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BEHAVIOUR OF A SOIL SLOPE SUBJECTED TO HEAVY RAINFALL IN THAILAND: MONITORING AND WARNING SYSTEM FOR LANDSLIDES

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Abstract: This paper reports on behaviour of a soil slope subjected to rainfall in Thailand, as monitored using an instrumentation system developed at Kasetsart University as well as their predictions based on DACSAR Finite Element programme. A methodology has been developed to predict the deformation of soil slope based on known pore water pressure distributions. Field monitoring results of pore water pressure and shear strains within the soil slope near Thadan dam, Nakornnayok Thailand have been used to validate such method. The sudden surge of shear strain (1.2%), due to sudden increase of pore water pressure, observed in the slope can be satisfactorily simulated using the FE programme. The programme could be used to estimate the value of shear strain at the measurement point which is expected to occur when the slope starts to undergo overall failure, and be used as an approximate threshold value for early warning system of landslide. In addition, unsaturated shearing behaviour of the material is also investigated using suction monitored direct shear test. The soil-water characteristic curve has also been used tested in order to estimate the amount of rainfall required to saturate the slope which is previously at the field capacity and used as a criterion for landslide. Three types of threshold values, namely rainfall, pore water pressure, and shear strains can finally be used as criteria for landslide warning   system.

Key Words: Landslide, Slope stability, Critical rainfall, Warning system, Deformation

1. INTRODUCTION

Rainfall-induced landslides and debris flow in Thailand have occurred more frequently in the past decades. The disasters caused considerable loss of lives, properties, as well as economies. A number of works have thus been carried out in Thailand in order to mitigate such threats to the infrastructure such as hazard zonation, slope stabilization, development of early warning system (Mairaing, 2008, Jamnongpipatkul et al., 2008, Soralump & Bunpoat, 2006, Jotisankasa & Vathananukij, 2008). The main triggering factor of flash flood and debris flow is the excessive amount of rainfall. In Thailand early warnings will be issued to communities at risk near hill slopes when the daily rainfall exceeds 100-300mm (Department of Mineral Resource, 2004). The warning rainfall amount will be dependent upon such factors as slope gradient, vegetation, as well as geological settings of the area. The rainfall criteria for landslide warning in Thailand are generally based on local

experience and statistics of landslide occurrence.

a)

b)

Figure 1. Photographs of a) numerous shallow landslide/debris flow in Uttaradit, Northern Thailand, 2006 b) Cut slope failure along road ascending Thadan dam, Nakornnayok, 2004 and regraded slope in 2007

Shown in Figure 2 are the rainfall events in Thailand that were observed before major landslides (those involving numerous debris flows) and medium landslides (those involving failure of several cut slopes or highway slopes). Note that a minor localized slide could happen even when there was no rain, provided that the 3 day antecedent rainfall was great enough. This is probably linked to either delayed infiltration or yielding of the material in the slope. A kind of critical rainfall envelope can be constructed and used as a tool for roughly indicating when landslides are likely to occur. The two such lines are approximated in Figure 3 and represent the total rainfalls of 150 mm and 300 mm, over 4-day periods (1 day on the failure day + 3 day antecedent). The -1:1 gradient of the lines implicitly assume that evaporation, and deep percolation are negligible over these 4 day periods. Although these critical rainfall patterns are very useful in providing early warning for landslides, the accuracy of this approach could still be limited. The actual behavior during rainfall of slopes needs to be investigated for more effective landslide monitoring system to be realized. In this regards, Jotisankasa & Porlila (2008) developed a slope monitoring system, consisting of MEMs tensiometer/piezometer for pore water pressure measurement (Jotisankasa et al., 2007) and MEMs inclinometer for shear strains. The prototype monitoring system has been installed since May 2007 in a slope of failed soil

mass (Figure 1b) that had been re-graded in 2004. Slope failure in 2004 was triggered by an intense rainstorm which amounted to about 300mm in three days. The slope is situated in Nakornnayok province, east of the central region, where the geology consists of undifferentiated Permo-triassic volcanics rocks, including rhyolite, andesite, tuffs, and agglomerate (Royal Irrigation Deparment, 2004). The material on the slope is classified as medium plasticity silts (MH/ML) with basic properties summarized in Table 1. Jotisankasa (2008) carried out detailed studies of the material properties including, shear strength-suction relationships, and soil-water characteristic curves. Suction-monitored direct shear tests were also carried out to determine shear strength function for the volcanic soil in unsaturated state. The device used is as shown in Figure 3 and the test results illustrated in Figures 4, 5 & 6.
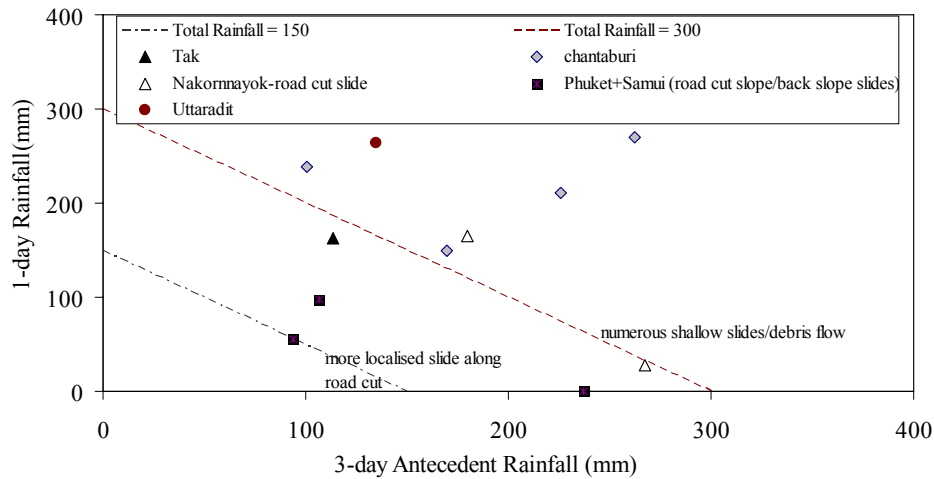

Figure 2. Rainfall patterns leading to landslides in Thailand

Table 1 Basic properties of the material at monitored site

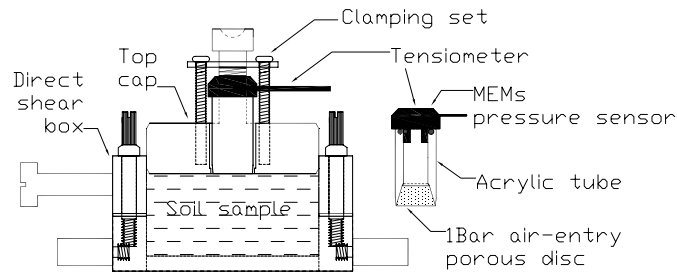| Liquid Limit	Plasticity Index	% gravel	% sand	% silt	% clay	Soil Type
46-51	6-18	0.5-5.5	13.7-18.9	38.9-53.9	31.9-36.7	Silts MH/ML

Figure 3. Experimental set up of suction-monitored direct shear tests and KU-tensiometer
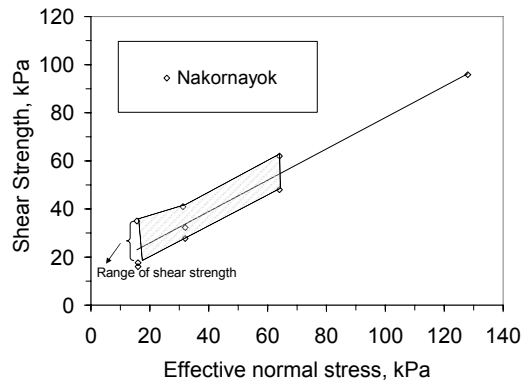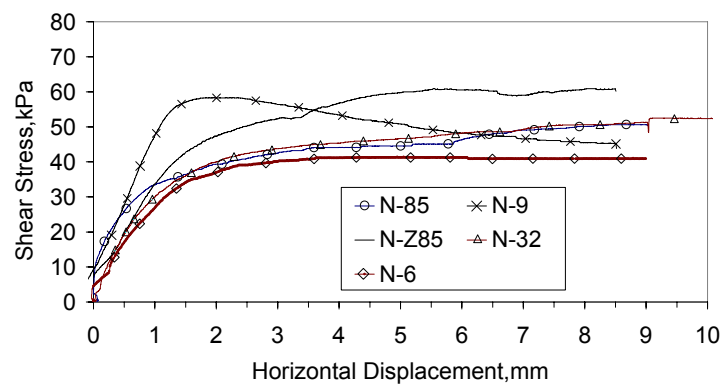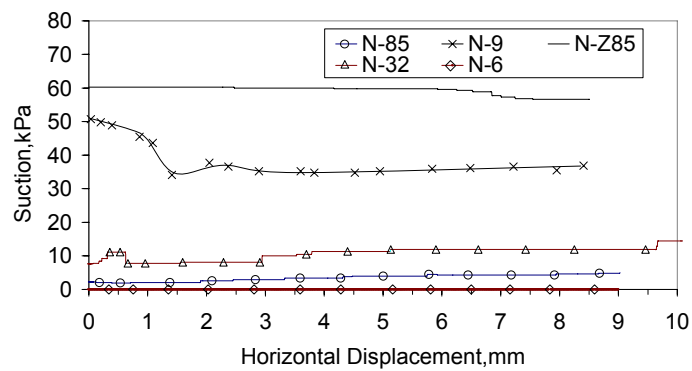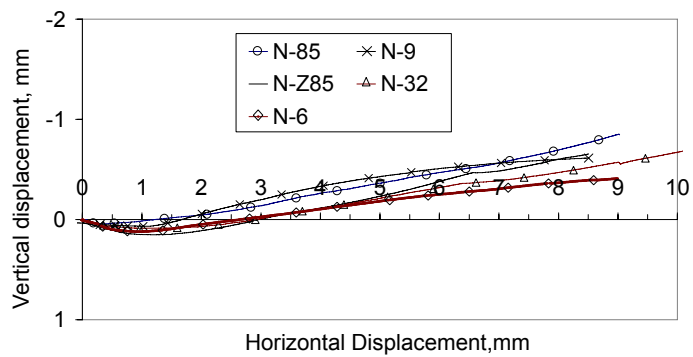
Figure 4. Failure envelope of the silty soil at Nakornnayok site

a)

b)

c)

Figure 5. Shearing behaviour of a volcanic residual soil at different suctions in suction-monitored direct shear box tested at a normal stress of 31 kPa
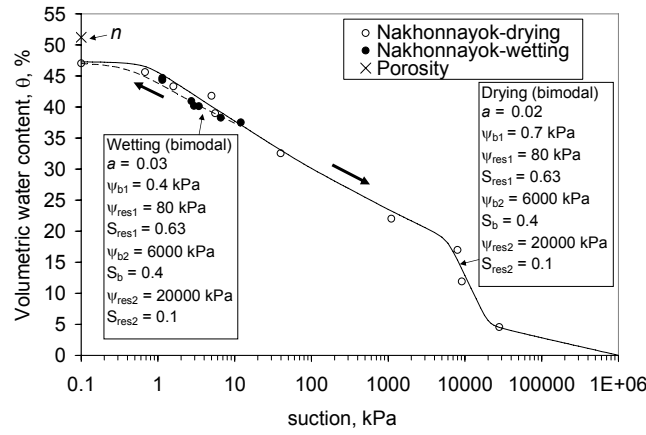
Figure 6 Soil-Water characteristic curve of the volcanic residual soil

Also indicated in Figure 6 are the fitting parameters of the characteristic curve based on Gitirana & Fredlund (2004) model. Equation 1 can be used to describe the shear strength both in unsaturated state as follows.

$$\tau = c' + \sigma \cdot \tan \phi' - u_w \tan \phi^b \tag{1}$$

The shear strength parameters of the silty soil are as follows, $c' = 12.8 \text{kPa}$ $\phi' = 33.1$, $\phi^b = 24.6$. For unsaturated slope the follow equation can be used to estimate the factor of safety of infinite slope.

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

where,

$$\phi^b = \phi' \qquad \text{if } u_w > 0 \qquad \text{(saturated case)} \tag{3a}$$

$$\phi^b = \phi^b \qquad \text{if } u_w \le 0 \qquad \text{(unsaturated case)} \tag{3b}$$

Equation 2 can be used to calculate the real-time values of factor of safety for slope as demonstrated by Jotisankasa & Porlila (2007). As also explained in Jotisankasa & Vathananukij (2008), the total amount of critical rain, R_c, required to saturate the uniform soil slope initially at the field capacity, to a critical depth, D_c, and potentially cause slope failure is as follows,

$$R_c = (\theta_s - \theta_f) \cdot D_c \tag{4}$$

where θ_f is the volumetric water content at field capacity (or suction equals 33 kPa) and θ_s the water content at soaked state, θ_s. The soil-water characteristic curve can thus be used to estimate the amount of critical rainfall used to provide early warning. Based on the values of $(\theta_s - \theta_f)$ in Figure 6 and an average depth of about 2 metres, the critical total rain can be estimated to be 300 mm, which is a good agreement to statistic data in Figure 2. Nevertheless, this value is only an approximate since the rain infiltration and consequent shear strength reduction are complex phenomena which requires much further

investigations before concrete conclusion can be arrived at.

2. MONITORING RESULTS AND NUMERICAL SIMULATION

The finite element mesh of the soil slope profile, shown in Figure 7, has been based on investigation by research students of Kasetsart University using a light weight dynamic penetrometer, so-called Kunzelstab (weight of 10kg, with falling height of 0.5 metre) and a compass-clinometer. It is noted that the mesh only shows the soil mantle, characterized by Kunzelstab blow counts of around 5 or lower (per 0.20 m) (equivalent to SPT blow counts of 3), which has been estimated to be only around 2 to 3 metres in thickness. The sounding tests were carried out during rainy season when pore water pressure in the ground are close to zero (around -2 to 0 kPa). Below the soil mantle lies bedrock of volcanic origin (KPT >20-60), which is assumed to be stationary in the analysis. The freedom of movement is thus disallowed in vertical and horizontal directions for all finite element nodes at the base of soil slope.

The instruments were installed on the slope in two locations as shown in Figure 7. Pore water pressures were monitored using miniature tensiometers developed at Kasetsart University (Jotisankasa et al., 2007). This device is capable of measuring both positive and negative pore water pressure (range of -80 to 600 kPa). The inclinometers were installed at only Point 1 where degrees of tilting have been monitored at depth of 0.7 and 1.35 metre on the side of PVC tube, fixed at the lower end about 0.3 metre into the bedrock. Details of installation procedure for these devices can be found in Jotisankasa et al. (2007) and Jotisankasa & Porlila (2008). Figure 8 shows the overall results of pore water pressure and rainfall over 1.5 year period. The correspondence between the pore water pressure and rainfall is evident, whereby pore water pressure became progressively more negative during the dry season as evapo-transpiration continued without rainfall. During rainy season, however, the pore water pressure became close to zero and at times become positive after intense rainstorm (greater than ~100 mm/day). The degree of tilting from inclinometer remained relatively unchanged until a heavy rainfall (~230mm) in the week of 13-19 September 2008, when the pulses of tilting, as well as surges in pore water pressure were observed. In this respect, Finite Element analysis using DACSAR-M programme (Iizuka & Ohta, 1987, and Takeyama et al., 2006) were performed, based on the monitored pore water pressure values as input data, in order to reproduce the deformation of the soil slope that has been observed in the field. The analysis was also used to predict the shear strains when slope undergoes overall failure and used as a criteria for early warning.
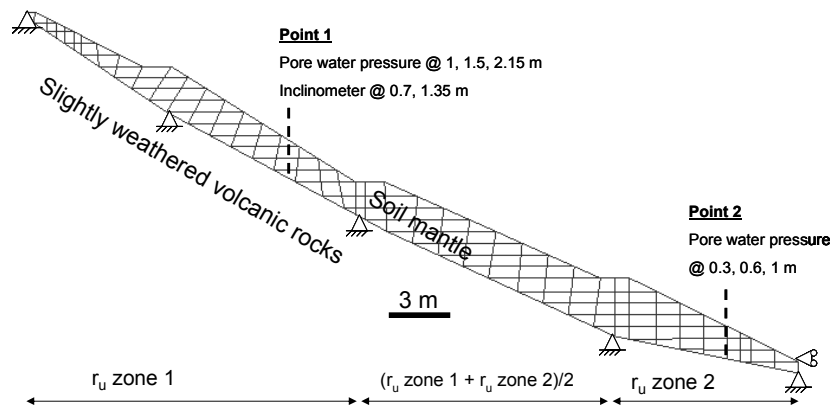

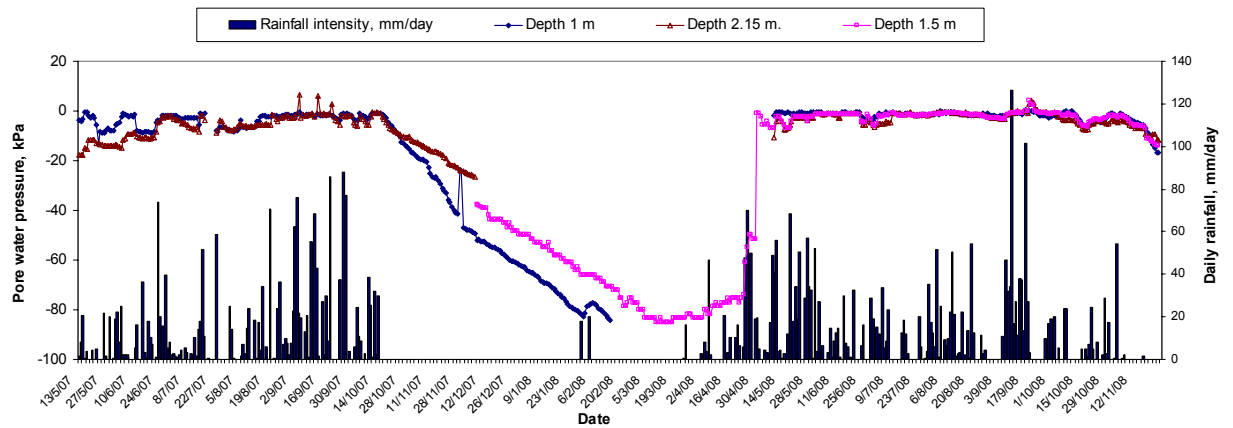Figure 7. Slope profile with meshes, boundary conditions and locations of measurement points

Figure 8. Slope profile with meshes, boundary conditions and locations of measurement points

Table 2 Summary of material properties used in FE analysis

Properties	Values	Properties	Values
Effective cohesion c', kPa	12.8	Young's modulus, E', kPa	299
Effective angle of shearing resistance ϕ', degree	33.1	Poisson ratio, ν'	0.312
Saturated unit weight γ_{sat}, kN/m^3	17.61	Coefficient of earth pressure at rest, K_i	0.454
Permeability k, m/s	2.1 E-4	Initial void ratio, e_i	1.00

The field measurements of rainfall, pore water pressure and inclinometer readings of shear strain as well as simulated shear strains are shown in Figure 8. It is evident that 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. 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. The strains from field measurements at 0.70 m depth appeared to rotate backwards (negative values) on 12/09/08 and were somehow reproduced in the FEM analysis. Yet this backwards rotation shift to positive value as the pore water pressure increased further. The backward rotation was thought to be due to the initial pore water pressure surge at the toe of the slope while the water pressure at the upper part was still relatively unchanged. It is interesting to note that Uchimura et al. (2008) also observed this type of behaviour at ground surface in their instrumented slope model.

Another usefulness of this type of numerical simulation is to predict the value of threshold shear strain for early warning of slope failure (Jotisankasa et al., 2009). An analysis has been carried out whereby the pore water pressure coefficient r_u is increased incrementally in the slope from 0.1 to 0.9. Nevertheless, since the soil is assumed to have true effective cohesion, c' (see Table 2), hence even at relatively high pore water pressure

when r_u = 0.9, the slope did not seem to fail in the FE analysis. In this respect, Limit Equilibrium approach, based on Infinite slope model, as in Equation 2, was used instead with the sliding mass having representative gradient β of 24° and thickness of 2 metres. The critical value of r_u, 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 and shear strains can be used as an approximate threshold values for early warning of the current landslide monitoring system, in addition to critical rainfall of 300 mm as explained previously.
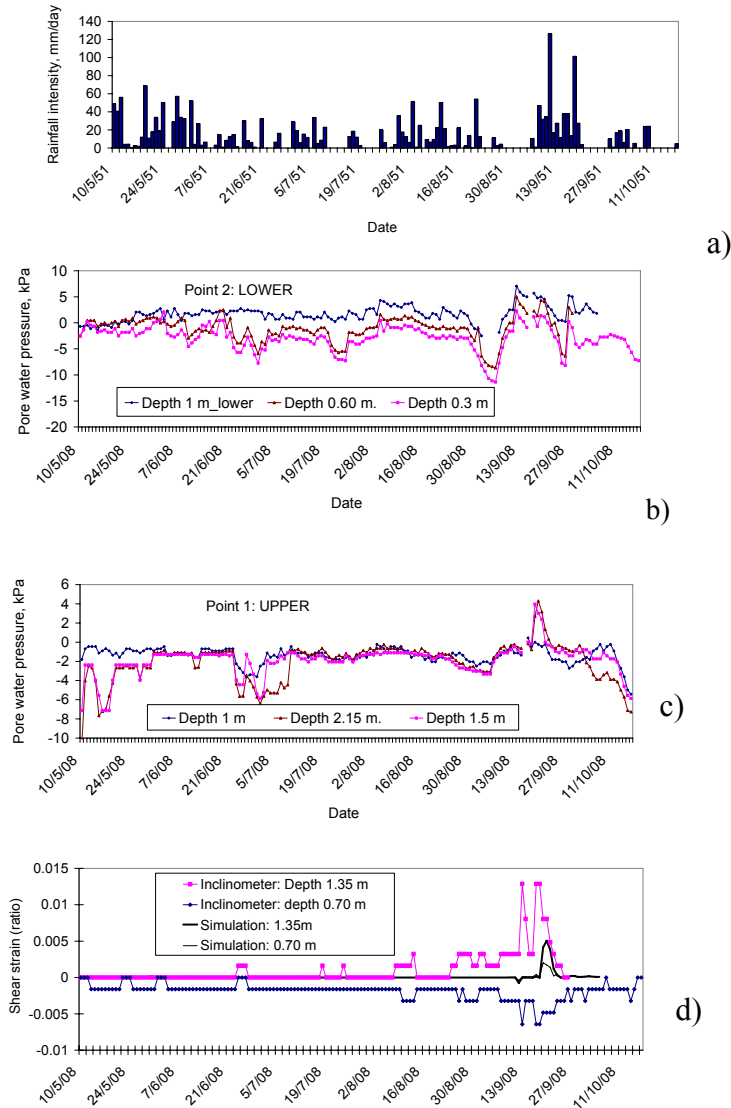

Figure 9 Field measurements of rainfall (a), pore water pressure (b,c) and shear strains from inclinometer and simulation (d)

5. CONCLUSIONS

A slope monitoring system, developed at Kasetsart University consisting of MEMs tensiometer/piezometer for pore water pressure measurement and MEMs inclinometer for shear strains, has been used to monitor behaviour of slope subjected to rainfall from year 2007-2008 in Nakonnayok, Thailand. The pore water pressure appeared to be negative

during dry season, while becoming close to zero during rainy seasons, and at times showing positive values during intense storms. Only during these sudden jumps in positive pore water pressure did the slope start to deform significantly.

Various threshold values can be estimated for landslide warning system at this site. Critical rainfall amount can be estimated from statistic rain data or the soil-water characteristic curve (~300mm). The critical pore water pressure can also be approximated by simple infinite slope analysis (r_u ~ about 0.75) and the threshold shear strain (0.044) can be estimated by stress-strain FE analysis.

6. ACKNOWLEDGEMENTS

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