Dynamic Landslide Warning from Rainfall and Soil Suction Measurement

Warakorn Mairaing
Associate Professor, Civil Engineering Department, Kasetsart University, Jatuchak, Bangkok, Thailand

Santi Thaiyuenwong
Doctoral Student, Civil Engineering Department, Kasetsart University, Jatuchak, Bangkok, Thailand

Reference :
Warakorn Mairaing, Santi Thaiyuenwong, 2010. Dynamic Landslide Warning from Rainfall and Soil Suction Measurement. 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: rainfall triggered landslide, soil suction, infiltration model, stability of slope

ABSTRACT: Landslides due to heavy rainfall are remarkably increased during the last decade. Past recordshows that Thailand had lost in average 15 lives and 105 mbaht annually. The method of prediction and warning can be efficiently analyzed by geotechnical engineering method. The soil sampling and testing of unsaturated characteristics such as SWCC, permeability function, Fredlund's strength model etc. had to be carefully done. Infiltration model during the rain can be predicted and verified by the field observation. Prediction of stability and probability of failure on the target area was applied the GIS and database to obtain the real-time result and presentation on the map. The merit of the model is that when the rainfall data was input continuously to the model the potential landslide area can be shown almost real time after quick calculation. Triggered rain fall chart of 24 hrs triggered and 3 days pre-wetted rainfall can also pre-analyzed in advance for manually warning for specific area without computer system. The case study at Pathong Bay area, Phuket is given as the example for the prediction.

1 INTRODUCTION

In the last decade, landslide triggered by rainfall is one of the major natural disasters that become more important problem in the mountainous area of Thailand. Many people had loss their life and their casualties every year. Estimated value of economic loss from landslide disaster, from both of natural event and human activity, is more than expectation.

Database of landslide occurring during the last 30 years in Thailand were fairly well recorded by Geotechnical Engineering Research and Development Center, Kasetsart University (GERD, 2006) as shown in Figure 1 and Table 1. It can be seen that the landslide occurred mostly in the northern and southern part of the country. From landslide hazard study in Thailand (Soralump, 2007), it's found that the frequency of the landslide event is increasing sharply during the last decade starting from 1996. Figure 2 shows statistic data of landslide events that caused economic loss of greater than 100 million baht. Soralump (2007, 2010) has reported that 2 types of landslides were observed namely the localized or limited area landslides and the large area landslides. More than 95% of limited area landslides are always caused by the disturbance of human activities such as highway slopes, building and agricultural development on hillside which changes the landform or surface and underground water flow characteristics. When the large scale landslides are usually occur on natural slopes due to heavy rain.

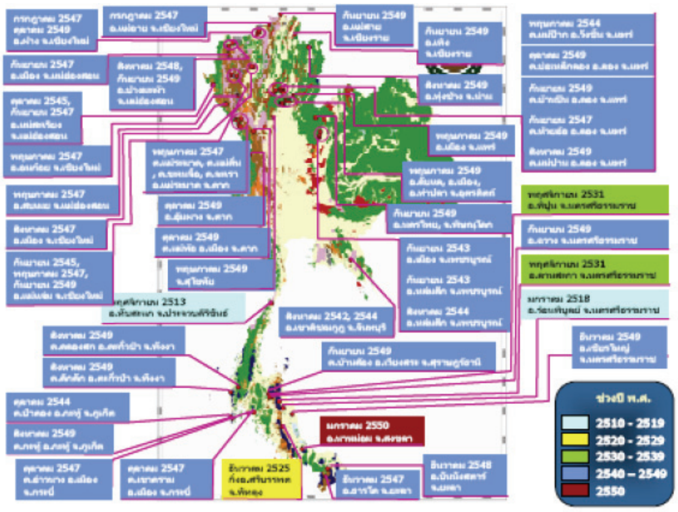


Figure 1: Landslide events in Thailand from 1970-2006 (GERD, 2006).

Behaviors of unsaturated soil on the natural slope and soil shear strength highly depend on water content change due to rainfall. The water content increasing cause decreasing of soil suction in consequence the shear strength is decreased. In mid rainy season, the slope is on marginal stable at the initial state, then landslide is possible due to further loss ofshear strength on the first rain.

Table 1: Landslide Records.

Year	Locations	Live loss
Nov 1970	Tubsakea, Prachubkirikan	12
Jan 1975	Ronpibol, Nakorn Srithumarat	58
Dec 1982	Sibunpot, Pattalung	4
Nov 1988	Pipun, Nakorn Srithumarat	> 200
Nov 1988	Lansaka, Nakorn Srithumarat	12
Aug 1999	Kao-kichakud, Chantabuti	1
Sep 2000	Lumsak-Muang, Phetchabun	> 10
May 2001	Wangchin, Phae	> 30
Aug 2001	Lumsak, Phetchabun	132
May 2004	Mae Ramad, Tak	5
July 2004	Mae Aye, Cheingmai	1
May 2004	Mae Chame, Cheingmai	1
May 2004	Omkoi, Cheingmai	1
Oct 2004	Muang, Krabi	3
May 2006	Muang, Uttradit	71
May 2006	Bangtuk, Sukhothai	7
May 2006	Choehae, Phae	5
Oct 2006	Fang, Cheingmai	8

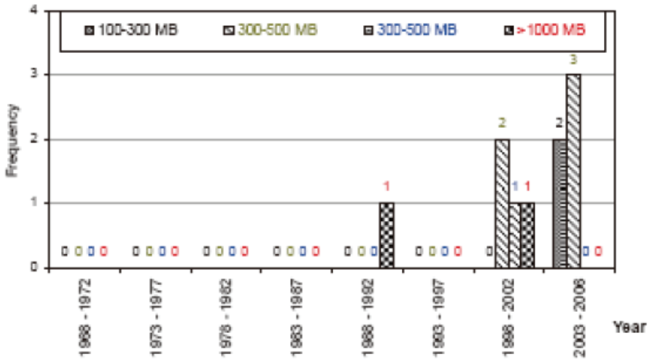


Figure 2: Direct damage greater than 100 million baht from landslide events in Thailand (Soralump, 2007).

For warning, landslide hazard can be predicted from rainfall measuring data. This method is used in many countries. For example, landslide research in Hong Kong (Lumb, 1975 and Brand, 1985) has shown the relationship between landslides and triggering rainfalls. In Thailand, this concept was attempted but due to the lack of landslide inventories and rainfall records make it difficult to study.

2 SOIL-WATER RELATIONSHIP CHANGE BY RAINFALL

Abramson et al. (1996) divided natural soil into 2 zones according to water contained in void of soil mass as illustrated in Figure 3. First is saturated zone below the water table and second is unsaturated zone above water table. In the unsaturated zone void is contained with air and water, pore pressure lower than atmospheric pressure (negative) called matric suction. Generally matric suction is increased with the distance from water table.

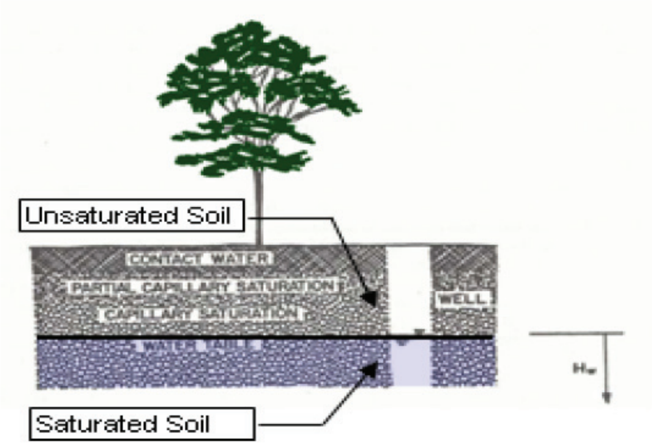


Figure 3: Water zone in soil mass (Dunn et al., 1980).

During the year, the water content in unsaturated soil is not constant due to climate change such as rainfall. Figure 4 shows when rain infiltrate into soil layer, water content increases and cause the matric suction to decrease graduately. The relation between water content and matric suction is called soil-water characteristic curve(SWCC). The level of matric suction also relate to the hydraulic conductivity of soil called "permeability function" (Fredlund et al., 1997) as shown in Figure 5.

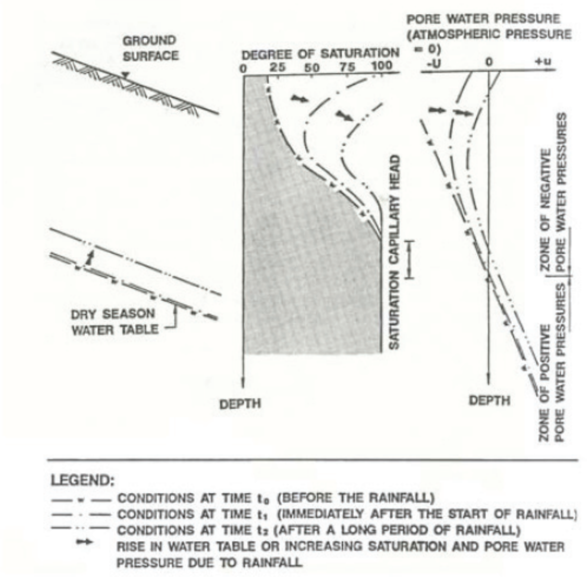


Figure 4: Typical change in water table, degree of saturation (S) and pore water pressure (μ) are due to rainfall (Geotechnical Control Office, 1984).

Mairaing et al. (2006) studied landslide behavior on mountainous area around Kamala bay, tourist point on Phuket Island, as shown in figure 6. It was the first study that automatic rain gauge and tensiometer were installed in the observation well for water content change monitoring as related to rainfall (Figures 7 and 8). Unsaturated soil behavior was monitored from year 2006 to 2007. The result can be shown in Figure 9. Rainfall intensity was measured by automatic rain gauge and record by data logger. Water content was determined by field sampling and laboratory testing. And matric suction was measured by tensiometer manually. From the study we found that water content and matric suction were changed relatively by rainfall. On the upper soil layer is more sensitive to rainfall than lower layer. The matric suction on the second year is not sensitive to the amount of rainfall because of improper de-airing.

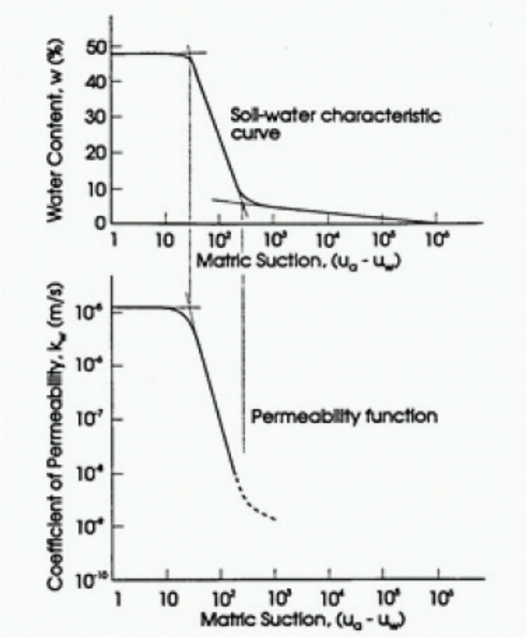


Figure 5: Soil-water characteristic curve and permeability function (Fredlund *et al.*, 1997).

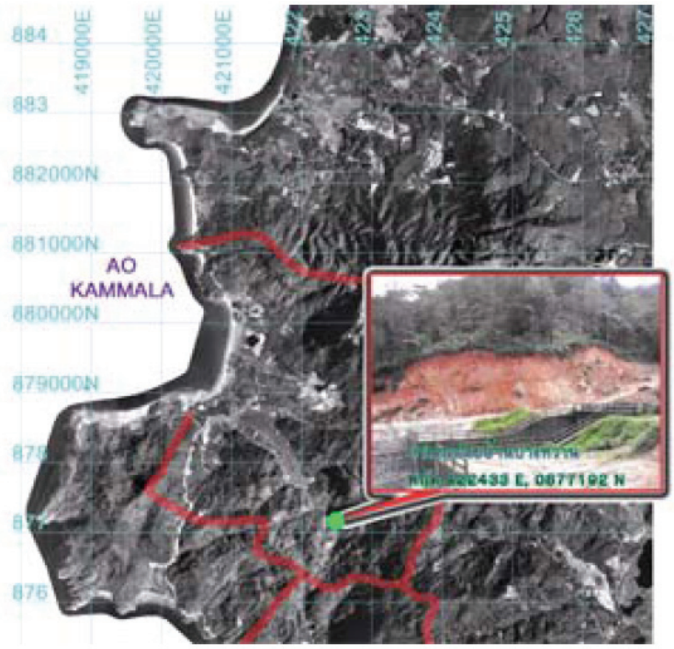


Figure 6: Study area at Kamala bay, Phuket Island, Thailand. (Mairaing *et al.*, 2006).

Figure 7: Tensiometer installation. (Mairaing et al., 2006).

Figure 8: Automatic rain gauge. (Mairaing et al., 2006).

3 SHEAR STRENGTH OF UNSATURATED SOIL

Fredlund et al. (1973) propose to modify the classical Mohr-Coulomb's Equation for unsaturated soil as shown on Equation 1. The strength envelope can be illustrated by 3-D Strength surface as on Figure 10.

$$\tau = c' + (\sigma_n - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b \tag{1}$$

where c' = effective cohesion at saturated condition

u_a = pore air pressure

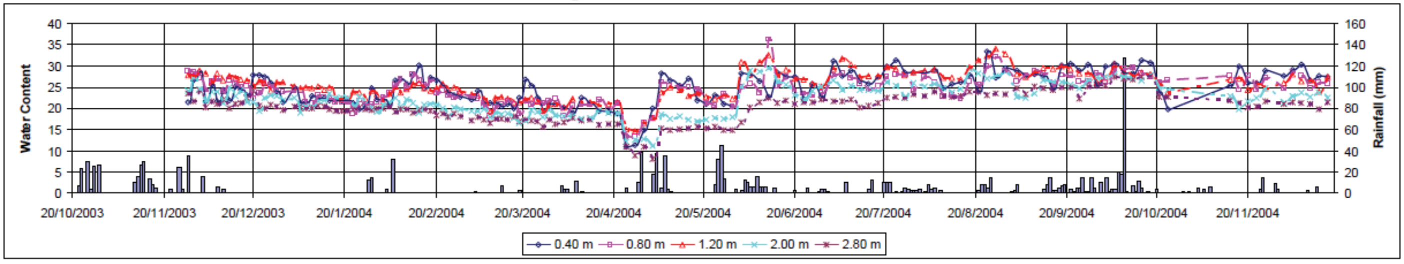
$\sigma_n - u_a$ = net normal stress

$u_a - u_w$ = matric suction

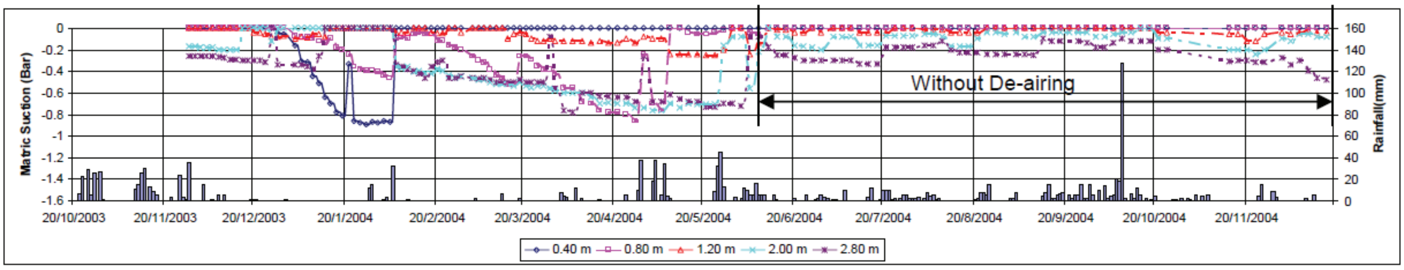
ϕ' = effective angle of internal friction

ϕ^b = angle of increase rate of strength due to suction

Shear strength can be tested in laboratory for the limited number of sample, the multi-stage direct shear test (KU-MDS) was used to minimize the



a. Water content changing



b. Matric suction changing

Figure 9: Record of water content and matric suction changing related rainfall (Mairaing *et al*., 2006).

testing sample (Mairaing, 2008). Only one soil sample of the specified moisture content was applied the initial normal stress close to existing overburden pressure. Then the sample was sheared until approach failure, the first stage was then stop. The higher normal stresses were applied and repeated the shearing process on the similar manner until full envelope obtained . The discrepancy was about 3-5 % on the conservative side of the conventional direct shear test. The typical results from multistage direct shear test with moisture content variation are as shown on Figures11 and 12.

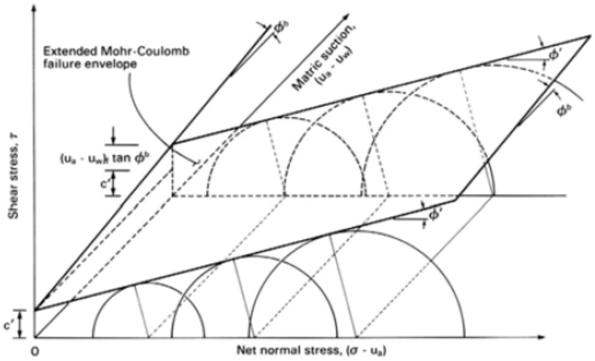


Figure 10: Extended Mohr-Coulomb Envelope for Unsaturated Soil (Fredlund, and Rahardjo, 1993).

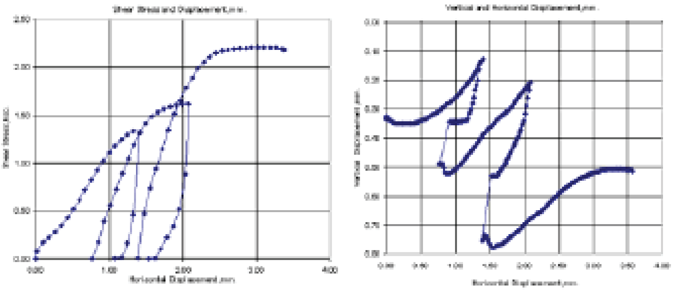


Figure 11: Stress-strain from multi-stage direct shear test (Mairaing, 2008).

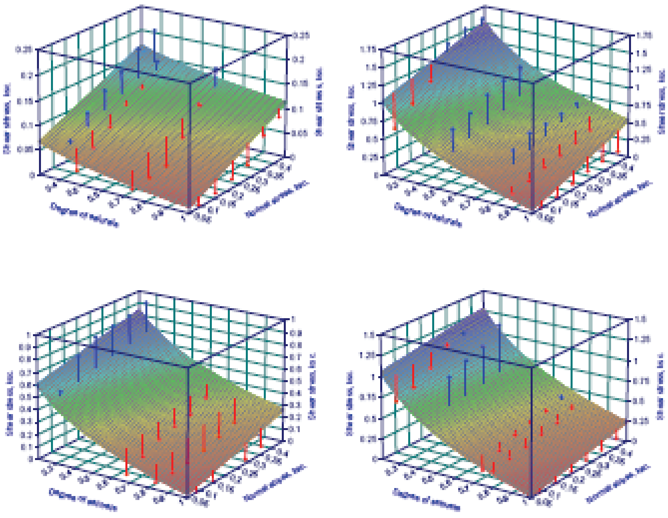


Figure 12: Results from Multistage Direct Shear Test.

4 SOIL MOISTURE CHANGE DUE TO RAIN INFILTRATION

From preliminary analysis of long slope on the relative pervious underlying rock, it is reveal that the vertical flow is dominated. Thus flow regime of rain-infiltration through unsaturated soil can be explained by simple vertical 1-d flow of water as shown in Figure 13. This flow through soil is unsteady flow thus the velocity is varied. The water content is not constant through the depth depending on elapsed time as shown in Equation 2. Change of water content through soil layer, could be calculated from the flow model with emphasized on potential failure zone. The rainfall patterns are also the factor affecting infiltration regime.

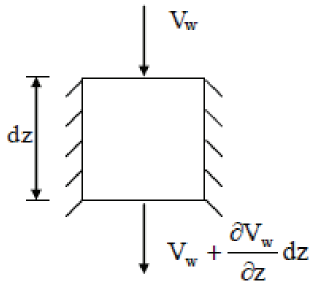


Figure 13: Vertical 1-d unsteady flow model.

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} K \frac{\partial H}{\partial z} \tag{2}$$

where θ = Volumetric water content (V/V)
t = Time (T)
z = Distance (L)
K = Hydraulic conductivity (L/T)
H = Total hydraulic head (L)

5 LANDSLIDE HAZARD ANALYSIS

Landslide hazard triggered by rainfall can be assessed by various methods (Mairaing and Thaiyuenwong, 2007). One is geotechnical engineering method which landslide hazard is considered from slope stability analysis.

For large extended area, slope stability is analyzed by using infinite slope model (Abramson et. al., 1996), which conceptual is shown in Figure 14 and Eqation 3. The analysis is performed by considering unsaturated soil behavior in which the shear strength relate to normal stress and matrix suction as shown in Equation 1 and Figure 10. For deterministic approach, landslide hazard is shown in term of safety factor (FS) which can be changed related to rainfall. For probabilistic approach, landslide hazard is probability of slope failure (P_f) that can be estimated from uncertainty of parameter in difference water content.

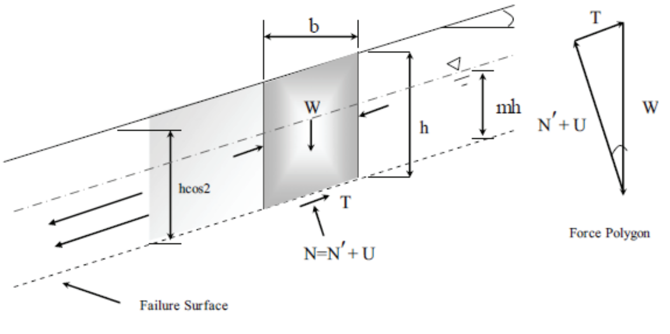


Figure 14: Infinite slop stability analysis model.

$$FS = \frac{c' + h\cos^2\beta \tan\phi' \left[(1-m)\gamma_m + m\gamma' \right]}{h \sin\beta \cos\beta \left[(1-m)\gamma_m + m\gamma_{sat} \right]} \tag{3}$$

where c' = Effective cohesion strength
h = Depth of failure plane
β = Slope Angle
ϕ' = Effective internal friction
m = Height of water table above failure plane and Depth of failure plane ratio
γ_m = Moist density
γ' = Soil buoyant density $(\gamma_{sat} - \gamma_w)$
γ_{sat} = Saturated density
γ_w = Water density

6 DYNAMIC LANDSLIDE HAZARD PREDICTION

Figure 15 illustrate procedure of dynamic landslide hazard prediction due to non-uniform rainfall. The result is FS or P_f relate to rainfall. Volume of rainfall triggering landslide is divided into 2 parts. First is cumulative antecedent rainfall for 3 to 15 days earlier and present observed rainfall for 1 day or 24 hrs of rain storm which is the trigger rainfall before landslide is occurred. These pair of rainfall is plotted on critical triggering rainfall envelope.

For example case study in Hong Kong (Lumb, 1975), the critical triggering rainfall chart is shown in Figure 16. landslide-rainfall triggering relationship came from landslide the past events. X-axis is 15- days antecedence rainfall and y-axis is the last 1-day rainfall before landslide. In Thailand, Mairaing et al. (2006) estimated critical rainfall from prior rainfall data for the event in 1998 at Nakhon Si Thammarat and Suratthani on south Thailand as shown in Figure 17. Mairaing and Thaiyuenwong (2007) produced critical triggering rainfall chart for landslide prediction on Phuket Area as shown in Figure 18. Relationship between landslide hazard level and rainfall came from analysis. The cumulative rainfall within 4-days duration was divided into 3-days antecedence rainfall before prediction and 24-hr. expected rainfall. The relationship between both of amount of rainfall can create the warning level chart. In each point has a value of probability of landslide. The interval of probability was defined from the rainfall chart.

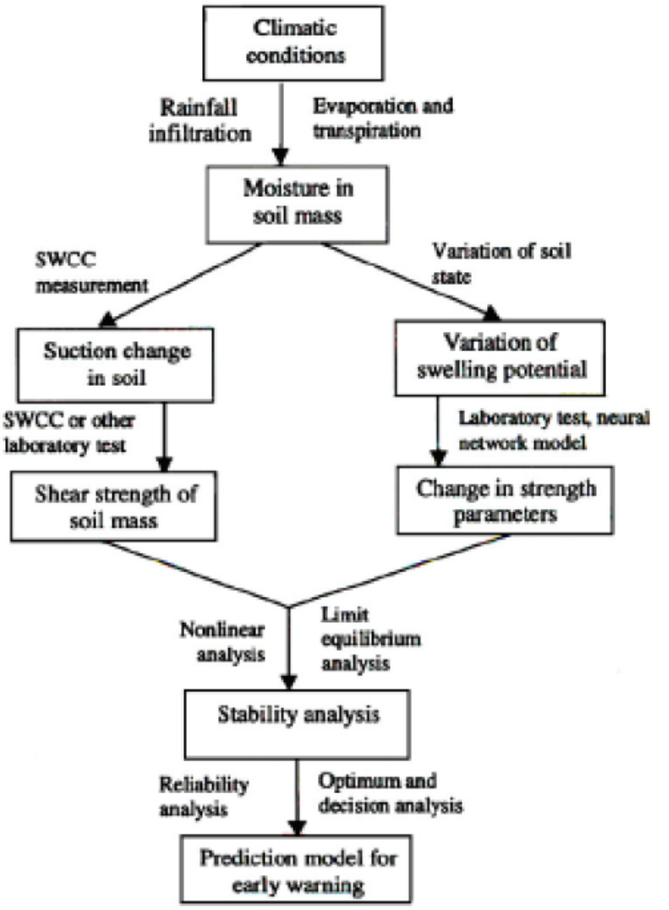


Figure 15: Geotechnical Engineering Method for Landslide Prediction and Warning.

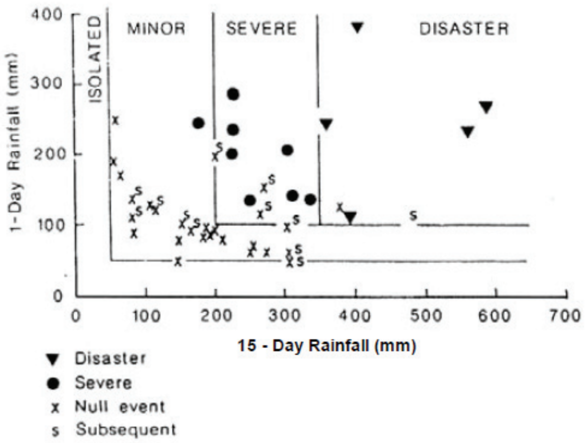


Figure 16: Relationship between rainfall and landslide in Hong Kong (Lumb, 1975).

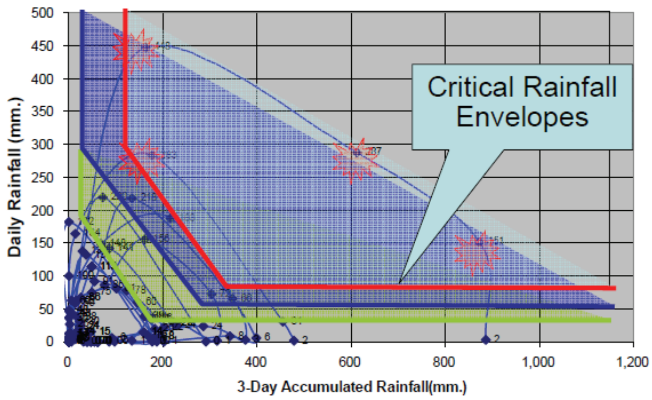
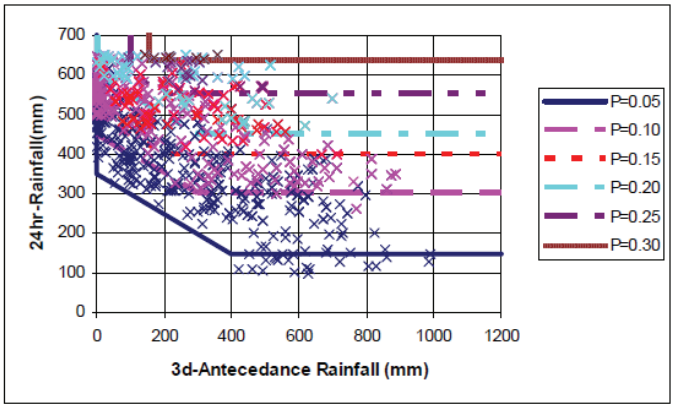


Figure 17: Critical rainfall in southern Thailand in 1998 (Mairaing et al., 2006)



Note: P is Probability of landslide occuring

Figure 18 Relationship between probability of landslide and rainfall (Mairaing and Thaiyuenwong 2007).

During the prediction process, landslide hazard will be calculated from relationship between probability of landslide and rainfall input data in each sub-area. The result will be distributed over the target area as map by using GIS technique. This map is dynamic map that landslide hazard can be recalculated from new rainfall input data and map can show the probability of failure automatically.

By using GIS, the target area was classified to sub-area by landslide causal factors such as geology, slope angles and land use as shown in Figure 19. This information is very important to preset in advance as static parameters for calculation of Factor of Safety(F.S.) and Probability of Failure (P_f) whenever the rainfall as dynamic data input to the model. Database of landslide hazard level related to 3-days antecedence and 24 hr. rainfall was stored in GIS database. For convenience in prediction of end user, data input dialog box and automatic calculation was prepared by GIS process control script code writing as shown in Figure 20. After in put new rainfall data, the probability of landslide in each sub-area was calculated and generated over entire target area.

For example, landslide prediction on 3 days rainfall was performed on the mountainous area of Patong Bay area, west coast of Phuket Island. The input of rainfall data by using GIS can be shown in Figure 19. Daily rainfall data are 300, 400 and 500 mm. respectively. Landslide hazard in the first day with 3-days antecedence rainfall is 100 mm. and 24 hr. estimated rainfall is 200 mm. show almost no landslide area in figure 21a. For the second day with 3-days antecedence rainfall is 300 mm. and 24 hr. estimated rainfall is 400 mm., the landslide area increased as shown in Figure 21b. And the third day with 3-days antecedence rainfall is 700 mm. and 24 hr. estimated rainfall is 500 mm., the large areas of landslide expanded as shown in figure 21c. By using these maps showing the possible failure area, it can provide the local administrator the information for proper warning procedure. For the specific area that extended past rainfall and landslide records are available, pre-analyses of landslide warning chart can be established in advance as shown on Figures 17 and 18. This chart is useful for warning to the area where the computer and GIS system is not available.

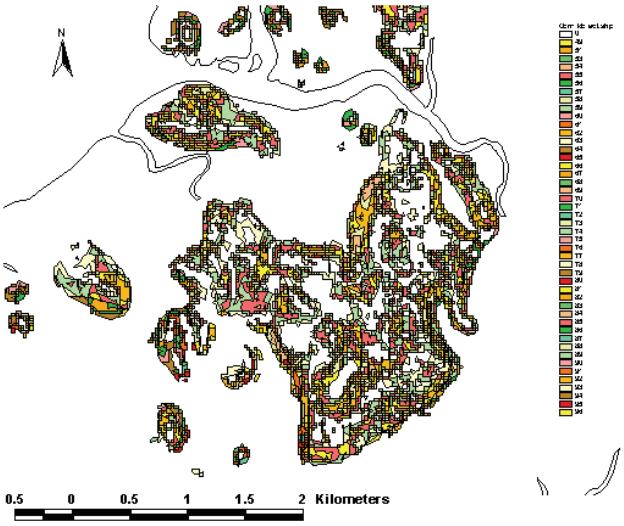


Figure 19: The example of sub-area classification by causal factors.

	3D Ra	24hr Ri
Station 564001	300.00	600.00
Station 564201	400.00	300.00

Figure 20: Rainfall data input by using GIS. (Mairaing and Thaiyuenwong 2007).

7 CONCLUSION

Rainfall-triggered Landslide in Thailand is increased remarkably during the last decade due to the change of land-use and climate. It can be predicted in systematic way by using geotechnical method and real-time rainfall data. However the extensive studies of soil unsaturated characteristic both infiltration and strength during the heavy rain had to be done. The analysis model of the large area for factor of safety and probability of failure needs GIS technique for calculation and presentation of the results. Pre-stored parameters and the real time rainfall information are the key data to the calculating model. The results can be the dynamic probability mapping showing the critical area during rain storm or the pre- analysis map for the local authority to issue the proper warning. The results for analysis and field monitoring at Pathong Bay Area, Phuket give the valuable information on prediction and calibration of the infiltration model. Potential uses of this warning system was extended to other area in Thailand such as Doi Tung and Uttraradit, northern of Thailand.

a. Probability of landslide due to 100 mm. of 3-days antecedence rainfall and 200 mm. of 24 hr. estimated rainfall.

b. Probability of landslide due to 300 mm. of 3-days antecedence rainfall and 400 mm. of 24 hr. estimated rainfall

c. Probability of landslide due to 700 mm. of 3-days antecedence rainfall and 500 mm. of 24 hr. estimated rainfall

Figure 21: Example of landslide prediction over the target area by using GIS. (Mairaing and Thaiyuenwong 2007).

REFERENCES

Abramson, W.L., L.S. Thomas, S. Sunil and B.M. Glenn. 1996. Slope stability and stabilization method. John Wiley & Sons, Inc., New York.

Brand, E.W., and H.B. Phillipson. 1985. Review of International Practice for Sampling and Testing of Residual Soils. In Sampling and Testing of Soil (E.W. Brand and H.B. Phillipson, eds.), Scorpion Press, Hong Kong, pp. 7-21.

Dunn, I.S., L.R. Anderson and F.W. Kiefer. 1980. Fundamentals of geotechnical analysis. John Wiley & Sons, Inc., New York.

Fredlund, D.G. and H. Rahardjo, 1993. Soil mechanics for unsaturated soil, New York: Wiley.

Fredlund, M.D., G.W. Wilson and D.G. Fredlund. 1997. Indirect Procedures to determine unsaturated soil property functions. Proceeding of the 50th Canadian Conference, Ottawa, Ontario, Canada.

Geotechnical Control Office. 1984. Geotechnical manual for slopes, 2nd ed. Hong Kong: Civil engineering service department.

Geotechnical Engineering Research and Development Center (GERD), 2006, "Landslide data base of Thailand"

Lumb, P. 1975. Slope Failures in Hong Kong. Quarterly Journal of Engineering Geology, GeologicalSocity of London, Vol. 8, pp. 31-55.

Mairiang W. 2008. Landslide Problems and Warning by Geotechnical Methods, CAFEO26 (26th Conference of the ASEAN Federation of Engineering Organization). Sofitel Centara Grand Hotel, Thailand.

Mairiang, W., S. Thaiyuenwong. 2007, Landslide hazard zoning map by dynamic factors in Andaman coastal area of Thailand. Thailand Research Fund (TRF).

Mairiang W., K Chantawarangul, T. Konksomboon and S.Soralump. 2006. A study of landslide behavior in Phuket province. Thailand Research Fund (TRF).

Soralump, S. 2007. Corporation of Geotechnical Engineering data for landslide hazard map in Thailand. EIT-JSCE Joint seminar on Rock Engineering, Bangkok, Thailand

Soralump, S. 2010. Rainfall-triggered Landslide: from research to mitigation practice in Thailand. The 17th Southeast Asian Geotechnical Conference, Taipei, Taiwan