Deformation and water seepage observed in a natural slope during failure process by artificial heavy rainfall

Déformation du sol et infiltration d'eau observes le long d'une pente naturelle pendant le processus de glissement du a de fortes pluies artificielles

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ABSTRACT: Monitoring and early warning is one of the most effective ways toward reduction of disasters induced by landslides due to heavy rainfall. The authors has developed a simple and low-cost early warning system which measures tilting angles on the surface and/or in the ground of a slope, as well as volumetric water contents in the ground. Unlike conventional sensing devices, measurement with tilt sensors is simple and easy, but the translation of the obtained data of tilting angle is still under consideration. The authors conducted an artificial rainfall test on a natural slope of weathered and loose andesite deposit in order to observe its prefailure behaviours. The tilt angles and volumetric water contents were measured during the deformation and failure process. The tilt sensors showed tilting rates between 0.1 and 0.5 degree / hour before failure. In addition, there was a unique relation between the deformation and the water content, which is independent of the time history of the artificial rainfall. Simple shear tests were also conducted to observe the prefailure deformation of an unsaturated soil. These observations will give us ideas on the warning criteria for slope failure based on monitoring of tilting angle and water contents.

RÉSUMÉ : Donner l'alerte au plus tôt est sûrement la solution efficace pour réduire l'ampleur des désastres induits par les glissements de terrain dus à des chutes massives de pluie. Un système d'alerte simple et à bas-coût qui mesure les angles d'inclinaison de la surface du sol et/ou dans la terre, ainsi que le volume d'eau absorbé est proposé. Contrairement aux appareils conventionnels, la mesure avec les sondes de l'inclinaison est simple et facile, mais la traduction des données obtenues est encore à l'étude. Un test de chute de pluie artificielle sur une pente naturelle d'andésite durcie et dégagée pour observer les comportements des pré-fractures a été réalisé. L'orientation de l'inclinaison ainsi que le volume d'eau ont été mesurés pendant la déformation de la surface. Les sondes ont révélé des pentes comprises entre 0,1 et 0,5 degré/heure avant glissement. De plus, une relation unique indépendante de la durée de la chute de pluie artificielle est établie entre la déformation du sol et le contenu d'eau. Des tests de cisaillement ont aussi été effectués pour observer la déformation des pré-fractures d'un sol non saturé. Ces observations nous donnent des informations sur les critères d'alerte pour prévenir un glissement de terrain.

KEYWORDS: landslide, slope failure, monitoring, early warning.

1 INTRODUCTION

There is a long history in prevention and mitigation of rainfall and/or scouring-induced landslides. Mechanical counter measures to prevent slope failure, like retaining walls and ground anchors, have been widely used. However, they are expensive and it is not realistic to apply such mechanical measures for all of these slopes with potential risk, because most of landslide occurs in small scale, but a large number of slopes. Therefore, careful monitoring of slope behaviors and consequent early warning is reasonable as alternatives.

The authors have proposed and developed an early warning system for slope failures, as one of feasible countermeasures (Figure 1) (Uchimura, et. al. 2010 & 2011a). The system consists of minimum number of low-cost sensors on a slope, and the data is transmitted through wireless network. Thus, the system is low-cost and simple so that the residents in risk areas can handle it to protect themselves from slope disasters.

There are several publications which report incremental deformation of slopes before failure due to heavy rainfall (Ochiai, et. al. 2004, Orense, et. al. 2003 & 2004). These behaviors can be used as criteria of early warning for slopes disasters. Extensometers and borehole inclinometers are conventional and widely used devices to detect such displacements of slopes. But, these devices require high skills and equipments for installation and operation, resulting in a respectable cost.

Therefore, the proposed early warning system uses tilt sensors to detect abnormal deformation of slopes as shown in Figure 1. The surface tilt sensor is installed with a rod inserted into the slope surface for a depth of 0.5 or more. It has a MEMS tilt meter (nominal resolution = 0.04 mm/m) to measures the tilting angle in the surface layer of the slope. The obtained tilt angle is equivalent to shear deformation of the surface layer, which can be translated to the surface displacement if the tip of rod reaches the intact base layer.

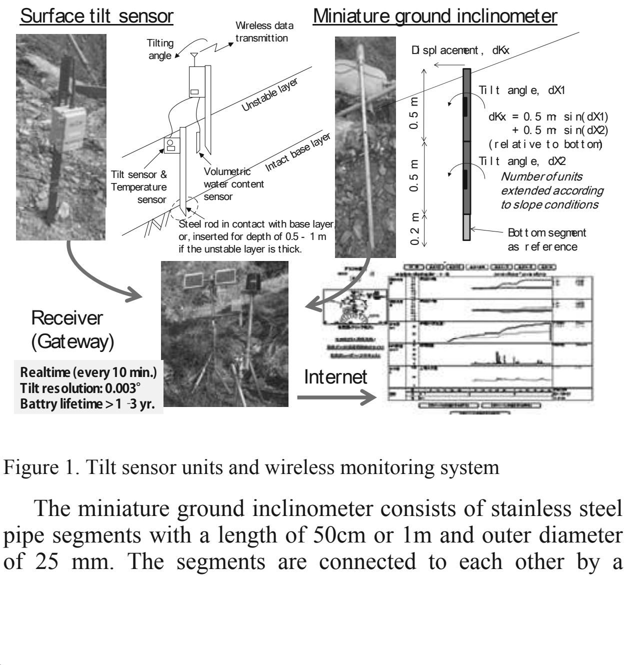

Figure 1. Tilt sensor units and wireless monitoring system

The miniature ground inclinometer consists of stainless steel pipe segments with a length of 50cm or 1m and outer diameter of 25 mm. The segments are connected to each other by a flexible mechanism, so that the device moves together with the ground displacement. A sensor unit covered by a small aluminum cylindrical case is installed in each segment. The sensor unit contains the MEMS tilt meter and a geomagnetic sensor (digital compass, nominal resolution = 0.5 deg) to detect the direction of unit. Each unit also contains a microcontroller chip, which control the sensors, and transfer the control commands and the obtained data to the next units by serial interfaces. A significant advantage of this device is that it can be installed quickly into the slope ground being blown with a hammer, as its diameter is as small as 25 mm. Besides, it can be installed into a deeper layer of slopes (3-5 m) by connecting the segments as many as needed.

Unlike conventional sensing devices, such as borehole inclinometer and extensometer which measures displacements of slope, measurement with tilt sensors is simple and easy. However, the translation of the obtained data of tilting angle is still under consideration. It is because there are few case histories of early warning with tilt sensors compared to those with conventional sensors. Therefore, it is essential to observe the behaviors of tilt angles in prefailure stages of slopes.

2 SLOPE FAILURE TESTS BY ARTIFICIAL RAINFALL

An artificial rainfall test was conducted on a natural slope of weathered and loose (N_d <10 for 10 cm of penetration by portable dynamic cone penetration tests) andesite deposit in order to observe its prefailure behaviour. The site is located on an unstable slope in Taziping, Sichuan Province, China. Figure 2 shows the cross-section and photo of the site together with the instruments. The slope angle is around 18 degrees, and its lower end was excavated for a depth of 1.4 m with an angle of 40 degrees. The deposit contains some big rocks with diameter of 300 mm or more. The particle size distribution of component finer than 100 mm is show in Figure 2. It is a sandy material containing some gravel and fine particles.

Figure 2 also shows surface tilt sensors (T50-1, T50-2, T200, and T300), and miniature ground inclinometer (K50 and K150). The number in the notation of each sensor represents the distance from the bottom end of slope in cm. Each rod of the surface tilt sensors was inserted into the ground by 75 cm. Each miniature ground inclinometer consists of 2 segments with a length of 500 mm.

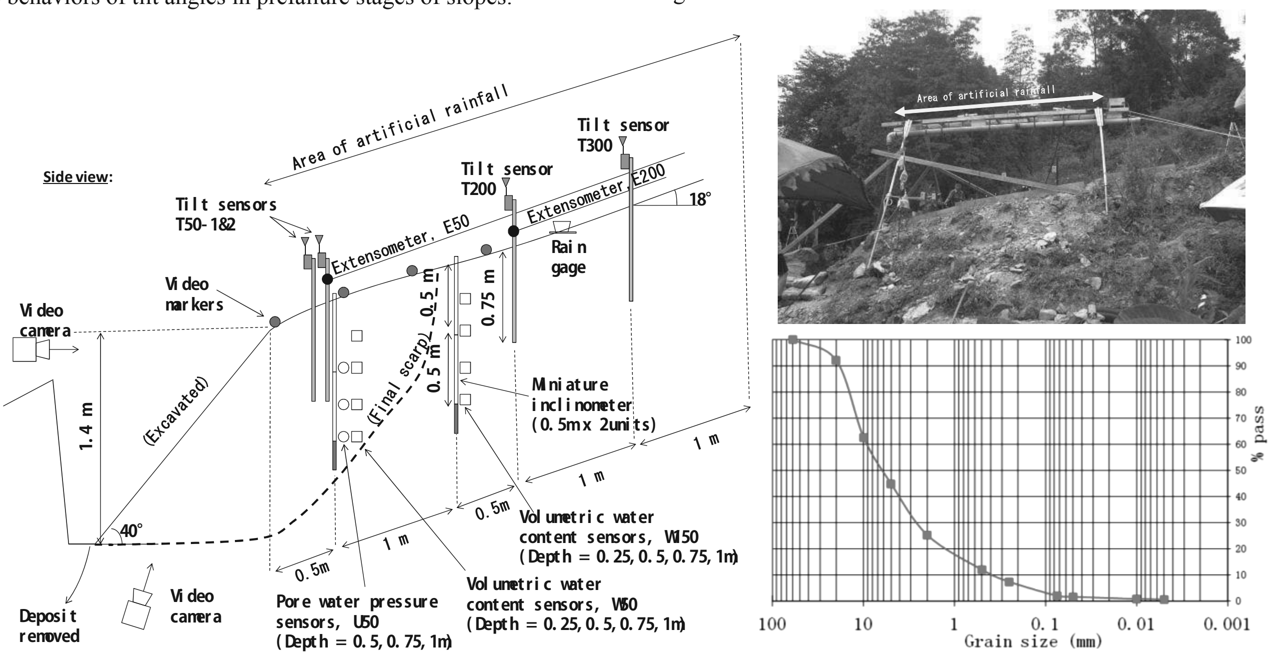

Figure 2. Cross-section, photo, and particle size distribution (finer part than 100 mm) of the site for the artificial rainfall test.

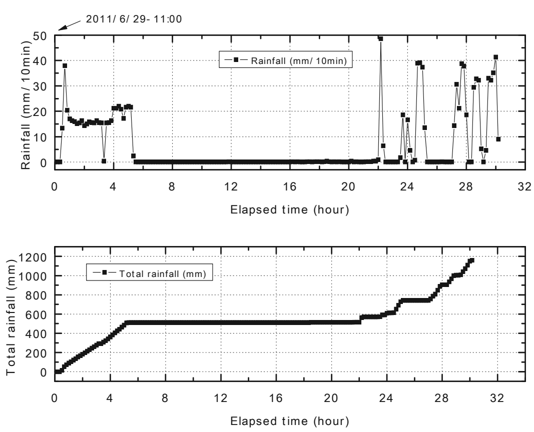

Figure 3. Records of the artificial rainfall.

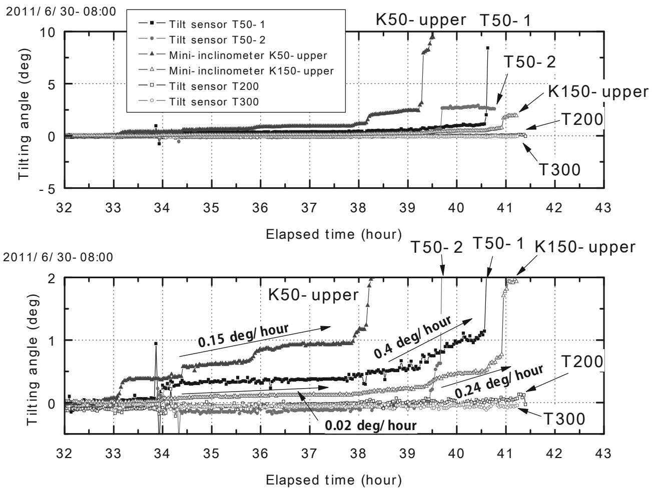

Figure 4. Tilting angles on the slope.

Artificial heavy rainfall was given as shown in Figure 3. The rainfall intensity fluctuated due to restriction of water supply, but around 500 mm of total of rain was applied in the first day, and 700 mm was given in the second day.

Major deformation was observed in the second day, and the slope failed progressively from the bottom with scarp angle of 40 to 50 degrees. The final shape of scarp is shown with thick broken line in Figure 2.

Figure 4 shows the changes in tilting angles detected by the tilt sensors due to the rainfall in the second day. Tilt angles of the upper segment are shown for the miniature ground inclinometers. The nearer to the bottom of slope, the more tilting angles are observed. The tilting rate for each sensor is between 0.1 and 0.5 degree / hour before failure. It is also remarkable that K150-upper, 150 cm apart from the bottom of slope, started to tilt slowly in the early stage, when the failure was observed only at the bottom scarp. This suggests that the sensor detected slight effects of the failure event at some distance of the sensor position. This behaviour is not visible to human eyes because its tilting rate was only 0.02 degree / hour.

Figure 5 shows the behaviours of the tilting angle of the upper unit of the miniature inclinometer, K50, at 50 cm from the bottom of slope. This represents the average shear deformation of the soil layer between depth of 0 and 50 cm. Besides, Figure 5 also shows the volumetric water content at a depth of 50cm at a position of 50 cm from the bottom of slope. The volumetric water content repeated to increase and decrease corresponding to the intermissive rainfall and drainage stages.

Figure 6 plots the tilting angle versus the volumetric water contents of Figure 5. This represents relationships between the shear deformation and water content. The deformation increased when the water content was high corresponding to rainfall, although some additional deformation was also recorded due to removal of soil which dropped and deposited in front of the bottom of slope.

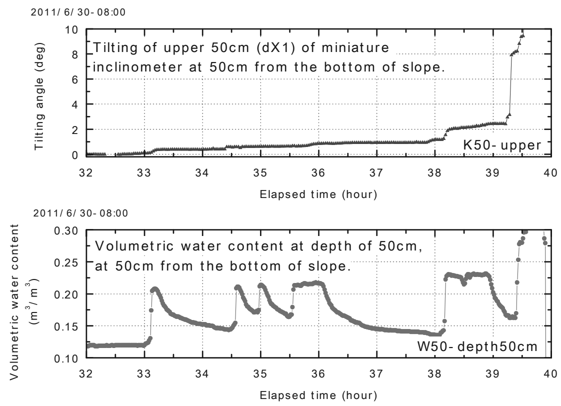

Figure 5 Time histories of tilting angles and volumetric water contents at 50 cm from the bottom of slope.

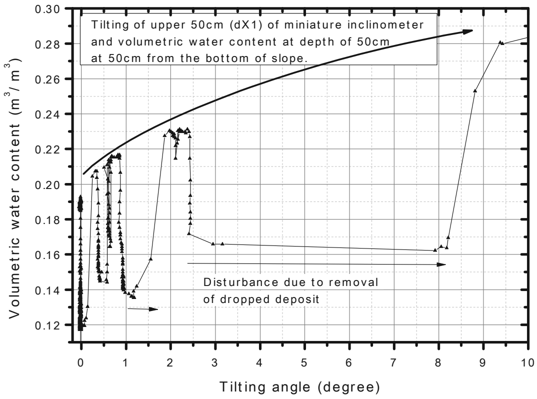

Figure 6 Tilting angles versus volumetric water contents at 50 cm from the bottom of slope.

A unique relation between the deformation and the water content can be drawn as an envelope of the plot, as indicated in Figure 6, which is independent of the time history of the artificial rainfall. Similar behaviours was be also observed in laboratory model tests on slip surface of unsaturated soil under constant shear stress and cyclic water infiltration/drainage processes (Uchimura et. al. 2011b).

3 SIMPLE SHEAR TESTS ON SLIP SURFACE

A series of simple shear tests were conducted on unsaturated sandy soil specimens to observe their prefailure behaviors more precisely. Figure 7 shows the arrangement of the testing device. Edosaki Sand (D_{max} = 2 mm, D_{50} = 0.23 mm, fine content = 6 %, Gs = 2.665, e_{max} = 1.685, e_{min} = 0.578) was compacted into a disc shape with a diameter of 60 mm and a height of 20 mm, and a relative density of Dr = 70 % with initial volumetric water content of 7 %. The specimen is surrounded by a stacked layers made of Teflon, which has low friction coefficient, to reduce the effect of friction. The specimen was loaded with 60 kPa of vertical confining pressure. And then, 15, 24, 30 kPa of constant shear stress was applied, which corresponds to 0.25, 0.4 and 0.5 of stress ratio, respectively. These three stress ratio simulate the stress state on the slip surface for gentle, medium, and steep slopes. Then, water was injected into the specimen from the top and bottom surface through ceramic discs with a constant injection rate of 310 ml/hr, which corresponds to a rainfall intensity 110 mm/hr fall on the top area of the specimen.

Figure 8 shows the obtained volumetric water contents and shear strain during the water infiltration process. It seems that there are three patterns of deformation and failure processes. In the case with stress ratio of 0.25 (gentle slope), the shear deformation increases with water infiltration, but it converged to a limited value not showing failure. On the other hand, in the case of steep slope with stress ratio of 0.5, the strain started to increase with a similar rate to that in the case of gentle slope, but it suddenly yielded at incremental volumetric water content of around 7 % and shear strain of around 1.7 %, followed by a quick deformation with high strain rate.

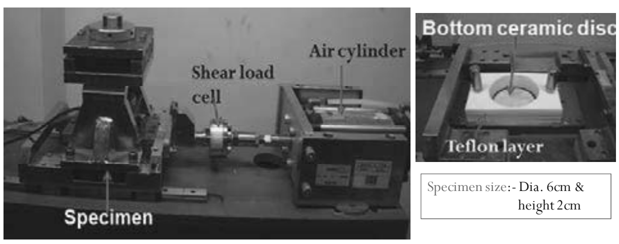

Figure 7 Equipments for direct shear tests.

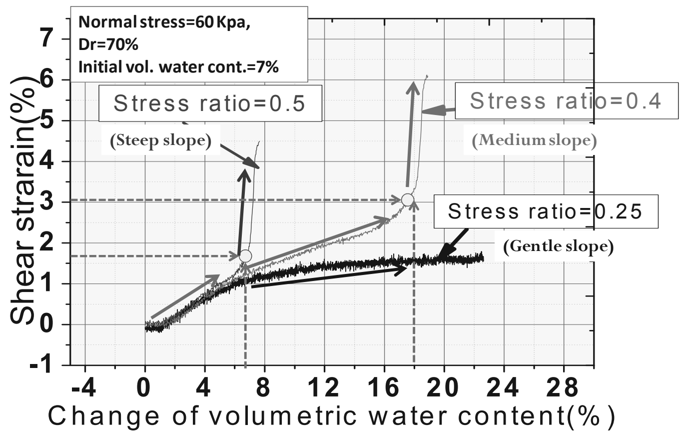

Figure 8 Shear strain versus volumetric water content under 3 values of constant stress ratio.

The behavior in the case of medium slope with stress ratio of 0.4 was more complicated. The strain started to increase with a similar rate to those in the other cases, but it slowed down when the change of volumetric water content was between around 7 % and 18 %. And then, it yielded, followed by a quick deformation with high strain rate.

The reason for the slowing down of strain rate observed in the case of medium slope could be explained with the behaviors of suction. The authors developed a miniature suction sensor to measure the suction in the specimen (Figure 9). A tiny metal pipe (ϕ1.5 mm x 4 mm) with small hole is wrapped with a micro-porous membrane. One end of the pipe is connected to a water pressure transducer via a plastic tube, while the other end is closed. The membrane allows water to pass through, but prevent air to pass by capillary effect. Thus, the pipe with the membrane works just like a miniature ceramic cup. Properties of a similar membrane are studied by Nishimura et. al. (2011). Due to its small size, the miniature suction sensor can be installed with minimum disturbance to deformation and water seepage in the specimen as seen in Figure 9.

Figure 10 shows relationships between the suction and the change of volumetric water content measured in another specimen during water infiltration process. The suction decreases with fast rate until the change of volumetric water content reaches around 4.5 %. Then, the decreasing rate of suction slowed down.

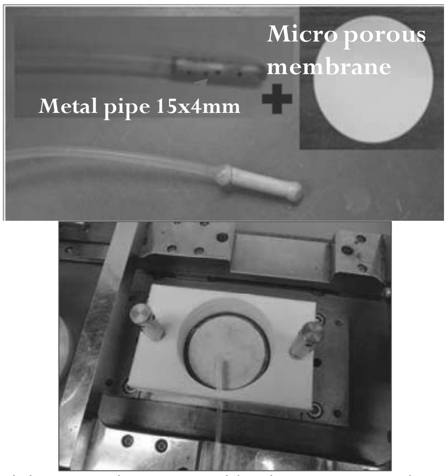

Figure 9 Miniature suction sensor with microporous membrane.

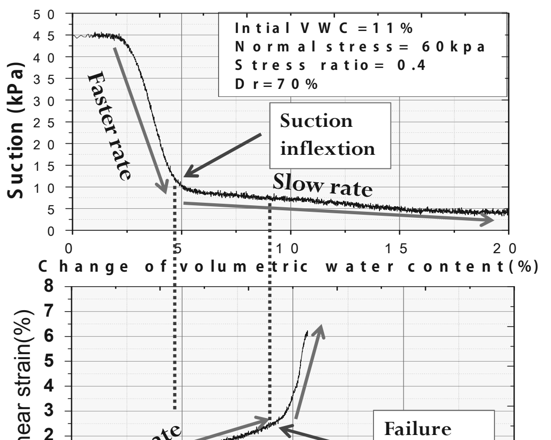

Figure 10 Relations among volumetric water content, suction, and shear strain.

The strain rate of the specimen also slowed down at the same change of volumetric water content. Thus, this behavior can be explained with the suction-water characteristics curve (SWCC) of the soil. Finally, the specimen yielded at higher change of volumetric water content, corresponding to lower suction.

This observation suggests that a tentative slowing down of slope deformation does not always mean stabilization of slope.

4 CONCLUSIONS

A slope failure test with an artificial rainfall was conducted on a natural slope. The tilt sensors installed into the slope showed tilting rates between 0.1 and 0.5 degree / hour. These values of tilting rate could be used as criteria of early warning for slope disasters.

The deformation proceeded when the water content was high corresponding to rainfall, while it is less progressive when the water content is low. Similar behaviours were also observed in model test in laboratory, where an unsaturated soil layer was sheared under constant shear stress with cyclic water infiltration and drainage. It seems that there is a unique relation between the deformation and the water content, which is independent of the time history of the artificial rainfall. These results suggest a possibility of conbined monitoring of tilting angle and water contents for more precise comprehension of the status of slopes.

The results of direct shear tests on unsaturated soil under constant shear stress and constant water injection rate suggest that there are three patterns of deformation and failure processes corresponding to the slope angle. In a case of medium slope, the strain rate may slow down due to the SWCC of the soil even though water is injected with a constant rate. However, it does not always mean that the slope is getting stable.

5 ACKNOWLEDGEMENTS

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