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Landslide Hazard Mapping with New Topographic Factors: A Study Case of Penang Island, Malaysia

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ABSTRACT

Landslide is one of the destructive natural geohazards in Malaysia. In addition to rainfall as triggering factos for landslide in Malaysia, geological factors and topographic factors play a very important role in the landslide susceptibility. Conventional topographic factors such as elevation, slope angle, slope aspect, plan curvature and profile curvature have been considered as landslide causative factors. However, other topographic factors such as tangential curvature, longitudinal curvature, diagonal length, surface area, surface roughness and rugosity have not been considered, especially for the research work in landslide hazard analysis in Malaysia. Landslide hazard map is very useful for urban development planning. This paper presents landslide hazard mapping using Frequency Ratio (FR) and the study area is Penang Island of Malaysia. Frequency ratio approach is a variant of probabilistic method that is based on the observed relationships between the distribution of landslides and each landslide-causative factor. Landslide hazard map of Penang Island is produced by considering twenty two landslide causative factors. Among these twenty two factors, fourteen factors are topographic factors. They are elevation, slope gradient, slope aspect, plan curvature, profile curvature, tangential curvature, longitudinal curvature, cross section curvature, general curvature, total curvature, diagonal length, surface area, surface roughness and rugosity. From the digital elevation model, topographic factors are extracted for Penang Island. Most of the topographic factors have not been considered in previous research works. The other eight non-topographic factors considered are land cover, vegetation cover, distance from road, distance from stream, distance from fault line, geology, soil texture and rainfall precipitation. Landslide hazard map was segregated into four categories of risks, i.e. Highly hazardous area, Hazardous area, Moderately hazardous area and Not hazardous area. Landslide hazard map was assessed using ROC (Rate of Curve) based on the area under the curve method (AUC). The result indicates an accuracy of seventy eight percent (78%) in the prediction of landslide occurrence.

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INTRODUCTION

Landslides are geological phenomenon that involves movement of a mass of rock, earth or debris due to soil erosion. Landslides are among the most aggressive natural disasters as they destroy properties and even claim human lives. In Malaysia, landslides happen rather frequently due to heavy rainfall during annual monsoons mainly known as Southwest Monsoon from late May to September**,** and Northeast Monsoon from November to March. These recent years from 2000 to 2009, damages due to landslides have been particularly high (Pradhan and Lee, 2010). Although it is difficult to predict a landslide event in space and time, an area may be divided into different ranks according to the degree of potential hazard due to mass movement (Varnes 1984). The identification of high risk areas is important in landslide prediction and warning system. In this paper, Penang Island is selected to be area of interest in landslide hazard analysis as it has suffered numerous damages due to landslide in recent years. In recent years, there have been many studies on landslide hazard evaluation using GIS and various evaluation techniques. Probabilistic methods such as frequency ratio have been applied many times to achieve favorable result in landslide hazard evaluation (Pradhan and Lee, 2010; Lee and Talib, 2005; Saha et al. 2005).

2. Study Area:

The study area selected in this paper is Penang Island (Fig. 1) due to its heavy frequency of landslide over the years. Penang is one of the 13 states of Malaysia located on the North-West of Peninsular Malaysia. It is bounded to the north and east of the state of Kedah, to the south of the state of Perak and to the west of Strait of Malacca.

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Penang consists of both the island of Penang and a coastal strip on the mainland known as Province Wellesley. In this paper, the island of Penang is considered for landslide evaluation mapping. The island which is separated from the mainland by a channel, covers an area of 285 km^2. It is located about 5^o 15'N to 5^o 30'N of latitudes and 100^o 10'E to 100^o 20'E of longitudes. Elevation of the terrain ranges from 0 to 820 meters above sea level and slope gradient ranges from 0^o to 87^o. Penang Island is affected by fault lines that run from north to south mainly in the centre of the island. Land-cover of Penang Island is consisted of mainly swamp, plantation, forest, grassland and urban area. Vegetation cover consists mainly of forest and fruit plantation. Temperature of Penang Island ranges from between 29 to 32^{o}C and the average amount of rainfall varies from 2254 to 2903 mm annually.

A. Data Set:

Data collection on geographical database of Penang Island is done through application of remote sensing methods and GIS. Topographical, geological and various images of Penang Island were obtained from various departments in Malaysia including Meteorological department, Jabatan Pengairan dan Saliran (JPS), Department of Agriculture (DOA), Minerals and Geoscience Department (JMG), Jabatan Ukur dan Pemetaan Malaysia (JUPEM) and Pusat PeGIS. Landslide occurrence points in Penang Island are also collected and transformed into spatial database for probabilistic landslide susceptibility analysis. Most landslides happened at the mountainous terrain of the island which is situated in the middle of the island. These landslides consist of mainly shallow rotational debris slides, debris flows and rock falls. Identification and mapping of a suitable set of instability and causative facts having relationship with the slope failures requires prior knowledge of the main causes of landslide (Guzzetti et al. 1999). To apply the probabilistic methods, data sets of landslide-causative factors were collected and constructed as spatial database. Twenty two landslide-causative factors were considered in calculating probability of landslides. From topographic database, digital elevation model (DEM) were constructed with a resolution of 10-meter. DEM provides the elevation of study area. Elevation was then used to compute slope angle, slope aspect, plan curvature, profile curvature, tangential curvature, longitudinal curvature, cross section curvature, general curvature, total curvature, diagonal length, surface area, surface roughness and rugosity. Distance from drainage and distance from road were calculated from drainage map and road map each available in digital map respectively. Van Westen et al. (2003) suggested that buffer zones for line features, such as, rivers and roads should be set to 50 m. Similarly, distances from fault lines of Penang Island were calculated and segregated into 100 m intervals. Soil texture database of the island which included sand, clay and urban land were obtained as well. Land use map consists of 17 classes of land usage. Vegetation cover map consists of 14 classes. Geology map, tabling the types of rocks and granites of Penang Island is used as one of the landslide-causative factors. Rainfall or precipitation is one of the most efficient triggering factors of landslide as it dampens soils and washes away debris and rocks, creating landslides. There are only several rain gauge stations in Penang Island, therefore, interpolation method had to be used to prepare the precipitation map. Using 29 years of historical rainfall data (1980-2008), statistical distribution of the accumulated average precipitation was prepared using inverse weight distance interpolation method in ArcGIS software.

Fig. 1: Penang Island, Malaysia.

3. Methodology:

A. Topographic Factors Extraction:

Topographic factors such as elevation, slope angle, aspect, profile and plan curvature were considered as significant factors which affect land stability (Lee, Ryu et al. 2004; Pradhan and Lee 2010). Other topographic factors which have been identified as important factors in this study include slope diagonal line length, general curvature, total curvature, cross-section curvature, tangential curvature, longitudinal curvature, surface area, roughness, and rugosity. These factors were extracted from the Penang Island Digital Elevation Map (DEM). The DEM with ten-meter resolutions of Penang Island was obtained from the Department of Survey and Mapping Malaysia. Fig. 2 shows the moving window and *W* denotes the grid resolution, which is equal to 10 meters in this study. If $Z = f(x,y)$ is a given point in the DEM surface, then f_x, f_y are the gradients in N–S and W–E directions, respectively. Equations (1) to (8) are the definitions needed for topographic extractions. These definitions are used in the Table 1 which provides the equations used to extract the thirteen topographic factors.

$$f_x = \frac{Z_8 - Z_2}{2W} \quad , \quad f_y = \frac{Z_6 - Z_4}{2W} \tag{1}$$

$$p = \frac{Z_3 + Z_6 + Z_9 - Z_1 - Z_4 - Z_7}{6W} \tag{2}$$

$$q = \frac{Z_1 + Z_2 + Z_3 - Z_7 - Z_8 - Z_9}{6W} \tag{3}$$

$$r = \frac{Z_1 + Z_3 + Z_4 + Z_6 + Z_7 + Z_9 - 2(Z_2 + Z_5 + Z_8)}{3W^2} \tag{4}$$

$$t = \frac{Z_1 + Z_2 + Z_3 + Z_7 + Z_8 + Z_9 - 2(Z_4 + Z_5 + Z_6)}{3W^2} \tag{5}$$

$$s = \frac{Z_3 + Z_7 - Z_1 - Z_9}{4W^2} \tag{6}$$

$$\text{Curvature value} = \begin{Bmatrix} convex & value > 0 \\ concave & value < 0 \\ flat & elsewhere \end{Bmatrix} \tag{7}$$

Adjustment factor = 1/cos (slope angle) (8)

$r = X_{direction}$, $t = Y_{direction}$, $s = Diagonal_{direction}$, $p = (East - West)_{gradient}$, $q = (North - South)_{gradient}$,

S = slope angle, $\overline{S}$ = mean slope in 3X3 moving window

Different methods have been developed to extract the topographic factors from the DEM. Topographic factors for the study area were extracted based on the literatures on slope factor and slope aspect (Zhou and Liu 2004), plan curvature, profile curvature (Zevenbergen 1987; Aggarwal 2005), general curvature, total curvature, tangential curvature, longitudinal curvature, cross-section curvature, diagonal line length and surface area (Jeff, 2013; Evans 1980; Wood 1996; Prodanovic D 2002).

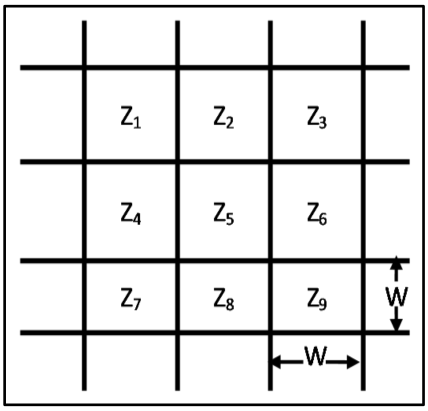

Fig. 2: 3x3 moving window.

Table 1: Topographic factors equation.

Slope angle	Slope angle = $\arctan\sqrt{f_x^2 + f_y^2}$ (9)
Slope aspect	Slope aspect = $270^o + \arctan\left(\frac{f_y}{f_x}\right) - 90^o \frac{f_x}{\lvert f_x \rvert}$ (10)
Plan curvature	Plan curvature = $\frac{\left(\frac{Z_4 + Z_6}{2} - Z_5\right)}{2W}$ (11)
Profile curvature	Profile curvature = $\frac{\left(\frac{Z_2 + Z_8}{2} - Z_5\right)}{2W}$ (12)
General curvature	General curvature = Plan curvature + Profile curvature (13)
Total curvature	Total curvature = $r^2 + 2s^2 + t^2$ (14)
Tangential curvature	Tangential curvature = $-\frac{\left(q^2 r - 2pqs + p^2 t\right)}{(p^2 + q^2)\sqrt{1 + p^2 + q^2}}$ (15)
Longitudinal curvature	Longitudinal curvature = $-2\left(\frac{p^2 r + pqs + q^2 t}{p^2 + q^2}\right)$ (16)
Cross section curvature	Cross-section curvature = $2\left(\frac{q^2 r - pqs + p^2 t}{p^2 + q^2}\right)$ (17)
Diagonal length	Diagonal length = $\sqrt{f_x^2 + f_y^2}$ (18)
Surface area	If adjustment factor value >1, Surface area = $\frac{W^2}{\cos(slope\ angle)}$ If adjustment factor value = 1,Surface area = W^2 (19)
Surface roughness	Surface Roughness $= \sqrt{\frac{1}{N}\sum_i^N (S_i - \bar{S})^2}$ (20)
Rugosity	Rugosity = $\frac{\text{Surface area of 3 X 3 neighborhood windows}}{\text{Plane area of 3 X 3 neighborhood windows}}$ (21)

B. Probabilistic method:

Probabilistic method of landslide hazard analysis has been proven to be very useful in landslide prediction. The advantages of this method lie in its high efficiency, low cost, easy implementation and better understanding of the relationships between landslides and landslide-causative factors. In probabilistic method, each factor's data weights are calculated based on class distribution and its landslide density (Suzen and Doyuran, 2004). These weights represent the importance of each factor to landslide occurrence and are used to produce a landslide hazard index.

Frequency ratio (FR) approach is a variant of probabilistic method that is based on the observed relationships between the distribution of landslides and landslide-causative factors. Spatial relationships and correlations between landslide and its factor are computed and these correlations show how closely related the factors are to landslide occurrence. Frequency ratio or weight of each class is computed by dividing the landslide density of a class with the total landslide density (Equation 22). Therefore a value of 1 is the unity value and value higher than 1 shows higher correlation and vice versa. To calculate the landslide hazard index (LHI), each pixel's frequency ratios of the map is summed up (Equation 23). It is then inferred that areas with higher values of frequency ratio are areas that are more prone to landslide.

$$FR_{ab} = \frac{A*_{ab}}{A_{ab}} * \frac{A}{A*} \quad (22)$$

FR = Frequency ratio of each factor.
$A_{ab}*$ = Area of observed landslide of class a of parameter b.
A_{ab} = Area of class a of parameter b.
A = Total area of the map.
A* = Total area of observed landslide of the map.

$$LHI = FR_1 + FR_2 + ... + FR_N \quad (23)$$

RESULT AND DISCUSSION

To verify the efficiency and accuracy of each method, ROC (Rate of Curve) method was employed. Two assumptions are needed in order to verify the maps. One is that landslides are related to spatial information such as slope and aspect, and the other is that the future landslides will be affected by triggering factor such as rainfall (Chung and Fabbri, 1999). Both assumptions are satisfied in this study. Verification by ROC is done by first sorting the landslide hazard indexes (LHI) in a descending order. The ordered indexes are then divided into 100 classes and set on y-axis, with accumulated 1% intervals on x-axis (Pradhan and Lee, 2010). The resulting graph shows a line curve that explains how well the model and factors predict future landslide (Chung and Fabbri, 1999). The area under the curves constitutes the accuracies of the prediction models and is one of the commonly used accuracy statistics in natural hazard assessments (Chung and Fabbri, 1999). Landslide hazard map produced using frequency method achieves an accuracy of 78% in this study area.

Landslide hazard mapping is done by segregating LHI (landslide hazard index) into several categories of risks. In this study, the indexes are categorized into 4 groups: Highly hazardous for the highest 10% of the indexes (90-100%), Hazardous for the next 10% (80-90%), Moderately hazardous for the next 20% (60-80%) and Not hazardous for the remaining 60% (0-60%). ROC line curves explain how well the prediction models fit the data of landslide-causative factors with landslide occurrences to predict future landslides. Fig. 3 shows the landslide hazard maps produced using frequency ratio method.

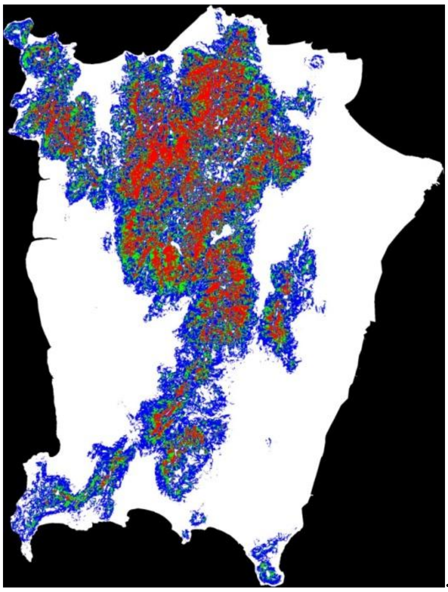

Fig. 3: Landslide hazard map for Penang Island produced using Frequency Ratio.

Conclusion:

Due to the limitation of flat land in Penang Island, more hill areas are being explored for housing and development. This creates a scenario where landslide alert system is needed to warn people of impending landslides on risky area. Prediction models such as statistical or probabilistic methods are simple methods which have been proven to yield good results in landslide prediction. Landslide causative factors depends on the availability of GIS images in the research area. In this paper, landslide hazard maps of Penang Island was produced with frequency ratio using twenty two landslide-causative factors. The accuracy achieved is 78%. Frequency method is proven to produce landslide hazard map with good accuracy. The resulting susceptibility map can be useful in planning of future urban infrastructures development.

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