Stability monitoring of soil slope in wetting and failure process using elastic wave velocity

Chen Yulong i), Uchimura Taro ii), Tao Shangning iii) and Xie Jiren iv)

i) Ph.D Student, Department of Civil Engineering, the University of Tokyo, 7-3-1, Hongo, Tokyo 113-8656, Japan.
ii) Associated Professor, Ph.D Student, Department of Civil Engineering, the University of Tokyo, 7-3-1, Hongo, Tokyo 113-8656, Japan.
iii) Master Student, Department of Civil Engineering, the University of Tokyo, 7-3-1, Hongo, Tokyo 113-8656, Japan.
v) Ph.D Student, Department of Civil Engineering, the University of Tokyo, 7-3-1, Hongo, Tokyo 113-8656, Japan.

ABSTRACT

Rainfall is a significant factor that triggers slope failures around world. This paper proposes a method for the prediction of landslide initiation by using elastic wave velocity in soil. Two cases of slope model tests were conducted. First case of test investigated the behavior of elastic wave velocities during wetting and failure process of soil slope with slope angle of 45°. It was found that a gradual decrease in wave velocities was followed by a rapid decrease once the failure was initiated. While the second case was conducted with slope angle of 0° and rainfall was given at early period and then soil model was inclined without rainfall in order to separately unravel the change in elastic wave velocity with increase of water content and deformation. The wave velocity was found to decrease slightly with increasing water content but largely with deformation. Based on these observations, ideas for the prediction of landslides using elastic wave propagation in soil are presented.

Keywords: slope stability, elastic wave velocity, rainfall infiltration, model test

1 INTRODUCTION

Slope failures world-wide cause many thousands of deaths each year. Petley (2012) reported records of over 32000 fatalities globally that occurred as a result of landslides during the period 2004 to 2010. Furthermore, landslides damage infrastructure and the built environment, costing billions of pounds to repair, resulting in thousands of people being made homeless and the breakdown of basic services such as water supply and transport. The large majority of deaths from slope failures occur in countries located in rainfall and earthquake-prone regions. Osanai et al. (2009) conducted a statistical study on 19035 cases of landslides between 1972 and 2007 in Japan. They reported that 93% of those landslides were caused by heavy rainfall. Therefore, the demand for monitoring and early warning methods against landslides and slope instabilities induced by rainfall is on the rise in every country.

In order to prevent and mitigate of rainfall induced landslides, many novel approaches have been developed to serve as early warning system. For example, the rainfall record is widely used for early warning (Baum and Godt, 2010; Chae and Kim, 2012; Keefer et al., 1987). 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. However, such a sparse arrangement of rain gages cannot properly detect cloudbursts, in which extremely heavy rainfalls occur in limited areas. Besides, soil properties and slope characteristics are not taken into consideration. Displacement is another term to be monitored. Ochiai et al. (2004) reported gradual and accelerating displacement on a slope surface before failure in a rainfall induced landslide test using strain probes. However, the exact locations of unstable soil masses often cannot be defined; and hence, the locations of the monitoring sensors cannot be decided distinctly. The rate of displacement is often used as an index to define the threshold of warning (Fukuzono 1985; Saito 1965, 1987). However, it is restricted to relatively low resolution that is insufficient for detecting the displacement of slopes in the very early stages. Acoustic emission monitoring is used to assess the stability of both natural and constructed slopes (e.g. Cadman and Goodman, 1967; Chichibu et al., 1989; Dixon et al., 2007, 2015a, 2015b; Nakajima et al., 1991; Rouse et al., 1991; Smith et al., 2014). Soils generate relatively low-energy acoustic emission signals that attenuate significantly over short distances, and this method is difficult for field application as well. With the objective of providing an early warning of slope instability to enable the evacuation of vulnerable people, a more flexible and effective method is...
preferred.

A novel concept of landslide prediction by monitoring elastic wave velocity changes in soil was presented by Irfan et al. (2013a, 2013b), who conducted triaxial tests on soil specimens with varying water content, and injected water into stressed soil sample. The elastic wave velocity was measured by a pair of disk type piezo-electric elements (similar to bender element), and it was found to decrease with increasing water content. More important is the acceleration in decrease of wave velocity, once failure is initiated. Therefore, we try to apply this finding to detect the wetting and failure process of soil slope.

Laboratory model test is regarded as the most reliable method for studying the rainfall-triggered landslide, in which the soil properties and boundary conditions can be controlled and the water content inside slope and deformation on the surface can be monitored. For the purpose of better understanding the changes in elastic wave velocity in soil slope in wetting and failure process as a result of rainfall, we performed two cases of slope model tests in the laboratory, slope angle=45° for one case at which artificial rainfall was continuously applied until slope failure and 0° for the other where rainfall was given at early period after which soil model was inclined without rainfall. The changes in wave velocity with coupling effect of water content and deformation or single effect are investigated.

2 TEST MODELS

2.1 Test sensors

Soil moisture sensors (Model: EC-5), manufactured by American Decagon Devices Inc., were used in the experiment to measure the water content designated as volumetric water content. Besides, tilt sensors based on Micro Electro Mechanical Systems technology were adopted to measure the tilt angles (rotations) in the unstable surface layer of slopes. Soil moisture sensors and Tilt sensors were connected to a data logger (Model: HOBO RX3000) for continuous logging of data during rainfall application. It was set to log data for every 1s from all the sensors connected with this logger. In addition, piezoelectric vibration sensors (Model: VS-BV201) developed by NEC TOKIN Corporation were employed to record the elastic wave signals. A high performance data logger (NR-500 by Keyence Corporation Ltd.) was used to realize continuous recording of wave signals with a sampling rate of 50kHz. Data acquisition was implemented using software NR-HA08 hi-speed measurement unit.

2.2 Wave exciter

Wave excitation was realized through a solenoid. Solenoid is a coil of wire in a corkscrew shape wrapped around an iron plunger, and it is used as an electromagnet to generate magnetic field when an electric current is passed through the wire. Electric current activates the solenoid by converting electrical energy to magnetic energy, which in turn causes the plunger to move forward to strike the iron frame of solenoid. Consequently, elastic wave is created. This plunger moves backward by a return spring twined at the endpiece of plunger when removing the electric current, which is what makes it useful as switches and valves and allows it to be entirely automated.

2.3 Stacking

Precise determination of the elastic wave velocity in soils is essential for the prediction of the slope instability. Unfortunately, raw signal inevitably comes noisy. In order to eliminate random signal noise and to enhance the signal to noise ratio of the signals, a microcontroller was designed to generate repeated pulse at once electric input. Accordingly, solenoid was triggered repeatedly for each measurement and the corresponding received signals were stacked. For each reading, twenty measurements of wave were stacked.

2.4 Artificial rainfall system

The artificial rainfall equipment was comprised of air compressor, pressure regulator, water tank, spray nozzle and pipeline. The applied air pressure drove water to eject from the nozzle. The experiments were conducted with rainfall intensity of 100 mm/h.

2.5 Soil properties

Test material used in this study comprised of Edosaki soil; brown colored natural soil procured from a trench pit in Tsukuba, Japan. Edosaki soil used in this study had around 9% fines, and a specific gravity (G_s) of 2.639; minimum (e_{min}) and maximum (e_{max}) void ratios were found out to be 0.647 and 1.160 respectively (all tests conducted according to Japanese Geotechnical Society (JGS) standards). Particle size distribution of Edosaki soil is shown in Fig. 1.

![Particle size distribution of Edosaki soil](image)

Fig. 1. Particle size distribution of Edosaki soil.

2.6 Slope model

Two slope models were constructed, as shown in Fig. 2. The slope was 30 cm wide for case 1 and 35 cm wide for case 2. One wave sensor was fixed next to the solenoid and the other three installed at superficial layer of slope to measure the wave travel time.

![Slope model](image)
2.7 Experimental design

The main purpose of the model tests was to study the processes of rainfall infiltration and slope failure, and their influences of different factors on elastic wave velocity. Two cases of slope model tests were conducted. The first case of test was a conventional model test on rainfall-induced landslide. The resulting change of wave velocity is coupled by increasing water content and deformation that appear to be interrelated.

For case 2, two stages of test scheme were applied. At the 1st stage, rainfall was continuously applied for 30min when water content reached a constant which was almost saturated. Wave signal was recorded at interval of 1min, at which the inclination of slope is 0°. At the 2nd stage, rainfall was stopped. Then, we inclined the slope slowly. Wave signal was recorded at every 5° of inclination which was measured using one tilt sensor (No.5) attached to the soil box, as shown in Fig.2. This was to separately investigate the change in elastic wave velocity with increase of water content and deformation.

3 RESULTS

Fig.3 gives the time histories of volumetric water content (VWC), tilt angle, and wave velocity normalized with the corresponding initial values from the onset of rainfall for case 1. As the rainfall progressed, the VWC and tilt angle at the different locations in the slope increased, while the normalized wave velocity started to decrease first slowly and then at a rapid rate.

Fig. 3. Time histories of volumetric water content (VWC), tilt angle, and wave velocity normalized with the corresponding initial values from the onset of rainfall for case 1.

Fig. 4 depicts the time histories of VWC, tilt angle, and normalized wave velocity for case 2. The VWC changed rapidly as the rainwater infiltrated into soil and it became nearly constant at t=1200s after which soil was almost saturated.

It can be seen that the VWC increase up to saturation did not change the tilt angle significantly in the first stage. Afterwards, tilt angle responded with incline. The inclination of slope model would definitely give rise to a certain of displacement of surface soil. The relative tilt angle \( \theta_s \) can be represented as \( \theta_s=\Delta \theta - \Delta \theta_b \), where \( \Delta \theta \) is the tilt angle change recorded by surface tilt sensor and \( \Delta \theta_b \) is the tile angle change detected by tilt sensor No.5.

The wave velocity is a function of water content and shear deformation. Fig.4 shows the relationship between the normalized wave velocity against VWC and relative tilt angle. Normalized wave velocity was observed to decrease slightly with VWC, while it decreased largely as relative tilt angle increased. Displacement was found to have more significant effect on normalized wave velocity than VWC. Based on this finding, wave propagation in soil can be utilized to predict the initiation of landslides.

Slope surfaces, at shallow depths, are generally in unsaturated state with soil matric suction (negative pore water pressure) playing an important role in their stability. During rainfall events, as water percolates the slope surface, matric suction is gradually lost resulting in reduction of shear strength. With the loss of available shear strength slope surface starts to become more and more unstable and this destabilization continues to a point at which equilibrium can no longer be sustained and the slope ultimately fails. Elastic wave velocity is function of deformation and moisture content. Elastic wave velocity in soil decreases with increasing saturation, and drops more as deformation occurs. These relationships between elastic wave velocity and
deformation and moisture content can therefore be utilized for the prediction of landslides.

The Changes of wave velocities with VWC are summarized in Fig. 5, together with data from bender element test during SWCC test (Irfan et al., 2014). The same soil type as well as density was considered in bender element test. It can be seen that the change trend of wave velocities with VWC obtained from model test is consistent with that obtained from SWCC test. It suggests that the received wave in model test should be S-wave.

Fig. 4. Time histories of VWC, tilt angle, and normalized wave velocity for case 2.

Fig. 5. Changes of wave velocities with VWC

4 CONCLUSIONS

An idea for prediction of landslides by using elastic wave velocity is presented. Wave velocity is found to decrease slightly with water content and significantly with deformation. Sensitivity of wave velocity to slope deformations can effectively be utilized to warn against landslide failures.

ACKNOWLEDGEMENTS

The research is supported by Grants-in-Aid for Scientific Research of Japan Society for the Promotion of Science (JSPS), and Coreto-Core Program “B. Asia-Africa Science Platforms” (JSPS).

REFERENCES

1) Baum, L.B. and Godt, J. W. (2010): Early warning of rainfall-induced shallow landslides and debris flows in the USA, Landslides, 7, 259–272.
2) Cadman, J.D. and Goodman, R.E. (1967): Landslide noise, Science, 158(3805), 1182-1184.
3) Chae, B. G. and Kim, M. I. (2012): Suggestion of a method for landslide early warning using the change in the volumetric water content gradient due to rainfall infiltration, Environmental Earth Sciences, 66(7), 1973-1986.
4) Chichibu, A., Jo, K., Nakamura, M., GOTO, T. and KAMATA, M. (1989): Acoustic emission characteristics of unstable slopes, Journal of Acoustic Emission, 8(4), 107-112.
5) Dixon, N. and Spriggs, M. (2007): Quantification of slope displacement rates using acoustic emission monitoring, Canadian Geotechnical Journal, 44(6): 966-976.
6) Dixon, N., Smith, A., Spriggs, M. P., Ridley, A., Meldrum, P., and Haslam, E. (2015b): Stability monitoring of a rail slope using acoustic emission, Proceedings of the Institution of Civil Engineers - Geotechnical Engineering, 168(5), 373-384.
7) Dixon, N., Spriggs, M. P., Smith, A., Meldrum, P. and Haslam, E. (2015a): Quantification of reactivated landslide behaviour using acoustic emission monitoring, Landslides, 12(3), 549-560.
8) Fukuzono, T. (1985): A new method for predicting the failure time of a slope. Proceedings of the IV International Conference and Field Workshop on Landslides, Tokyo,
9) Irfan, M. and Uchimura, T. (2013a): Effects of soil moisture on shear and dilatational wave velocities measured in laboratory triaxial tests, Proceedings of the 5th International Young Geotechnical Engineers’ Conference, Paris, France, 505-509.

10) Irfan, M., Uchimura, T. and Ghani, M.A.H. (2013b): Response of elastic wave velocities during constant shear stress drained tests on unsaturated triaxial specimens, 3rd Korea-Japan Workshop on Unsaturated Soils, Seoul, Korea, 45-51.

11) Keefer, D. K., Wilson, R. C., Mark, R. K., Brabb, E. E., Brown, W. M., Ellen, S. D., Harp, E. L., Wiecezorek, G. F., Alger, C. S. and Zatkin, R. S. (1987): Real-time landslide warning during heavy rainfall, Science, 238 (4829), 921–925.

12) Nakajima, I., Negishi, M., Ujihira, M. and Tanabe, T. (1991) Application of the acoustic emission monitoring rod to landslide measurement. Acoustic Emission/Microseismic Activity in Geologic Structures and Materials: Proceedings of the 5th Conference, Trans Tech Publications, Du¨rnten, Switzerland, 1-15.

13) Ochiai, H., Okada, Y., Furuya, G., Okura, Y., Matsui, T., Sammori, T., Terajima, T. and Sassa, K. (2004): A fluidized landslide on a natural slope by artificial rainfall, Landslides, 1 (3), 211–219.

14) Osanai, N., Tomita, Y., Akiyama, K. and Matsushita, T. (2009): Reality of cliff failure disaster, Technical Note of National Institute for Land and Infrastructure Management, 530.

15) Petley, D. (2012): Global patterns of loss of life from landslides, Geology, 40(10), 927-930.

16) Rouse, C., Styles, P. and Wilson, S.A. (1991): Microseismic emissions from flowslide-type movements in South Wales, Engineering Geology, 31(1), 91–110.

17) Saito, M. (1965): Forecasting the time of occurrence of a slope failure. Proceedings of the 6th International Conference on Soil Mechanics and Foundation Engineering, 2, 537–541.

18) Saito, M. (1987): On application of creep curves to forecast the time of slope failure-in answer to comments upon failure forecasting, Journal of the Japan Landslide Society, 24 (1), 30-38.

19) Smith, A., Dixon, N., Meldrum, P., Haslam, E. and Chambers, J. (2014) Acoustic emission monitoring of a soil slope: comparisons with continuous deformation measurements, Geotechnique Letters, 4(4): 255-261.

20) Irfan, M., Uchimura, T. and Chen, Y.L. (2014): A modified apparatus for laboratory assessment of soil water characteristic curve (SWCC) and associated wave velocities, GeoKANTO-2014, Japan, Tokyo, 1-4.