Development of A Wireless Landslide Monitoring System

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Reference :
Jotisankasa, A., Hunsachainan, N. Kwankeo, N., Chunrod, P. & Mancharoen, J., 2010. Development of a Wireless Landslide Monitoring System. International Conference on Slope 2010 : Geotechnique and Geosynthetics for Slopes, 27-30 July, 2010 Chiangmai, Thailand. organized by the Department of Highways, Thailand (DOH)

Keywords: landslide, slope monitoring, pore water pressure, wireless monitoring

ABSTRACT: This paper reports on development of a wireless landslide monitoring system. The monitoring devices employed consist of rain gauge, piezometers/tensiometers for measuring both positive and negative pore water pressure, as well as inclinometers. Such system can be used to evaluate current safety factor of natural or manmade slopes prone to rainfall-induced failure, as well as to assess the performance of some slope stabilization methods. Commercially available MEMs sensors have been used to fabricate these instruments at Kasetsart University, which means their costs are highly affordable. In order to overcome the difficulties in accessing the instrumented site, innovative wireless data logger has also been developed, based on GPRS and sensor network technology. The first prototype landslide monitoring system of this kind has been installed at Thadan dam, Nakhonnayok province, Thailand. Limit equilibrium and finite element analyses have been used to estimate the early warning criterion for this site based on the values of rainfall, pore water pressure as well as shear strains. Such warnings can thus be issued to communities at risk of landslide or to highway maintenance personnel quickly through the wireless data transfer system.

1 INTRODUCTION

Landslides are one of the most serious natural disasters in Thailand, affecting many infrastructures in the last two decades, such as highways, life-lines, and agricultural lands. Slope failures in Thailand are normally triggered by heavy rainfall (in excess of 100-300 mm/day) and are of various modes, such as shallow failure (with depth of 0.5-2 m), deep-seated slide, rock fall and slides along rock discontinuities. In the events of extremely heavy rainfall, destructive debris flow and flashflood usually took place together with thousands of shallow slides in a very wide area, e.g. ADPC (2006) and Soralump (2009).

The major triggering mechanism of these slides is thus attributed to the increase in pore water pressure due to rain infiltration, which gives rise to decrease in effective stress, shear strength and lastly to the overall instability. Other factors such as deforestation, oversteepening of the slopes, and population settlement in landslide-prone areas all play important roles in increasing landslide risk.

In order to mitigate the risk of landslide, various efforts, such as landslide hazard mapping, slope stabilization and development of early warning system, have been made by many organizations in Thailand such as Dept. of Highway, Dept. of Water Resource, and Dept. of Mineral Resource, etc. Most landslide warning systems installed across the country generally consist mainly of rain gauge (Figure 1), either manual or automatic types (with reading interval of 15min). Although this type of rain gauge-based system is very useful for preliminary warning of the landslide in a large area, it cannot give a precise warning at specific slopes, such as highway slopes, nor will it lead to an in-depth understanding of slope failure mechanism.

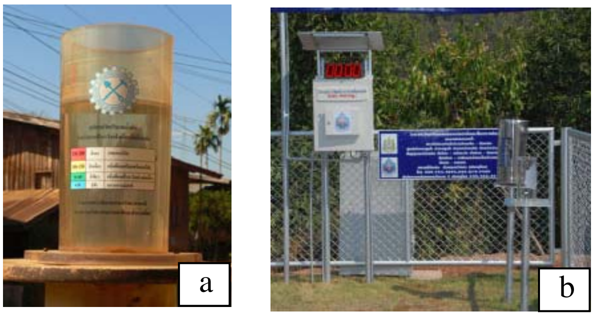

Figure 1: Rain gauge for warning of landslide in Thailand used by Department of Mineral Resource (a) and Department of Water Resource (b)

In order to address this issue, Jotisankasa & Porlila (2008) developed a prototype landslide monitoring system at Kasetsart University (KU), consisting of piezometers/tensiometers, and inclinometers. The system is capable of monitoring the necessary geotechnical parameters required to analyze the stability of slopes. It can then be used as a tool to evaluate a current safety factor of a particular slope, to understand mechanism of the rainfall-induced slope failure, as well as to advance the-state-of-the-art. This paper presents further development of the KU landslide monitoring system in the aspect of wireless data transfer system and some long-term monitoring result from the prototype site at Thadan dam, Nakornnayok province, Thailand.

2 INSTRUMENTATION

2.1 Piezometer/Tensiometer

As mentioned earlier, mechanism of rainfall-induced landslide is fundamentally related to water infiltration and the increase in pore water pressure in the most critical portion of soil slope. For many slopes in the tropics, the soil profile at shallow depth is normally unsaturated and is of negative pore water pressure during most times of the year (e.g. Tsaparas et al., 2003, Jotisankasa et al., 2008). This negative pore water pressure or soil suction gives rise to additional cohesion of the soil which helps to stabilize the slope. Slope instability then starts to take place when there is prolonged and heavy rainfall, which diminishes the soil suction to zero, or even causes positive pore water pressure or a perched water table to rise. In particular, some slopes with a steep gradient (say greater that 45 deg) might fail even when the pore water pressure approaches zero (without necessarily becoming positive) as evidenced by Godt et al., (2009).

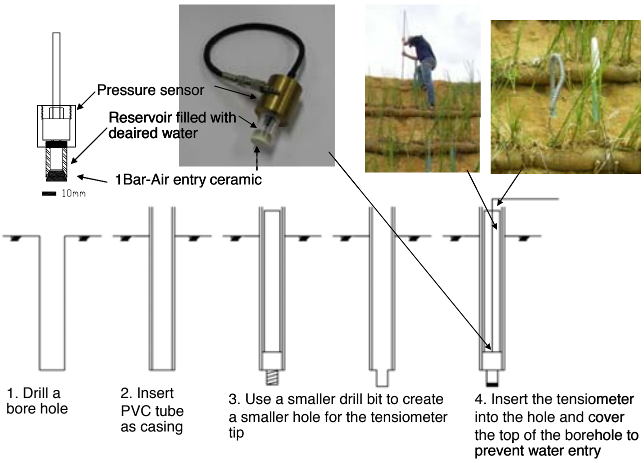

Figure 2: KU-Tensiometer and installation in the field

Consequently, any devices used for monitoring the pore water pressure in tropical slopes should be capable of monitoring both positive and negative values (i.e. devices work as piezometer and tensiometer). At Kasetsart University (KU), Jotisankasa et al., (2007) developed the KU miniature tensiometers using MEMs pressure sensors, as shown in Figure 2. The device is able to measure pore water pressure in the range of -100 to 600 kPa, both in conventional laboratory tests (e.g. Jotisankasa & Mairaing, 2010) and in the field.

Figure 2 shows the installation method of KU tensiometers in the field. It is well known that conventional tensiometers need periodic water saturation and water refilling of the reservoir during dry season so that the tensile stress within soil water is always effectively transferred to the sensor. This is because normally during dry season, air bubbles will start to form within the reservoir of tensiometer and hinder stress-transfer. Based on the authors' experience in Thailand, for the installation depth greater than 1 metre, the frequency of tensiometer water-refilling is only once a year. The common practice is to refill and saturate the tensiometer with water after a dry season, just at the start of rainy season and the tensiometers usually work well for the rest of the rainy season. The field KU-tensiometer can be easily removed from the borehole through the PVC tube, up to the ground, for re-filling with water.

Even though many slopes will destabilize only when pore water pressure goes positive (e.g. Anantasech, 2006, Jotisankasa et al., 2009), it is still important to monitor the negative pore water pressure in the slope. Since the pore water pressure can seasonally alternate between negative and positive value, piezometers with low air entry filter might desaturate easily during dry season and eventually will not response fast enough to the pulse of positive pore water pressure due to heavy rainfall. The use of piezometer with high air entry value filter or the tensiometer is thus required. The value of pore water pressure, which trigger the slope failure (correspond to the slope with Factor of Safety, FS =1), should always be estimated before choosing the device. The first approximation of threshold pore water pressure can be made using the infinite slope equation taking into account both positive and negative pore water pressure as follows.

$$F = \frac{c' + (\gamma \cdot z \cos^2 \beta) \cdot \tan \phi' - u_w \cdot \tan \phi''}{\gamma \cdot z \sin \beta \cdot \cos \beta} \qquad (1)$$

if $F = 1$;

$$u_w^{failure} = \frac{c' + (\gamma \cdot z \cos^2 \beta) \cdot \tan \phi' - \gamma \cdot z \sin \beta \cdot \cos \beta}{\tan \phi''}$$

(2)

where $\phi'' = \phi'$ if $u_w > 0$, and $\phi'' = \phi^b$ if $u_w \le 0$; u_w is pore water pressure, c' is effective cohesion intercept, ϕ' is effective angle of shearing resistance, ϕ^b is angle of shearing due to suction or negative pore water pressure (Fredlund & Rahardjo, 1993) , γ is total unit weight, β is slope gradient, and z is depth of failure.

2.1 Inclinometer

Inclinometers are routinely used for investigating slope behaviour in geotechnical engineering works. Nevertheless, it is sometimes not possible to install inclinometers in as many locations on the slope as one would like, due to limited budget. In this regard, Jotisankasa & Porlila (2008) developed a low-cost inclinometer as shown in Figure 3, using MEMs tiltmeter or accelerometer attached to a PVC tube which is buried to a depth of relatively competent bedrock. Conventional grout is used between the PVC tube and the drilled hole. The differential tilting of the PVC can then be converted to shear strain, γ, as well as the horizontal displacement as usual (Eq. 2).

$$\gamma = \frac{U_x}{U_y} \qquad (2)$$

where U_x is the horizontal displacement and U_y the distance between each tiltmeter sensor along PVC tube. Two tiltmeters are installed at the same position but with opposing sensitivity convention with the purpose of canceling out any sensor drift, as shown in Figure 3. The average of the two readings is then used. The limitation of this prototype inclinometer is its accuracy of shear strain value which is about 0.002. Nevertheless, a far better improvement of its accuracy is possible and underway, given the current rapid development of the MEMs sensor technology.

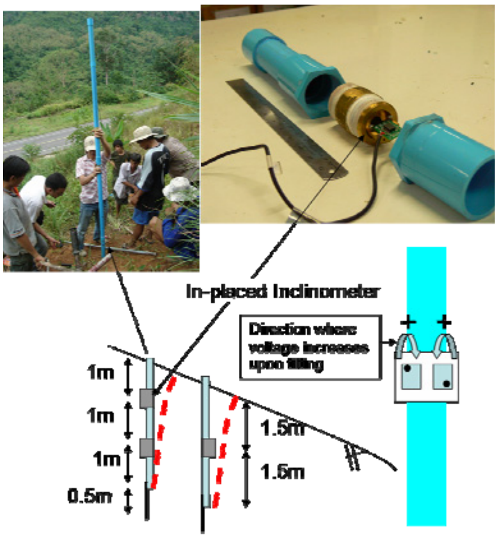

Figure 3: KU-Inclinometer installed at Thadan site

3 WIRELESS DATA LOGGER SYSTEM

The operation principle of the wireless data-logger system is illustrated in Figure 4. One nodal data-logger is assigned to a nest of instruments which can accommodate up to 8 sensors such as tensiometer, piezometer, and inclinometer (Figure 5). The current sampling rate of data-logger is 1 minute per sample. With the storage capacity of 65535 samples, each data-logger can keep the whole continuous data for 45 days.

Each of these nodal data-loggers will transfer the data to the main data-logger with GSM module via 2.4 GHz radio frequency communication. Every 10 minutes, the main data-logger will then connect with a data server at Kasetsart University via General Packet Radio Service (GPRS). If the connection to GPRS network is successful, the main data-logger will upload its data to the server. The server will get the data from data logger via TCP/IP and put all data in text file format, which contain data logger ID number, Date/Month/Year, Time, and voltage of all 8 channels in numerical order as shown in Figure 6. These data can be processed either manually using spreadsheet program or automatically using software, which can show semi-realtime data on-line.

Nevertheless, the communication between the main data-logger and nodal data-logger can be limited by some obstacles such as dense vegetation. In such case, the nodal data-logger needs to be upgraded with a GSM module and operate in the same way as the main data-logger.

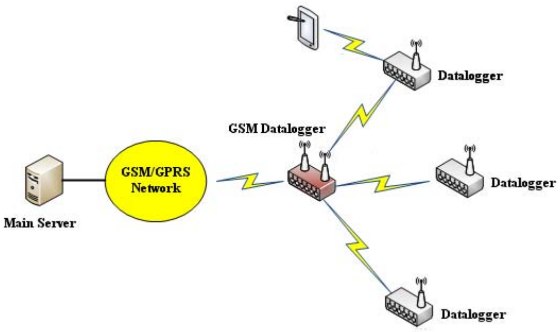

Figure 4: Operation principle of the wireless data-logger system

Figure 5: A data logger assigned to a nest of instruments

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    8494,21/01/00,04:31:37,2.475586,2.406006,2.30102
5,2.073975,2.199707,0.6555176,2.369385,3.394775
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Figure 6: Example of data format in text file

4 MONITORING RESULTS

The prototype monitoring system has been installed since May 2007 in a volcanic slope in Nakornnayok province which failed in 2004 and then regraded as shown in Figure 7. The slope failure of soil mantle down to the bedrock was triggered by an intense rainstorm of about 300mm in three days. The geology in the area of the slope consists of undifferentiated Permo-triassic volcanics rocks, namely rhyolite, andesite, tuffs, and agglomerate. The soil mantle on the slope is about 2-3 metre thick, and classified as medium plasticity silts (MH/ML). The soil slope profile was based on light weight dynamic cone penetration (Kunzelstab) test (Jotisankasa et al., 2009).

Pore water pressure has been monitored at three different locations along the slopes (upper, middle and lower) at various depths from 0.3 to 2.15 metre as shown in Figure 7. Figures 8, 9 & 10 show the annual cyclic variation of the pore water pressure with time. The pore water pressure at the toe of slope appears to be greater and more positive than those in other parts. In generally, the pore water pressure was close to zero during rainy season and at times become positive due to exceptionally heavy rain. In the upper part of slope, the pore water pressure remained negative throughout most of the year and only became positive once the rainfall exceed about 100 mm/day.

The rate at which the pore water pressure decreases during drying season also depends on the depth. The pore water pressure at shallower depth decreases at a much faster rate than those at deeper level. Understandably the surface soil will interact with the atmosphere to a greater extent than the deeper soil, and thus their pore water pressure will fluctuate more.

The wireless datalogger nevertheless was only operating for a period between August until December 2009. Therefore, the preliminary results are provided with the logging interval of 1 minute only during that time, while the daily reading is available for the rest of monitoring period. It can be seen in Figure 10 that the 1minute interval reading of pore water pressure close to the soil surface can capture any sudden pulses of the pore water pressure much better than the 1 day reading interval.

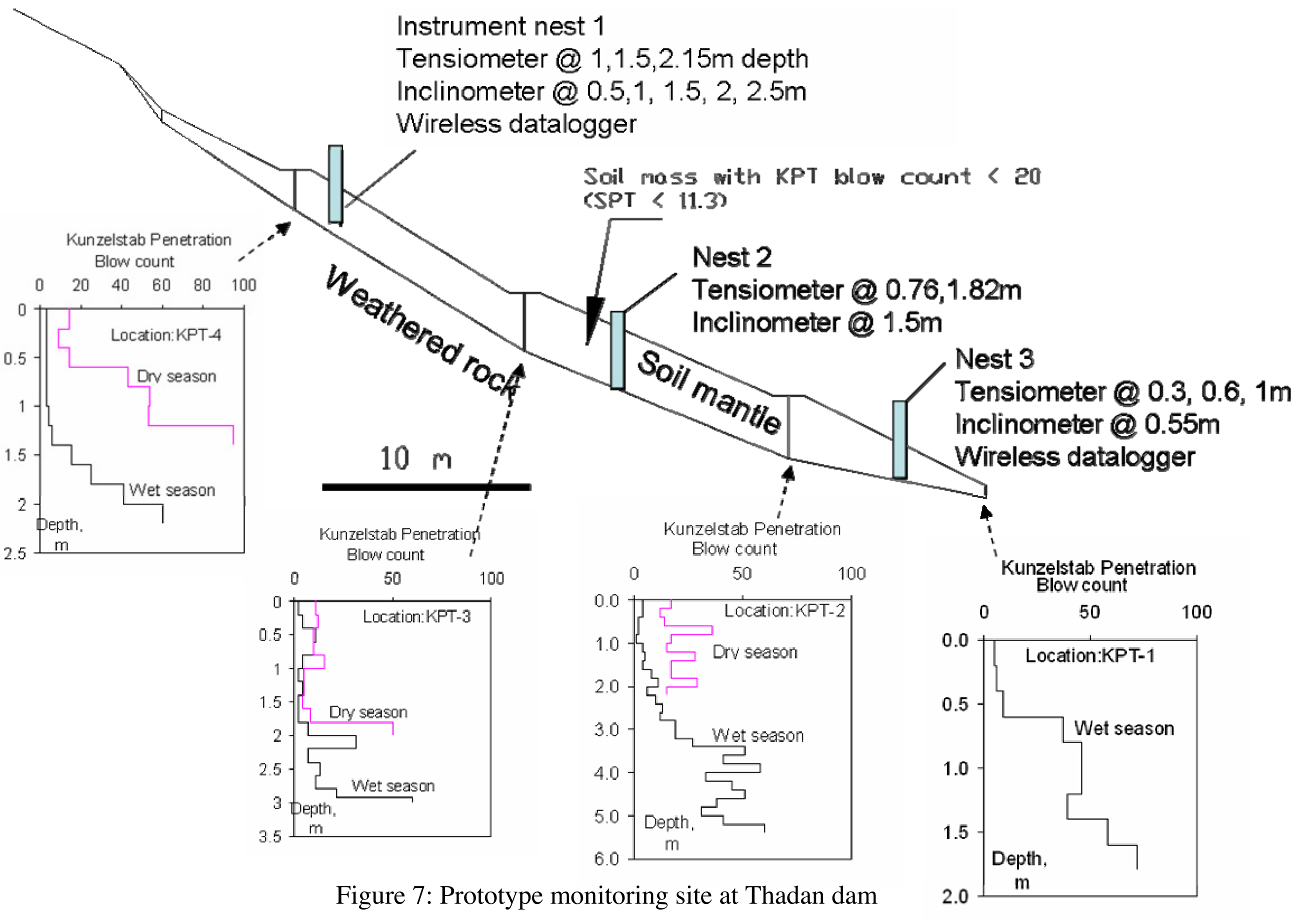

Figure 7: Prototype monitoring site at Thadan dam

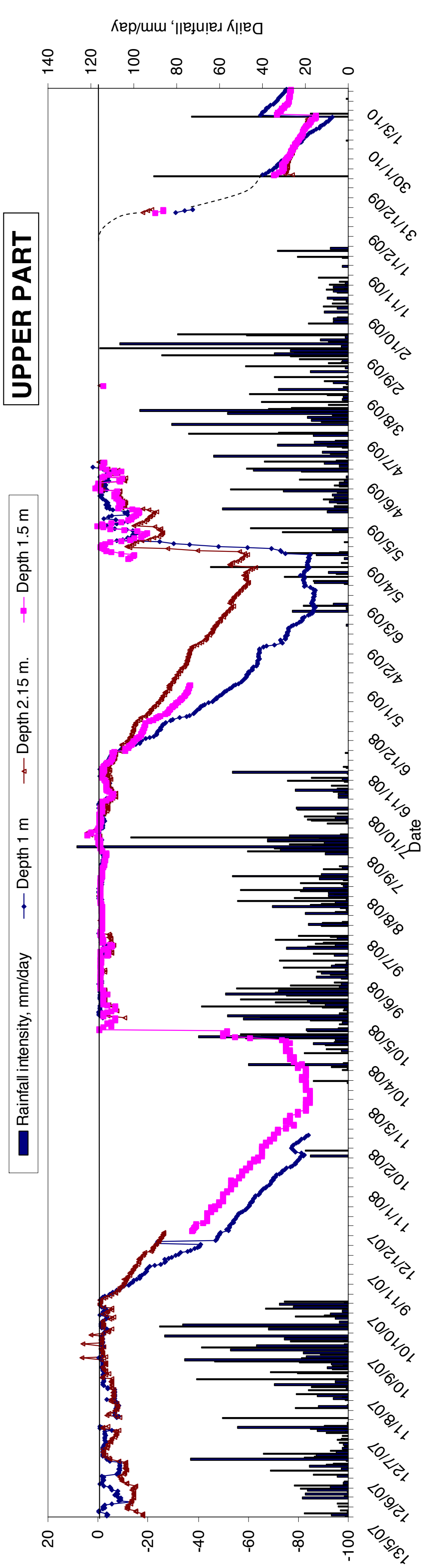

Figure 8: Pore water pressure at nest 1 (upper nest)

Figures 11 and 12 show the contour of total hydraulic head during rainy and dry season, which can be used to approximate the direction of seepage (which is perpendicular to the equipotential line). In this site, side flow along the slope and sub-vertical flow appears to dominate both during dry and wet season. Obviously, a more accurate picture of seepage direction will be obtained if more instruments are installed throughout the slope.

Regarding the deformation, an interesting behaviour was observed during September 2008, as reported by Jotisankasa et al. (2009). As shown in Figure 13, the heavy rainfall during 11/9/08 until 19/9/08 brought about the increase in pore water pressure and corresponding shear deformation in the soil slope. The deformation appear to be elastic, being recoverable after the rainfall stopped and pore water pressure decreased. Jotisankasa et al. (2009) perform numerical analysis using FE code DACSAR in order to simulate such correspondence between the deformation and pore water pressure increase. At depth of 1.35 metre, the shear strain on 19/9/08 was reasonably well captured in the numerical analysis, though the simulated values are only about half the measured values. After successful simulation of the instrumented results, the model was then used to predict the threshold value of shear strain for warning of the slope as will be explained in the following.

5 WARNING CRITERIA

Determination of threshold values for landslide warning has been a subject of extensive research for a long time (e.g. Lumb, 1975, Brand, 1982, Johnson & Sitar, 1990, Abramson et al., 2002, Baum et al., 2008, etc). Three groups of parameters can be used as warning criteria as summarised in Table 1 together with the methods by which these criteria can be calculated. Rainfall is the most convenient parameter for warning of landslide in a large area due to the simplicity of its measurement. Normally the relationship of current rainfall (can be either daily rainfall, hourly or 15 min) and the antecedent rainfall (e.g. accumulated over 3 to 15 days), which represents the state of soil moisture or suction, are required for the warning.

As explained earlier, the FE simulation was also used to predict the value of threshold shear strain for early warning of slope failure (Jotisankasa et al., 2009). In this respect, Limit Equilibrium approach, based on Infinite slope model, as in Equation 2, was also used with the sliding mass having representative gradient of 24^{o} and thickness of 2 metres. The critical value of $r_u = u/(\gamma h)$, when factor of safety becomes 1, is found to be 0.75. This value corresponds to the shear strain of about 0.044 from FE analysis. The value of r_u or pore water pressure and shear strains can be used as an approximate threshold values for early warning of the current landslide monitoring system, in addition to the critical rainfall of 300 mm over three days which was statistically obtained.

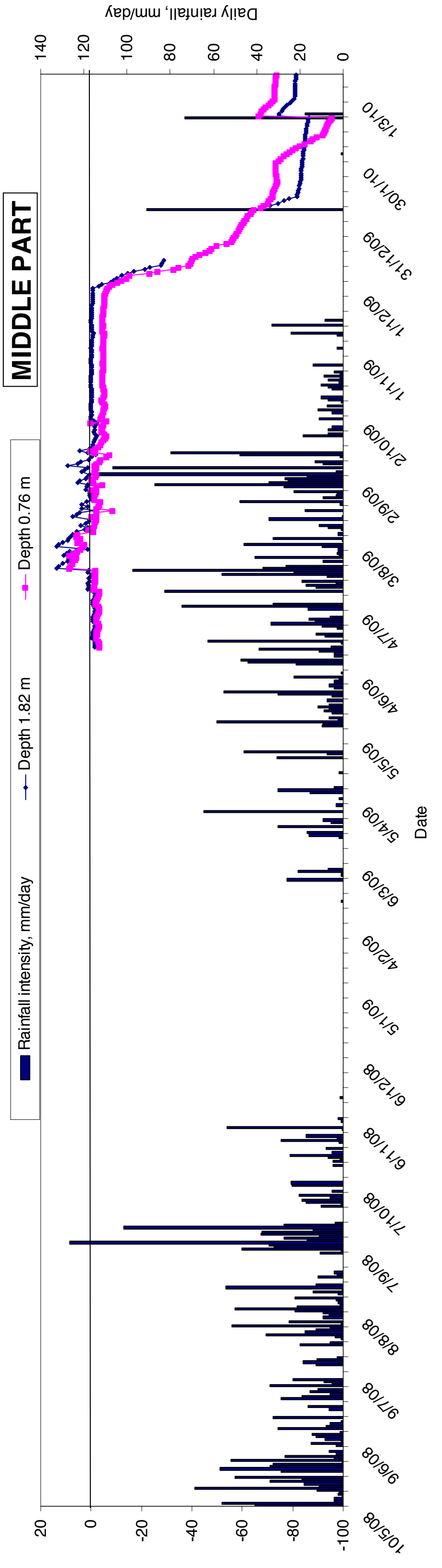

Figure 9: Pore water pressure at nest 2 (middle nest)

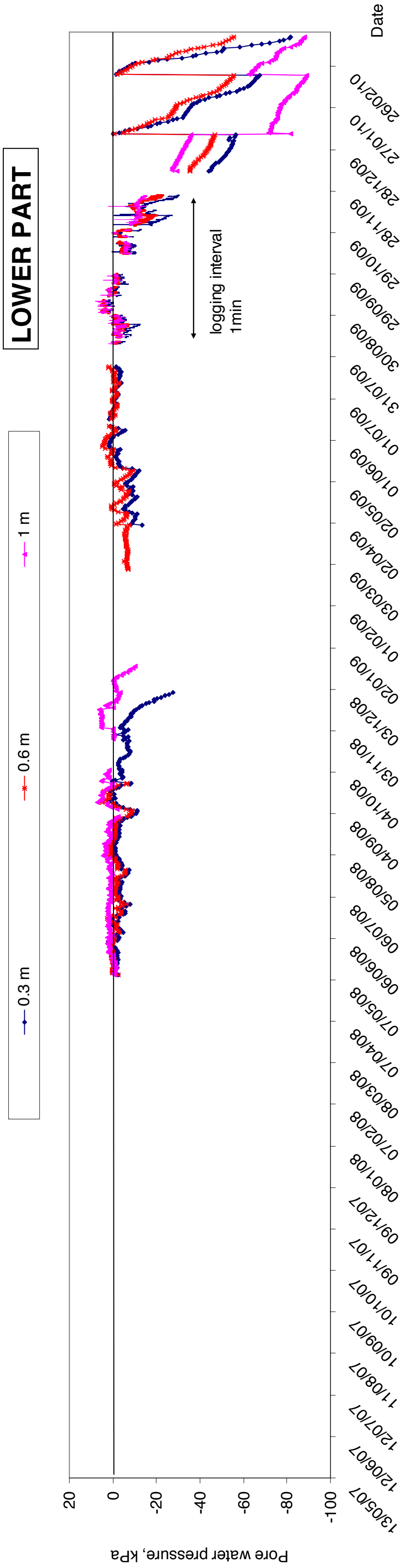

Figure 10: Pore water pressure at nest 3 (lower nest)

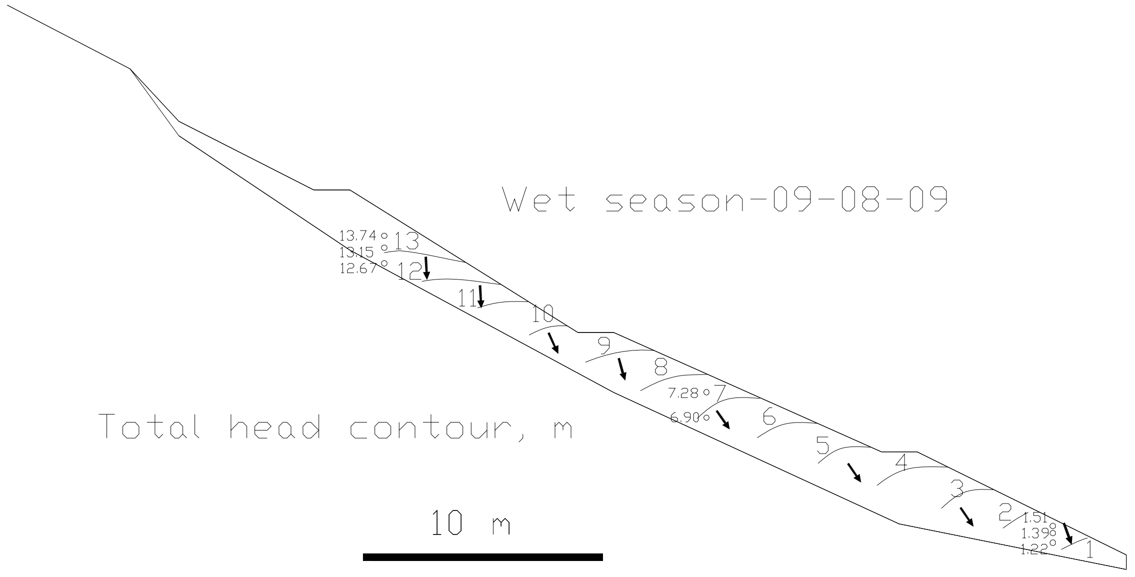

Figure 11: Contour of total hydraulic head and seepage direction during rainy season

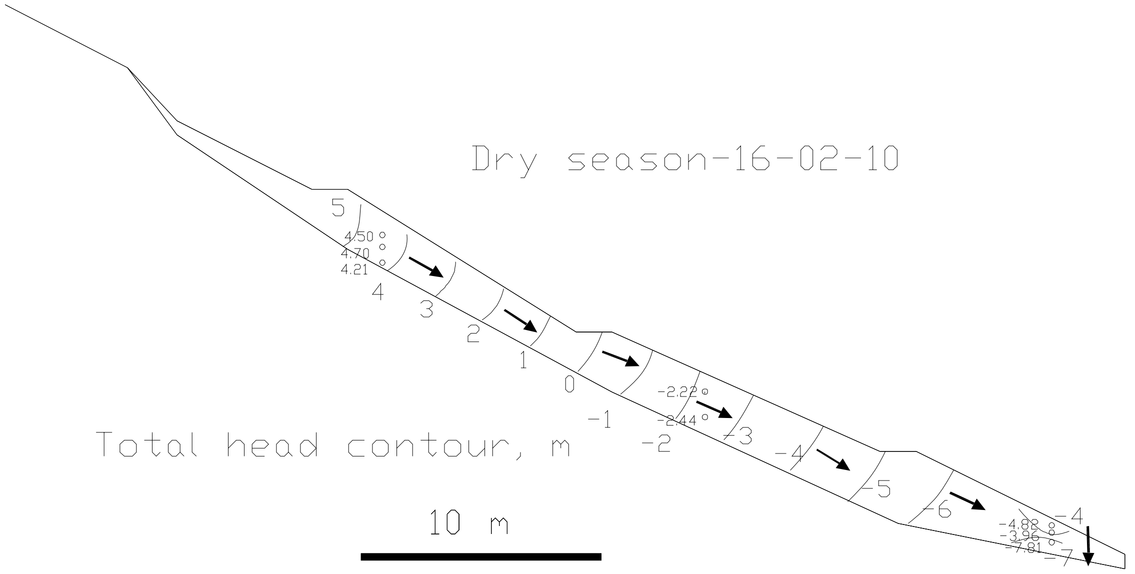

Figure 12: Contour of total hydraulic head and seepage direction during dry season

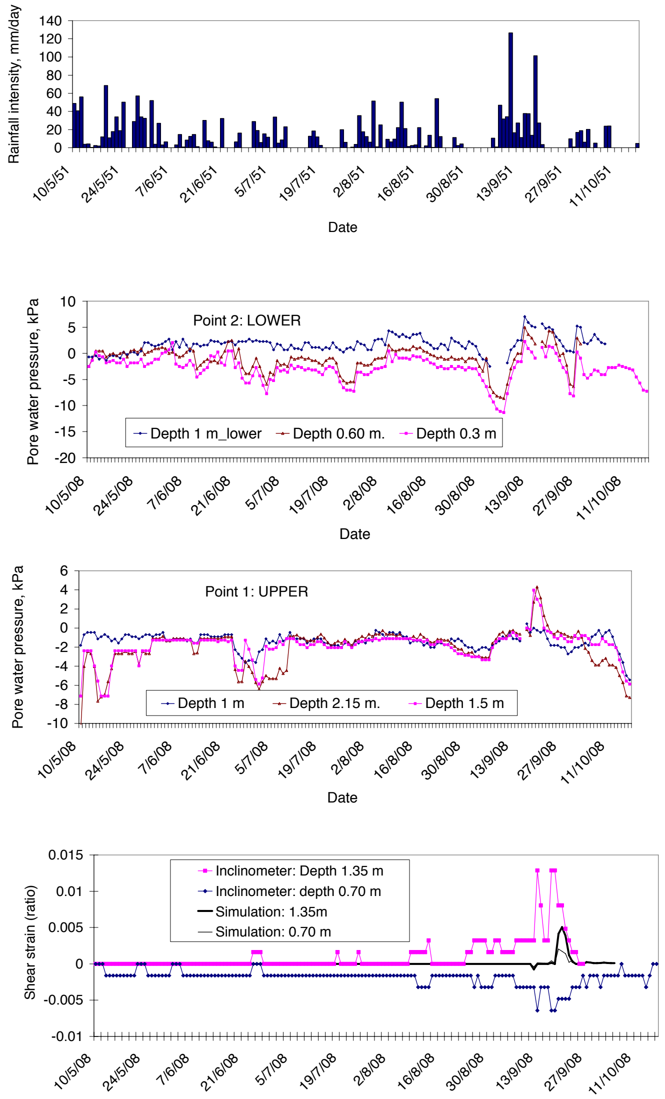

Figure 13: Movement of the slope during heavy rainfall (Jotisankasa et al., 2009)

Since pore water pressure is directly related to the effective stress, it is therefore one of the most direct indicators of slope instability. However, many researchers make use of moisture content as the variable to express unsaturated shear strength and stability of slope. This seems to be more convenient since often there is less maintenance requirement for the moisture content sensor than it is required for the tensiometer. There are however some intrinsic difficulties involved in this approach which is related to the hysteresis of SWCC as illustrated at the Thadan monitoring site in Figure 14. The figure shows soil water characteristic curves determined from volumetric moisture content and suction readings in the field from the toe of slope during wetting and drying periods. For instance, at the volumetric water content of 61%, the pore water pressure varies between -2 and 5 kPa, which corresponds to the range of safety factor from 1.95 to 1.23 respectively (calculated using a simple infinite slope stability analysis as in Equation 1). The measurement of volumetric water content alone thus seems to be inadequate to capture the change of shear strength due to pore water pressure increase and saturation.

Table 1. Criteria commonly used for landslide warning

Parameter	Methods for determining threshold values	Some selected References
Rainfall & Antecedent rainfall	1. Statistical data, Historical record, 2. Estimation from moisture content or suction and soil-water characteristic curve 3. Estimation from numerical infiltration & stability analysis	1. Lumb (1975), Brand (1982) 2. Johnson & sitar (1990), Jotisankasa & Vathananukij (2008), Soralump (2010) 3. Lumb (1975) , Valentino et al. (2009), Mairaing (2010), Baum et al., (2008)
Pore water pressure	Limit equilibrium considering both negative and positive pore water pressure	Millis et al., (2008), Mackay et al., (2008), Jotisankasa et al, (2009)
Shear strain or slope movement	1. Inverse of displacement velocity 2.Deformation analysis, Finite Element method etc	1.Fukuzono, T. (1985) 2.Millis et al., (2008), Jotisankasa et al, (2009)

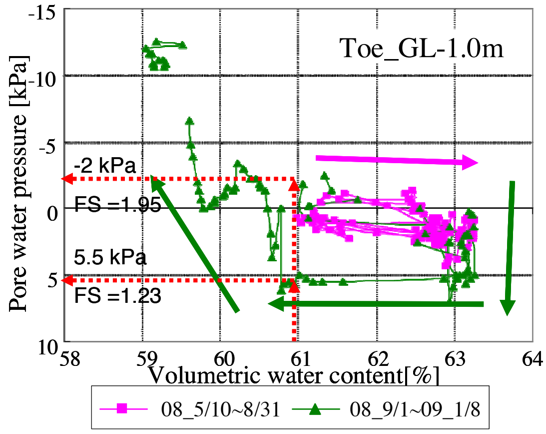

Figure 14: Soil Water Characteristic curves determined in the field at the slope toe, depth of 1 m (modified from Ohtsu et al., 2009, Niimura, 2010)

6 CONCLUSIONS

A prototype landslide monitoring system has been developed at Kasetsart University (KU), consisting of piezometers/tensiometers, and inclinometers together with a wireless logger system. The system was installed at the slope of access rod to Thadan dam, Nakornnayok. The wireless data logger system consists of nodal data-loggers and a main data-logger which connect to a data server at Kasetsart University via General Packet Radio Service

(GPRS). The long term monitoring results show the annual cyclic variation of the pore water pressure with time, where pore water pressure at the slope toe and middle part appears greater and fluctuates more than those in upper parts. The seepage direction, as inferred from total head contours, shows sub-vertical flow and inclined flow down the slope during dry and wet seasons.

The threshold values for landslide warning criteria have been determined in previous works and summarized in this paper including rainfall, pore water pressure and shear strain. Due to hysteresis, there can be various values of suction at the same water content, leading to intrinsic error when estimating the factor of safety from water content alone. The measurement of volumetric water content alone thus seems to be inadequate to capture the change of shear strength for landslide warning purpose. Therefore, the measurement of water content should always be supplemented with the pore water pressure readings for estimation of shear strength.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the research grant no. OR-CHOR 4.51 by the Kasetsart University Research and Development Institute (KURDI). Also gratefully acknowledged is the instruments used for development of wireless data logger provided by the Telecommunications Research and Industrial Development Institute, National Telecommunications Commission.

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