Triggered-Rainfall Landslide Hazard Prediction

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Abstract

Thailand is one of many countries suffering from landslide problem due to heavy rainfall. Many people had loss their life and their casualties every year. The estimated value of economic loss is more than expectation. Landslide, in geotechnical engineering field, is problem of slope stability on unsaturated soil. In general, main causal factors of landslide contain static factors such as slope angle, geology and land use combined with dynamic factors and rainfall triggering factor. The slope stability is varied depend on water content in soil mass from rainfall. Whenever rainfall occurring, soil water content increased, soil shear strength decreased affect to slope instability and possible failure. This paper presents the method of landslide prediction from rainfall data in study area of Phuket of southern Thailand. Study area was classified according to static factors. Infinite slope model and probabilistic approach were used in stability analysis. Water content changing was calculated by 1D-flow finite difference method. Probability of landslide for each zone was calculated from rainfall data, consisting of recent 1 day rainfall and antecedent 3-days rainfall. Geographical Information System (GIS) is used as a tool for the analysis and presentation. Dynamic landslide hazard can be mapped and used for warning system. However, the verification of the results with the past landslides is needed to confirm for a particular location before giving warning system.

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.

Reason of unsaturated soil behavior on the natural slope, soil shear strength varies with water content change due to rainfall. The water content increasing by adequate rainfall intensity and duration then in consequence the shear strength is decreased. In case of the slope on marginal stable at the initial state, landslide is possible due to the loss of shear strength on the first rain.

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 the past, Thai researchers try to apply this concept also but due to the lack of landslide inventories and rainfall records make it difficult to study.

This paper presents the method of landslide prediction by using rainfall data. The probability of landslide related to rainfall is analyzed by geotechnical engineering method incorporated with probabilistic approach by Monte Carlo simulation. The analysis was performed with the different water content over target area. Then probabilities of landslide related to triggered rainfall will be presented by dynamic map which probability can be re- calculated and changed automatically from real-time rainfall data input.

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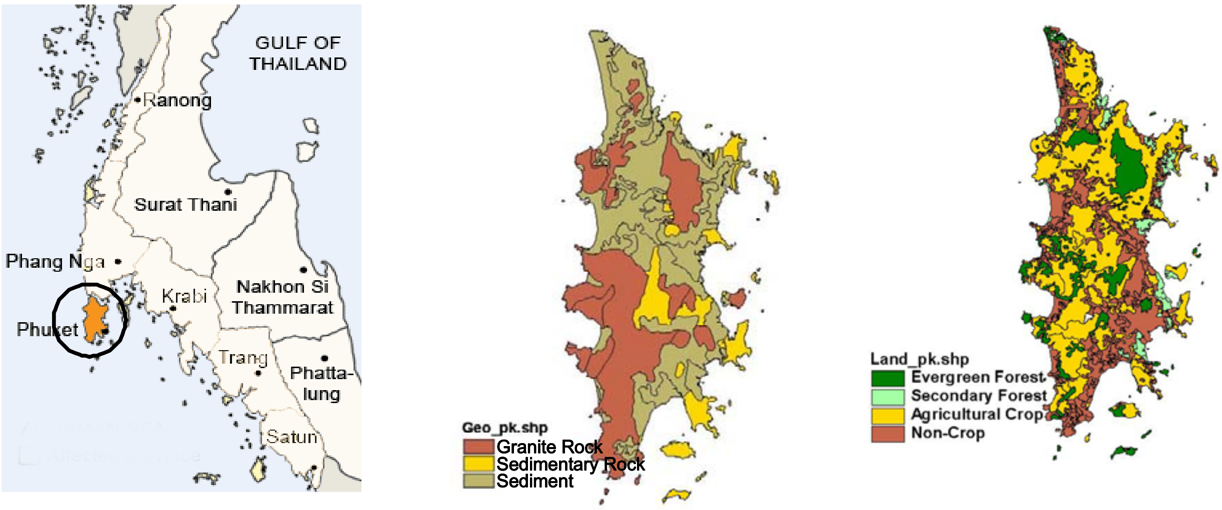
2. STUDY AREA

The study area on Phuket island, a province on Andaman sea, southern Thailand. It covers the area of 540 km^2 with 70 % of mountainous area and steep slopes (Figure 1a). Landslides were recorded on the mountainous area mostly on the west coast of the island.

The geological map and field investigation of mountainous area show the igneous rock as majority with some sedimentary rock as on figure 1b. The granitic residual soil is very thick up to 10-15 m. was found to be the major landslide prone area as indicated on the landslide report in study area. Another is Sedimentary rocks, can be divided into 4 major type including Mudstone, Sandstone, Siltstone and Limestone with shallow weathered layer and less frequency of landslide.

Land use modification from natural forest and plantation area to urban area in Phuket also creates more landslide risk. Considering root reinforcement, the area can be classified into 4 types; Evergreen forest, Secondary forest, Agricultural crop and Non-plant covered area as shown in figure 1c. For the first two types, their roots are deep and widely distributed, so that they increase the resistance force against slope failure. The last two types, which are generally caused by human activities, not only reduce the resisting force but some time increase the additional load on surface.



a. Location of study area b. Geology c. Land use

Figure 1 Location and characteristic of Phuket Island

3. METHODOLOGY

In this research, the study process can be divided into 3 parts as the data preparation, landslide hazard analysis and landslide prediction as shown in figure 2. The detail can be explained as follow:

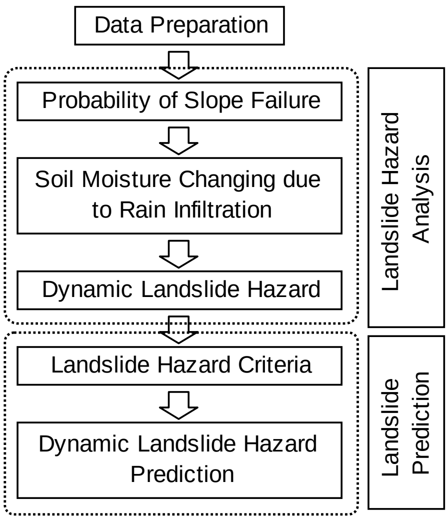


Figure 2 Flow chart of the methodology

3.1 Data Preparation

The data in this research are from "A study of landslide behavior in Phuket province" (Warakorn M. et. al., 2006) and "Study for prevention and reduction impact landslide disasters" (Geotechnical Engineering Research and Development Center, Kasetsart university; 2006). The first is emphasized on the western mountainous area of this island. And the second worked on Andaman coastal area cover 6 provinces such as Ranong, Pang-Nga, Phuket, Krabi, Trung and Satun.

The required data are 3 groups including; static, triggering and dynamic factors. The first contain factor geological data, land use and area slope. The second is rainfall data that was used to estimated rainfall intensity, pattern and frequency of occurrence on the study area. The last group is soil moisture movement and unsaturated strength which is major factors on landslide.

3.2 Probability of slope failure analysis

Landslide hazard triggered by rainfall is probability of slope failure (P_f). It can be changed due to soil water content changing related to rainfall. For large extended area, slope stability is analyzed by using infinite slope model (Abramson et. al., 1996) as shown in figure 3 and Eq. 1. The analysis is performed by considering unsaturated soil behavior in which the shear strength relate to normal stress and matrix suction as shown in Eq. 2 and figure 4. Incorporate with probabilistic approach, P_f can be estimated from uncertainty of parameter by Monte Carlo simulation method in difference water content. Factor of Safety (FS) is parameter indicate the stability of slope. It can be calculated for every pixel of specified area. Theoretically, for unstable slope, the calculated FS is less than unity.

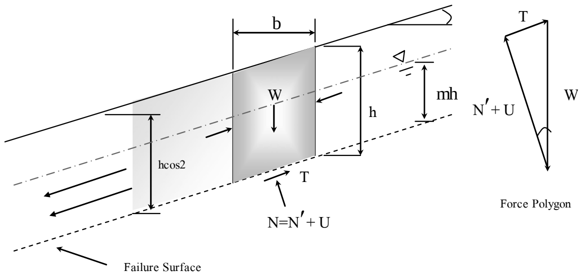


Figure 3 Infinite slop stability analysis model

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

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

$$\tau' = c' + (\sigma - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b \quad (2)$$

Where
τ' = Effective shear strength
$(\sigma - \mu_a)$ = Normal stress on shear plane
$(\mu_a - \mu_w)$ = Matrix suction
c' = Effective cohesion strength
ϕ' = Effective internal friction angle
$\tan\phi^b$ = Slope of matrix suction versus shear strength

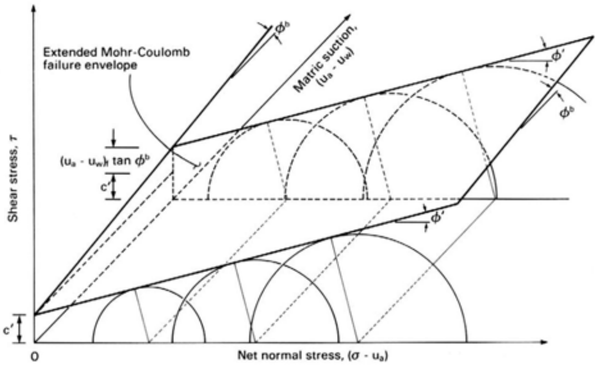


Figure 4 Mohr-Coulomb failure envelope for unsaturated soil (Fredlund and Rahardjo, 1993)

The study area was classified into sub-area by considering causal factors which is static factor. P_f is calculated by using shear strength varied with degree of saturation from 100%, 95%, 90%, etc. Calculation process is performed until P_f is not occurred. Minimum degree of saturation that P_f occur is called critical degree of saturation (Sr_c).

Soil parameters for slope stability analysis such as shear strength according to the rock origin, degree of saturation, land use and slope angles can be shown in table 1 - 3.

Table 1 Soil shear strength parameter

Rock Type	Case	Degree of Saturation (%)	C_MEAN (T/m^2)	C_STDEV	PHI_MEAN (°)	PHI_STDEV	DENSITY (T/m^3)
Granite	R1_01	100	0.714	0.972	37.84	4.49	1.915
	R1_02	95	1.056	0.899	37.84	4.49	1.892
	R1_03	90	1.416	0.826	37.84	4.49	1.87
	R1_04	85	1.797	0.755	37.84	4.49	1.848
	R1_05	80	2.201	0.688	37.84	4.49	1.825
Sedimentary Rock	R2_01	100	1.997	3.703	39.24	7.36	1.96
	R2_02	95	2.367	3.247	39.24	7.36	1.939
	R2_03	90	2.757	2.804	39.24	7.36	1.918
	R2_04	85	3.169	2.402	39.24	7.36	1.897
	R2_05	80	3.606	2.091	39.24	7.36	1.876

C_MEAN = Average cohesion strength (T/m^2)
PHI_MEAN = Average internal friction angle (°)
C_STDEV = Standard deviation of cohesion strength
PHI_STDEV = Standard deviation of internal friction angle
DENSITY = Soil density (T/m^3)

Table 2 Land use parameter

Detail	Case	CR_ MIN	CR_ MAX	RDP_ MIN	RDP_ MAX
Tropical Evergreen Forest	L1	0.17	0.46	0	1.5
Secondary Forest	L2	0.08	0.24	0	0.8
Agricultural Crops	L3	0.09	0.35	0	1.5
Opened Area	L4	0	0	0	0

CR_MIN = Minimum reinforcing shear strength of root-soil (T/m^2)
CR_Max = Maximum reinforcing shear strength of root-soil (T/m^2)
RDP_MIN = Minimum root depth (m)
RDP_MAX = Maximum root depth (m)

Table 3 Slope parameter

Slope Range	Case	Slope	
		MIN	MAX
>85°	S01	85	89
80-85°	S02	80	85
75-80°	S03	75	80
70-75°	S04	70	75
65-70°	S05	65	70
60-65°	S06	60	65
55-60°	S07	55	60
50-55°	S08	50	55
45-50°	S09	45	50
40-45°	S10	40	45
35-40°	S11	35	40
30-35°	S12	30	35

3.3 Soil Moisture Change due to Rain Infiltration

Change of water content by triggered rainfall, was calculated from result of rain infiltration through potential failure zone on unsaturated soil slope. Finite different method was used for the analyses on one-dimension unsteady flow by using Richard's equation (Kumar, 2002) as shown in Eq. 3. Rainfall duration for analysis in this research is 4 days. Permeability parameter of unsaturated soil follows van Genuthen model (Genuthen, 1980) as shown in Eq. 4 and 5 and table 4. The result is probability of degree of saturation relate to rainfall.

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial z}K\frac{\partial H}{\partial z} \tag{3}$$

Where θ = Volumetric water content (V/V)

t = Time (T)

z = Distance (L)

K = Hydraulic conductivity (L/T)

H = Total hydraulic head (L)

For Soil-water characteristic curve (SWCC)

$$\frac{\theta-\theta_r}{\theta_s-\theta_r}=\left[\frac{1}{1+(\alpha h)^n}\right]^m \tag{4}$$

For Permeability function (PF)

$$\frac{K(\theta)}{K_s}=\left(\frac{\theta-\theta_r}{\theta_s-\theta_r}\right)^{1/2}\left\{1-\left[1-\left(\frac{\theta-\theta_r}{\theta_s-\theta_r}\right)^{1/m}\right]^m\right\}^2 \tag{5}$$

Where θ = Volumetric water content

θ_s = Saturated volumetric water content

θ_r = Residual volumetric water content

α,n = Shape factor

m = Shape factor, m=1-1/n

h = Matric suction

$K(\theta)$ = Hydraulic conductivity

K_s = Saturated hydraulic conductivity

Table 4 Unsaturated soil's permeability parameters

Geology	θs	θr	α	n	Ksat (cm/sec)
Granite	0.443	0.025	0.068	2.533	1.16E-03
Sedimentary Rock	0.414	0.029	0.045	2.078	1.17E-04

θ_s = Saturated volumetric water content

θ_s = Saturated volumetric water content

θ_r = Residual volumetric water content

α,n = Shape factors for van Genuchten's model of SWCC and PF

K_{sat} = Saturated hydraulic conductivity

3.4 Dynamic Landslide Hazard

Next step is analysis of dynamic landslide hazard which is probability of landslide occurring on study area depend on uncertainly rainfall. It is the conditional probability of failure depend probability of critical degree of saturation which relate to rainfall.

3.5 Landslide Hazard Criteria

From case study in Hong Kong (Lumb, 1975) as shown in figure 5, landslide-rainfall triggering relationship came from landslide the past events. X-axis is antecedence rainfall and y-axis is estimated 1-day rainfall in the future. In this research, 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 rainfall was created by chart plotting. In each point has a value of probability of landslide. The interval of probability was defined from the rainfall chart.

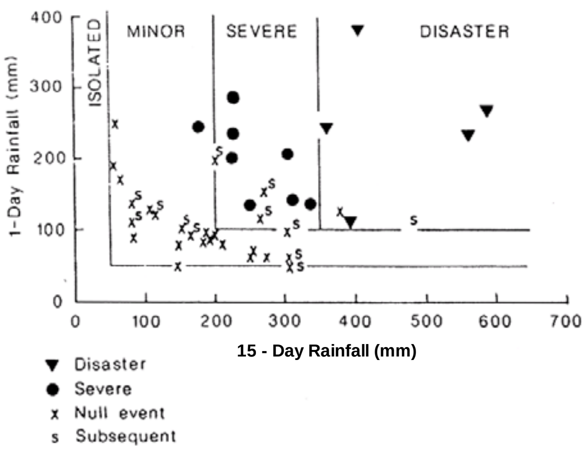


Figure 5 Relationship between rainfall and landslide in Hong Kong (Lumb, 1975)

3.6 Dynamic Landslide Hazard Prediction

The landslide prediction on target area is the probability of landslide which calculated from relationship between probability of landslide and rainfall as mention above. Calculation was performed for each sub-area and the result was distributed over the target area by using GIS technique. However the probability is not constant and varied according to triggered rainfall, therefore the prediction map will be changed as current rainfall input data.

4. RESULTS

The result from the probability of slope failure analysis, slope failure will be occurred when degree of saturation rise up to 80%. Dynamic landslide hazard was calculated by using 12,000 random rainfall patterns generated from frequency of occurrence (return period) on the study area. The result of dynamic landslide hazard related rainfall as shown in figure 6.

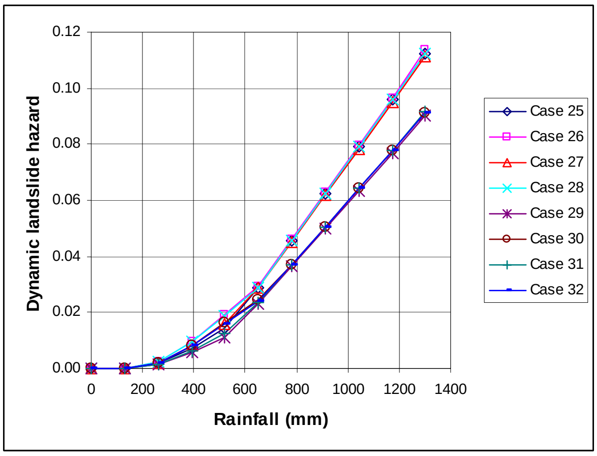
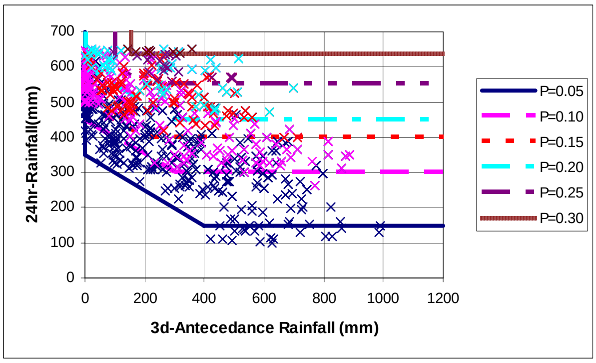


Figure 6 Dynamic landslide hazard related rainfall

Dynamic landslide hazard values were then plot in chart of relationship between 24 hr. expected rainfall and 3 days antecedence rainfall as shown in figure 7. Each point in this chart has a value of landslide hazard. Hazard levels were defined as probability of landslide occurrence from 0.05 with 0.05 interval.



Note: P is Probability of landslide occuring

Figure 7 Relationship between probability of landslide and rainfall

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

By using GIS, the target area was classified to sub-area by static factor as shown in figure 8 as example. 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 9. 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 9. 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. can be shown in figure 10a. For the second day with 3-days antecedence rainfall is 300 mm. and 24 hr. estimated rainfall is 400 mm., the probability of landslide can be shown in figure 10b. And the third day with 3-days antecedence rainfall is 700 mm. and 24 hr. estimated rainfall is 500 mm., landslide hazard can be shown in figure 10c respectively.

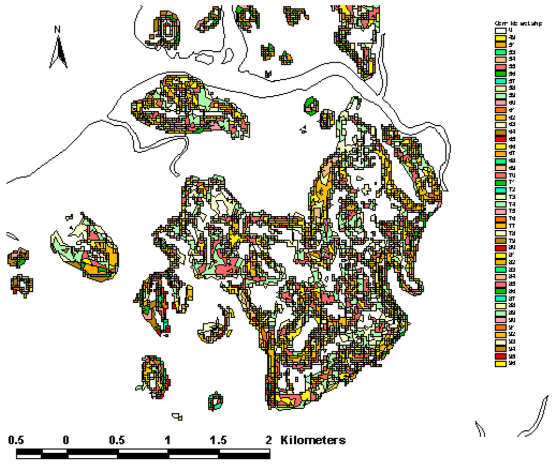


Figure 8 The example of sub-area classification by causal factors

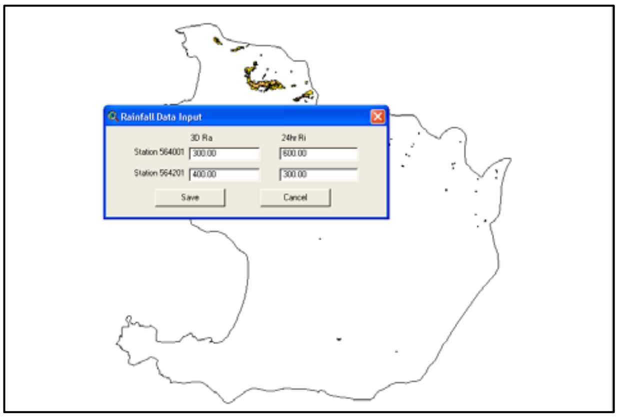
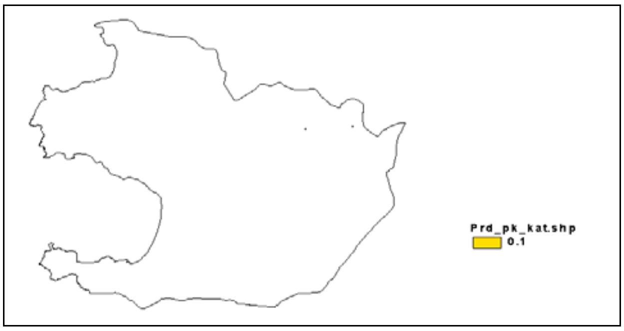
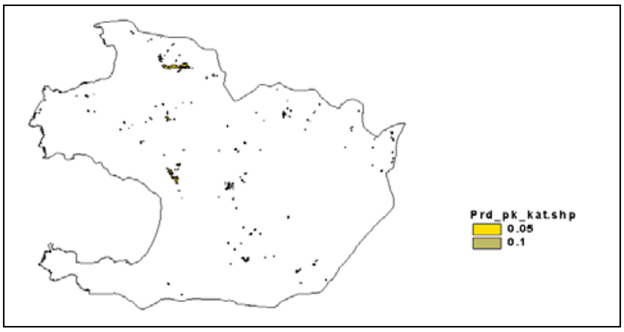


Figure 9 Rainfall data input by using GIS

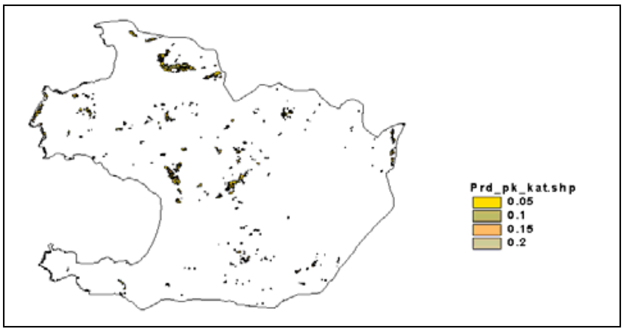


a. Probability of landslide due to 100 mm. of 3-days antecedence rainfall and 200 mm. of 24 hr. estimated rainfall

Figure 10 Example of landslide prediction over the target area by using GIS



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 10 (Cont) Example of landslide prediction over the target area by using GIS

5. Conclusion

In this research, probabilistic approach of slope stability analysis and one-dimension unsteady flow calculated by finite different method, which is geotechnical engineering method, was used to create the rainfall-landslide relationship on Phuket Island. The prediction was shown in term of probability of landslide, calculated from data of 3-days antecedence rainfall and 24 hr triggering rainfall over target area. The result of mapping the potential unstable area by GIS technique can be use for warning system. For reliability in warning, the verification of landslide hazard level and rainfall with the past landslide records is needed for adjustment to compatible for individual area in study area.

6. ACKNOWLEDGEMENTS

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