deformation of a damaged slope; and Site D: long-term deformation of a cut slope).

The tilting behaviors before slope failure were recorded by some sensor units for the artificial rainfall tests and Site A, while the slope was stabilized eventually for the other cases. Table 1 summarizes the duration remaining before the slope failed or the stabilized versus the tilting rate observed at the position of the sensor unit. Fig. 24 explains the tilting rate and the duration listed on this table. In cases where the slope failed at the position of the tilt sensor, duration T is measured from the time tilting rate *R* was observed to the time of failure. In cases where the slope did not fail and stabilized finally, *T* is measured from the time *R* was observed to the time the slope was stabilized. In the later cases, the tilting motion was stopped due to the end of rainfall (K150 of the artificial rainfall, Site B, and Site C) or the countermeasure works (Site D). If the rainfall had continued, or the countermeasure work had not taken place, the slope would have failed after some duration longer than T. Particularly in the case of K150, for the artificial rainfall, the progressive failure was imminent at the position of K150, but the rainfall was stopped just before K150 was dropped.

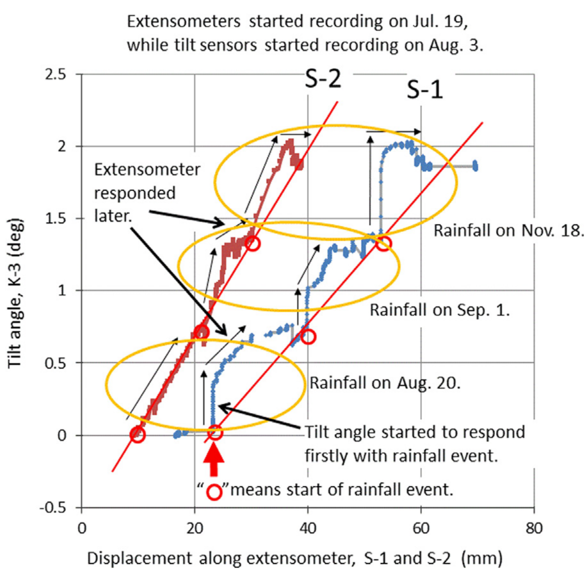

Fig. 19. Comparison between data from extensometer (S-1 and S-2) and surface tilt sensor (K-3).

Fig. 25 shows the relationships between the tilting rates and the duration before failure or stabilization. The observed tilting rate was more than 0.01°/h for all the cases in which the slope finally failed or nearly failed, while it was less than 0.1°/h for all other cases. At Site B, the tilting rate exceeded 0.1°/h, while the slope did not failed at the position of the sensor. However, another failure occurred at a very adjacent place. Therefore, the authors propose the issuance of a warning at a tilting rate exceeding 0.1°/h and a precaution at a tilting rate of 0.01°/h for the sake of safety.

Fig. 25 also suggests that the tilting rate tends to increase toward failure, and that a shorter duration remains before failure when a higher tilting rate is observed. Durations of 1–10 h remained before failure when a tilting rate of 0.1°/h was observed.

This is an empirical conclusion based on the limited case studies described in this paper. The geological conditions of

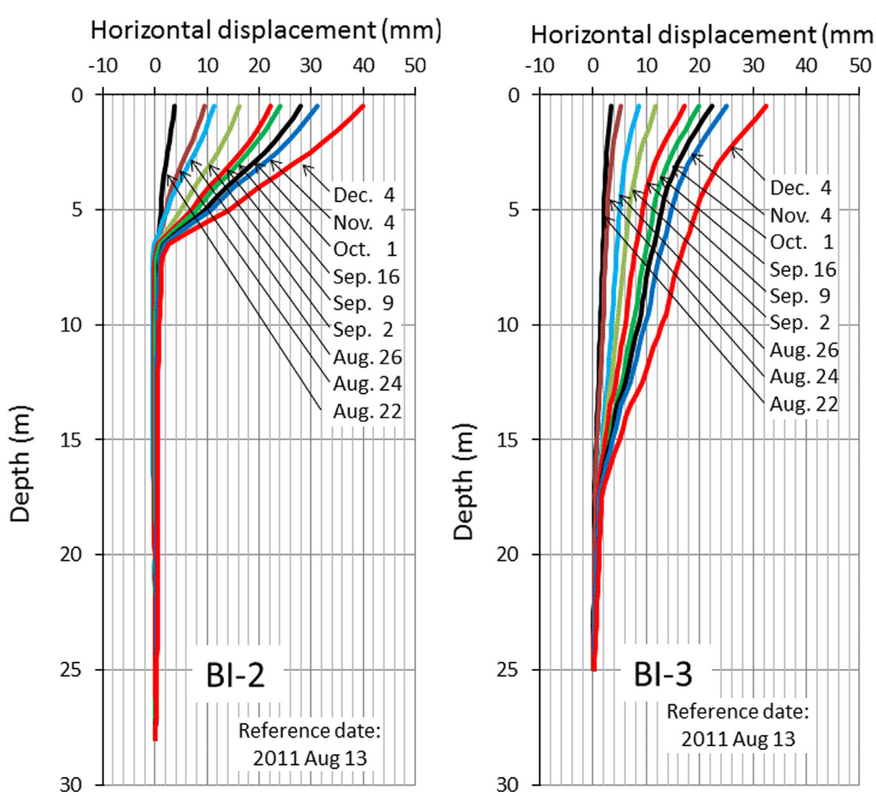

Fig. 20. The results of multiple borehole inclinometers.

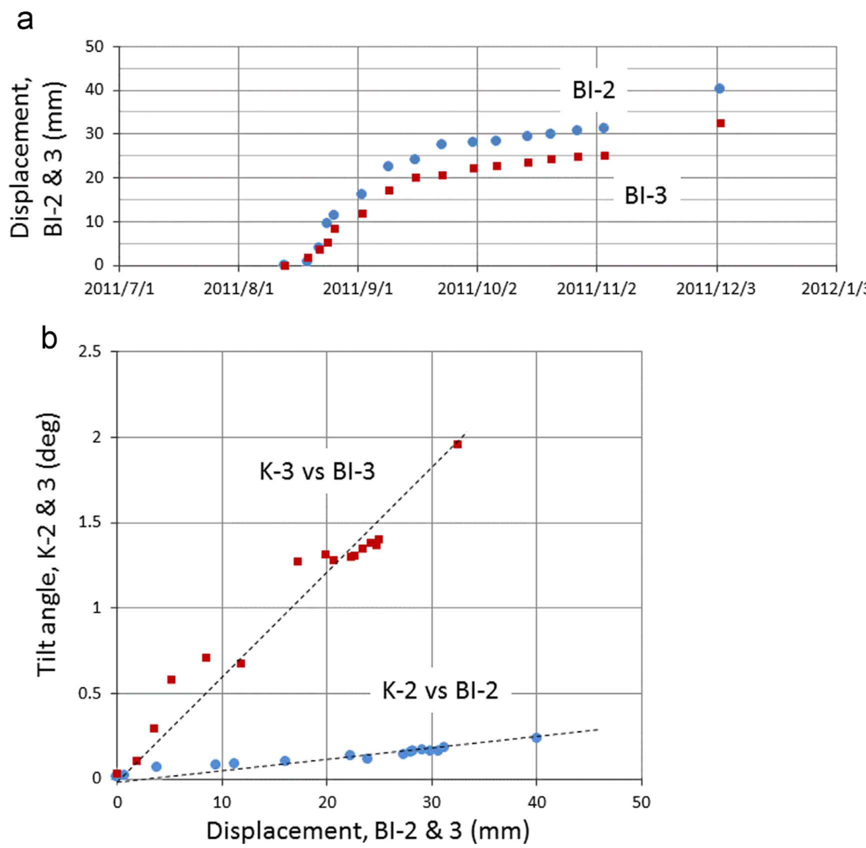

Fig. 21. Surface displacement obtained by bore hole inclinometers, BI-2 and 3: (a) time history and (b) comparison with tilt angles, K-2 and 3.

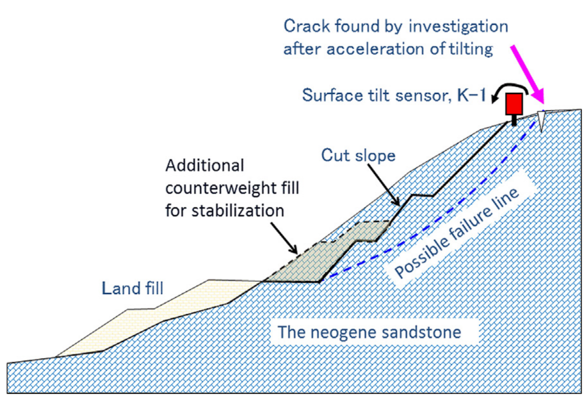

Fig. 22. Long-term deformation of slope due to cutting work.

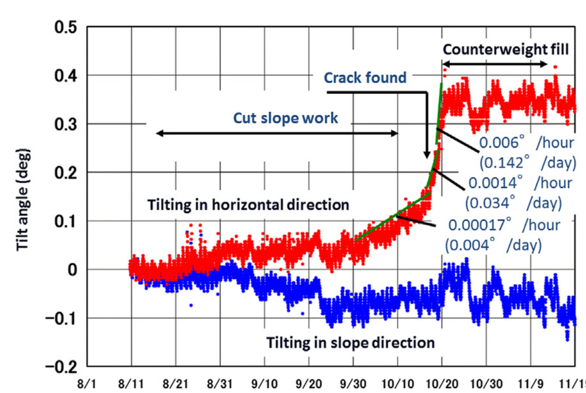

Fig. 23. Long-term deformation of slope due to cutting work.

the referred cases are weathered andesite (artificial rainfall test site), highly weathered granite (Sites A and C), clay with crushed mud stone (Site B), and neogene sandstone (Site D). Their slope angles are between 15 and 40°. The artificial rainfall test site, Sites A, B, and D were exposed to heavy rainfall, as mentioned above, while the deformation of Site D was caused by excavation works. The authors' empirical conclusion is valid for a range of these site conditions.

The expected tilting behavior in the pre-failure stages of slopes may depend on the site conditions, and further refinement of the warning criteria is expected by means of more data collection. It would also be valuable to clarify the reason for these values of observed tilting rates based on soil mechanics, but this will require an extension of this study.

7. Conclusions

A simple monitoring method for the precaution of rainfall-induced landslides is proposed, which uses tilt sensors on the slope surface to detect abnormal deformation. The tilt sensors are attached to steel rods and installed at depths of 0.5–1 m from the surface layer of slopes. A wireless sensor unit, with a MEMS tilt sensor and a volumetric water content sensor, was developed and installed on several real slopes in Japan and China, and long-term monitoring was attempted.

Table 1
Summary of the tilting rate and duration observed on slope surface.

Site	Sensor unit	Tilting rate, R (°/h)	Duration before failure/ stabilization, T	Failed or stabilized
Artificial rainfall test	K50	0.15	6.75	Failed
		3.81	1.75	
		0.096	1.5	
		45	0.5	
	T50-1	0.02	6.66	Failed
		0.4	2.66	
		195	0.16	
	T50-2	–	–	(Blocked by stone)
	K150	0.016	7.177	Nearly failed
		0.094	3.177	
		0.46	1.847	
		0.79	0.68	
		21	0.28	
	T200	0.016	7.5	Stabilized
	T300	0	-	(Not moved)
Site A	Unit2	0.16	1	Failed
Site B	Unit2	0.01	372	Stabilized (Another failure at adjacent place)
		0.12	12	
Site C	K-3	0.006	95	Stabilized
		0.013	130	
		0.079	6	
Site D	K-1	0.00017	456	Stabilized by countermeasures
		0.0014	96	
		0.006	24	

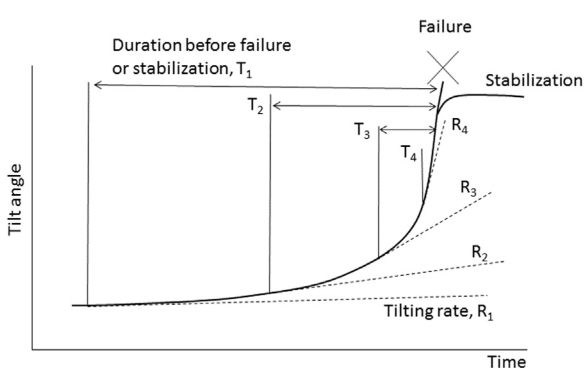

Fig. 24. Definition of the tilting rate and the durations on Table 1.

The use of tilt sensors for early warning is a newly proposed technique. Unlike extensometers, which have a long history with vast experience, the monitoring data obtained by tilt sensors is limited. The tilting behaviors in the pre-failure stages of slopes may depend on the site conditions as well as the positions of the sensors, and more data collection will be required for the further refinement of this early warning method. However, from the available case studies indicated in this paper, the following conclusions can be drawn from this study:

(1) Tilt sensors installed on slope surfaces can detect some pre-failure behaviors due to heavy rainfall. The observed tilt angles responded sensitively to heavy rainfall events, and

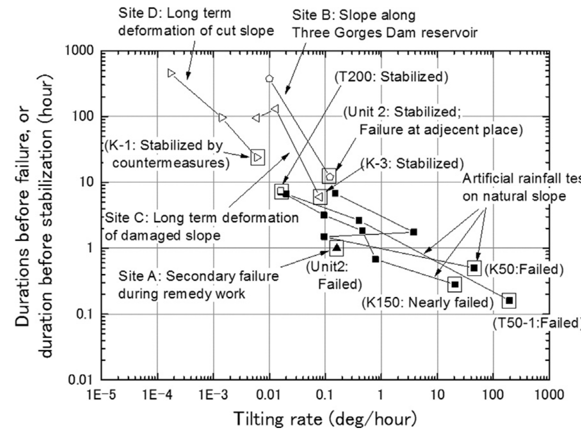

Fig. 25. Summary of the tilting rate and duration observed on slope surface.

continuous tilting was observed for several hours before failure.

(2) The order of the tilting rate observed with slope deformation varied widely from 10^{-4} to 10°/h depending on the situation. The observed tilting rate was more than 0.01°/h for all the cases in which the slope finally failed or nearly failed, while it was less than 0.1°/h for all other cases. Therefore, the authors propose that a warning be issued at a tilting rate exceeding 0.1°/h and that a precaution be issued at a tilting rate of 0.01°/h for the sake of safety.
(3) The tilting rate tended to increase toward failure, and a shorter duration remained before failure when a higher tilting rate was observed. Durations of 1–10 h remained before failure when a tilting rate of 0.1°/h was observed.
(4) In the artificial rainfall tests and the long-term monitoring on a slope damaged by heavy rainfall [Site C], the behaviors of the tilt angles were also consistent with the surface displacement monitored by extensometers and multiple borehole inclinometers which were installed together with the tilt sensors.
(5) In the artificial rainfall tests and the long-term monitoring on a slope damaged by heavy rainfall [Site C], the slope started to move from the bottom and then propagated upward. In such cases, it is effective to use a tilt sensor at the lower part of the slope for early warning.
(6) In the monitoring of a slope along the Three-Gorges Dam Reservoir [Site B], the tilting rate exceeded 0.1°/h, while the slope did not fail at the position of the sensor. However, another failure occurred at a very adjacent place. This suggests that a high tilting rate indicates the risk of disaster not only for the monitored slope, but also for other adjacent slopes in the area with similar conditions. Therefore, it is worth issuing a warning for the area based on the observed tilting behaviors.
(7) In the monitoring of the long-term deformation of a slope due to cutting work [Site D], a tilting rate of 0.00017°/h was observed at the beginning. Such very small behaviors can be detected only by continuous monitoring with high resolution sensors. Eventually, this monitoring successfully

contributed to the prevention of the ultimate failure of this slope.

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