ASM Sc. J., 11, Special Issue 2, 2018 for SANREM, 1-18

A Comparative Evaluation of Normal Polygon Geotechnical Deterministic Analysis (NPGDA) and GEOStatistical INterpolation Techniques (Kriging) (GEOSTAINT-K): A Case Study from Kota Kinabalu Area, Sabah, Malaysia

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A practical application for landslide susceptibility analysis (LSA) based on Normal Polygon Geotechnical Deterministic Analysis (NPGDA) and GEOSTAtistical INterpolation Techniques (Kriging) (GEOSTAINT-K) for the infinite slope model was used to calculate the factor of safety (FOS) and failure probabilities for the area of Kota Kinabalu, Sabah, Malaysia. LSA is defined as quantitative or qualitative assessment of the classification, volume (or area) and spatial distribution of landslides which exist or potentially may occur in an area. In this paper, LSA value can be expressed by a FOS, which is the ratio between the forces that make the slope fail and those that prevent the slope from failing. An geotechnical engineering properties data base has been developed on the basis of a series of parameter maps such as effective cohesion (C'), unit weight of soil (γ), depth of failure surface (Z), height of ground water table (Zw), Zw/Z dimensionless (m), unit weight of water (γw), slope surface inclination (β) and effective angle of shearing resistance (ϕ).A total of 367 landslides were identified by aerial photographs and satellite images interpretations, field observation and secondary data resources. The landslide inventory maps were randomly split into a dataset of 256 landslides (70 %) for running the both models and the remaining 110 landslides (30%) was used for validation purpose. For verification purpose, Area Under the Curve (AUC) method were used in the format of GIS (Geographic Information Systems). The verification result showed that LSA-NGDA (88%) performed better than LSA-GEOSTAINT-K (81%) for the study area. The resulting LSA map can be used by local administrator or developers to locate areas prone to landslides, determine the land use suitability area as well as to organize more detailed analysis of the identified "hot spot" areas.

Keywords: Landslide Susceptibility Analysis (LSA), Normal Geotechnical Deterministic Analysis (NGDA) & GEOSTAtistical INterpolation Techniques (Kriging) (GEOSTAINT-K)

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I. INTRODUCTION

Landslide is an issue which is still underdebate in the newspapers or any electronic media, especially in Kota Kinabalu, Sabah, Malaysia (Figure 1). The effect of the pressure of development activities that lead to rapid cut works or reclamation of slopes for road construction, infrastructure development and construction of dwellings or buildings is more widespread and has spread to hilly areas with a large population. The location of the study area is surrounded by the Crocker and Trusmadi Ranges and has a complex geological background, which also give a negative outlook for any exploration activities and further land development planning.

Landslides are amongst the most damaging natural hazards in the world. The term “zonation” in a general sense implies a division of the land into areas and their classification according to degrees of actual or potential landslide hazard or susceptibility (Varnes, 1984). The purpose of landslide susceptibility analysis (LSA) is to highlight the regional distribution of potentially unstable slopes based on a detailed study of the factors responsible for landslide (Aleotti & Chowdhury, 1999; Ayalew et al., 2005). LSA is defined as a quantitative or qualitative assessment of the classification, volume (or area) and spatial distribution of landslides which exist or potentially may occur in an area (International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE), www.engmath.dal.ca/tc32). Susceptibility may also include a description of the velocity and intensity of the existing or potential landsliding.

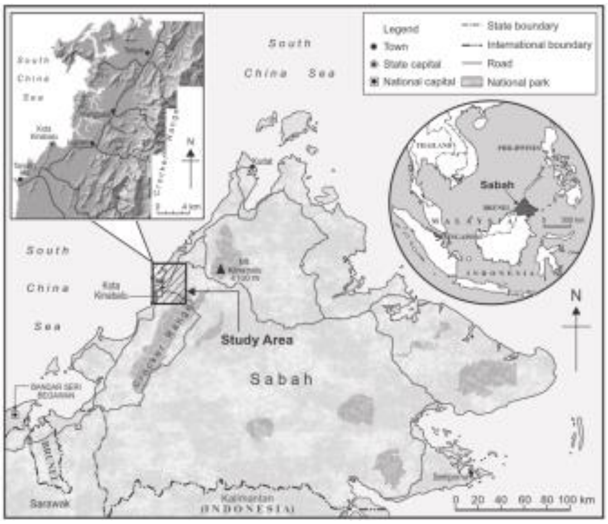


Figure 1. Locality map of the studied area

II. LITERATURE REVIEW

In the literature, various approaches to deterministic models for LSA have been developed. Some popular deterministic models for LSA are the infinite slope, SHAllow Landsliding STABility (SHALSTAB), Stability INdex MAPping (SINMAP), Transient response, Transient Rainfall Infiltration and Grid-based Regional Slope-stability analysis (TRIGRS), etc. The infinite slope model is a static stability model in which local stability conditions are determined by the means of the local equilibrium along a potential slip surface. Other models couple the infinite slope stability model with more or less complex rainfall infiltration models (Okimura & Kawatani, 1986; van Westen, 1993; Montgomery & Dietrich, 1994; Dietrich et al., 1995; Terlien et al., 1995; van Westen & Terlien, 1996; Dymond et al., 1999; Crosta & Dal Negro, 2003). SHAllow Landsliding STABility (SHALSTAB) model is a model that combines a hydrologic model (O'Loughlin, 1986) with an infinite slope stability equation, the Mohr-Coulomb failure law (Bolt et al., 1975), for the prediction of slope instabilities based upon the minimum amount of steady-state rainfall required to trigger landsliding (Montgomery & Dietrich, 1994). It required inputs are obtained from a DEM that is widely available within the U.S. and a few representative values of geotechnical parameters, such as soil bulk density, internal angle of friction and water table depth. This model calculates pore pressures for steady-state saturated water flow parallel to the slope plane. Pack et al. (1998) and Zaitchik et al. (2003) combined a slope stability model (Stability INdex MAPping, SINMAP) with a steady-state hydrology model in selected watersheds of northern Vancouver Island, British Columbia and in the central highlands of Honduras, respectively. The main difference between these two models is that SHALSTAB assumes zero soil cohesion because of the spatial and temporal heterogeneity of soil cohesion (and therefore the difficulty in obtaining values) and because assuming a zero cohesion value results in the most conservative estimate of slope instability (Dietrich et al., 2001). However, new versions of the model do allow for the inclusion of soil cohesion. Great attention should be paid to the accuracy and variability associated with the input parameters. Transient response model developed by Iverson (2000) uses unsaturated flow to calculate pore pressures and vertical flow. The International Institute for Aerospace Survey and Earth Sciences (ITC) has developed a GIS called the Integrated Land and Water Information System (ILWIS) that has modules incorporated in the GIS for deterministic instability zonation (Van Westen, 1997a). The Level I Stability Analysis (LISA) prepared for the U.S. Forest Service by Hammond et al. (1992) uses average estimates for geotechnical parameters in their model. Similar examples of regional modelling and prediction of shallow landslides using a transient rainfall infiltration model in combination with slope stability calculation (Transient Rainfall Infiltration and Grid-based Regional Slope-stability analysis; TRIGRS) were applied for the Seattle area, Washington State, USA (Baum et al. 2005) and the Umbria Region, central Italy (Salciarini et al. 2006). The TRIGRS model predicts a larger area of instability than the area that actually failed, mainly due to uncertainty in soil thickness, local variation in soil properties, and Digital Elevation Model (DEM) errors (Chang and Kim, 2004; Dahal et al., 2008; Safaeiet al., 2010; 2011).

III. MODEL CONCEPTS

A. Normal Polygon Geotechnical Deterministic Analysis

A Normal Polygon Geotechnical Deterministic Analysis (NPGDA) is a deterministic-based approach, a landslide stability model, is advantageous over other approaches on allowing us to calculate the quantitative value, the factor of safety. The factor of safety represents the ratio between the sheer stress for failure and the sheer stress for stability. The variables in the equation were identified by many landslide models. The data used is based on the existing vector polygon data derived from primary and secondary data.

B. GEOSTAtistical Interpolation Techniques (Kriging) (GEOSTAINT-K)

GEOSTAtistical INterpolation Techniques (Kriging) (GEOSTAINT-K) utilizes the statistical properties of the measured points. The purpose is to determine the probability of certain variables occurring over an area where identifying every possible location would be impossible. The approach used in GEOSTAINT-K method uses the concept ofa combination of deterministic models and geostatistical interpolation.

GEOSTAINT-K method is divided into two distinct tasks: quantifying the spatial structure of the data and producing a prediction. Quantifying the spatial data structure, known as variography, is fitting a spatial-dependence model to the data. To make a prediction for an unknown value for a specific location, kriging uses the fitted model from variography, the spatial data configuration, and the values of the measured sample points around the prediction location. GEOSTAINT-K is a moderately quick interpolation method that can be exact or smoothed depending on the measurement error model. It is very flexible and allows the user to investigate graphs of spatial autocorrelation. It uses statistical models that allow a variety of map outputs including predictions, prediction standard errors, standard error of indicators, and probability (Cressie, 1988; 1990; Rivoirard, 1994 & Stein, 1999). The flexibility of these methods require a lot of decision making and assumes the data comes from a stationary stochastic process, which is a collection of random variables that are ordered in space and/or time.

IV. MATERIALS AND METHODS

In this paper, the LSA degree can be expressed by the factor of safety (FOS), which is the ratio between the forces that make the slope fail and those that prevent the slope from failing. F-values larger than 1 indicate stable conditions, and vice-versa (Table 1). At F=1 the slope is at the point of failure. Many different models exist for the calculation of FOS (as described above). In this study one of the simplest models, the so-called infinite slope model was used. This two-dimensional model describes the stability of slopes with an infinitely large failure plane. It can be used in a GIS, as the calculation can be done on a pixel basis. In GIS environment, the grid form data of a layer consists of variable layers and calculates corresponding variable values using map algebra function. The pixels in the parameter maps can be considered as homogeneous units. For example, a grid value has 20 in the slope layer, and then the grid has uniformly 20°. The effect of the neighbouring pixels is not considered, and the model can be used to calculate the stability of each individual pixel, resulting in a hazard map of FOS. The FOS is calculated according the following formula (Brunsden & Prior, 1979; van Westen & Terlien, 1996):

$$F = c' + (\gamma - m\,\gamma w)\, z \cos 2\beta \tan\phi' / \gamma\, z \sin\beta \cos\beta \qquad (1)$$

in which: c' = effective cohesion (kPa= kN/m^2), γ = unit weight of soil (kN/m^3), z = depth of failure surface below the surface (m), zw = height of groundwater table above failure surface (m), $m = zw/z$ (dimensionless), γw = unit weight of water (kN/m^3), β = slope surface inclination (°) and ϕ' = effective angle of shearing resistance (°).

Table 1. Degrees of stability according to ranges of the factor of safety (FOS)

Factor of safety	Degree of stability	Susceptibility classification
< 0.50	Unstable conditions	Extremely High
0.51 – 0.75		Very High
0.76 – 1.00		High
1.01 – 1.25	Stable conditions	Moderate
1.25 – 1.50		Low
>1.50		Very Low

A. Phase 1: Landslide Hazard Identification Phase

Phase 1 as depicted in Figure 1 is the preliminary stages in landslide hazard assessment consisting of the landslide hazard identification phase (LHIP). LHIP involves three (3) main types of research namely desk, field and laboratory studies. The desk studies involved detailed aerial photograph interpretation and satellite images (using Erdas V.9.2 software) analyses, extensive literature review and secondary data collation. All of these sources were analysed and reclassified to get an idea or preliminary information about the landslide distribution and historical data aspects in the study area. The product from these desk studies were used to establish a landslide incidents background data-base and to generate the "Landslide Distribution Map" (LDM) for the study area by using Arc GIS V.9.3 software. The field studies in LHIP involved sampling of rocks and soils, engineering geology mapping, and observation of landslide hazard characterization parameters and extracting a digital elevation model (DEM). For the laboratory studies in LHIP, all samples of rocks and soils obtained from the field were analyzed and evaluated for their engineering properties in accordance to the standards recommended by the ISRM (1979; 1979b & 1985) and BS1377-1990 (Method of Test for Soils for Civil Engineering Purposes) such as the direct shear test for rock testing and the classification of grain size, Atterberg limit, and triaxial test (Consolidated isotropically undrained, CIU) for soil testing. After all the laboratory studies are completed, several LHIP thematic maps were produced such as effective cohesion (c'), unit weight of soil (γ), depth of failure surface (Z), height of ground water table (Zw), Zw/Z dimensionless (m), unit weight of water (γw), slope surface inclination (β) and effective angle of shearing resistance (ϕ).

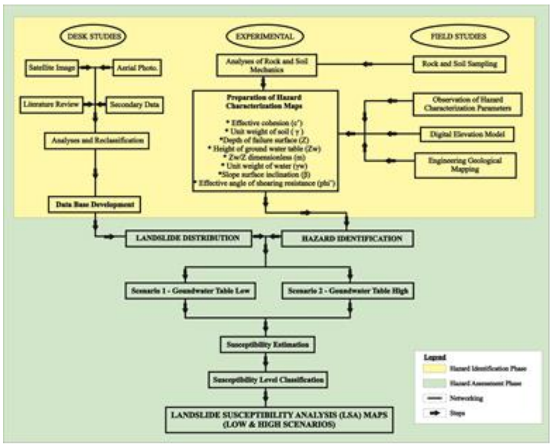


Figure 2. LSA Framework

B. Phase 2: Landslide Hazard Assessment Phase

In phase 2, taking into consideration the cause of the landslide, identified as groundwater change, the maximum groundwater level recorded corresponding to the actual situation of the most recent landslide is considered. A simple method for error propagation was used to calculate the variance of the FOS based on equation (1) and the probability that will be less than 1 for each pixel. The slope stability calculation is carried out by a combination of the input parametric maps with the GIS operations using a grid base. Finally, the resultant LSA maps are compared and validated with the data from LDM. The highest probability value of the various scenarios was selected for each pixel and final LSA map was constructed. Because the FOS in the final LSA map is assigned as a single value in every cell of a raster map, it is convenient to perform a reclassification of the calculated values (Table 1).

V. RESULTS AND DISCUSSIONS

A. Geological Background

The Geological map portraying information about the main geological units is shown in Figure 3. The different rock compositions and textures affect slope instability, influencing strength, permeability, and susceptibility to chemical and physical weathering of the rock masses. This map also represents the structural setting of the study area. Features such as sequence and type of layering, lithologic changes, planes, joints, faults and folds are accountable for LSA. The exposed rocks in the study area and its surroundings vary in type and age, from Late Eocene-Early Miocene sandstone and shale of the Crocker Formation to Young Alluvial sediments which are still being deposited (Rodeano et al., 2006). The sandstone-siltstone-shale unit is defined by an interbedded sandstone and shale with occasional siltstone. The thickness of the individual beds ranges from 2 cm to 130 cm. The sandstone is normally fine to very fine-grained and highly fractured while the shale layers are sheared. The shale unit is generally composed of red and grey types of shale. The grey variety is occasionally calcareous. This alternating sequence is commonly interbedded with siltstone or very fine-grained sandstone. The shale comprises about 12% of the total volume of the Crocker Formation. The sandstone composition is dominated by quartz with subordinate amounts of feldspars and chloritized, illitized or silicified lithic fragments.

Calcareous fractions are rare. These are poorly sorted and well compacted with the pores filled by fine grained detritus or squeezed lithoclasts resulting in very low to nil primary porosity. The sandstone unit is characterized by very low to nil porosity but moderate to high secondary permeability. It is defined by its great thickness, medium to very coarse-grained and sometime pebbly. Thin shale or siltstone bed between 3 to 40 cm thicknesses occurs between the thick sandstone beds. The argillaceous beds are frequently the site of shearing while the sandstone beds are the site of fracturing or jointing. The alluvium is restricted to the low-land areas. It mainly represents unconsolidated alluvial sediment on river terraces and flood plains composed of unsorted to well-sorted, sand, silt and clay of varying proportions which were derived from upstream bed rocks. They occur in irregular lenses varying in form and thickness. Towards the coastal area, the alluvium becomes finer-grained and interbedded with argillaceous deltaic and marine strata. The alluvium may also consist of a very thin layer of organic matter. The alluvium sediment is soft, compressible and may be prone to settlement.

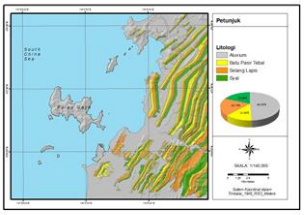


Figure 3. Geological map

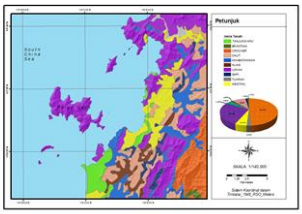


Figure 4. Soil types map

B. Soil Types

Information on soil types explaining the diversity of physical characteristics for unconsolidated deposition is as follows. Based on the soil types map derived from the Agriculture Department of Sabah, the soils association in the study area can be grouped into ten (10) categories, namely the Weston association (very silty sand textured, SM) (5.47%), the Tanjung Aru association (sand with little silty textured, SW) (2.98%), the Tuaran association (very silty sand textured, SM) (2.03%), the Kinabatangan association (very clayey sand textured, SC) (1.28%), the Sapi association (peat textured, Pt) (1.28%), the Klias association (organic textured, O) (1.69%), the Brantian association (clay textured, C) (1.07%), the Dalit association (very clayey sand textured, SC) (8.89%), the Lokan association (very silty sand textured, SM) (26.23%), and the Crocker association (clayey sand textured, S-C) (49.07%) (Figure 4).

C. Landslide Distribution

Landslide distribution is very useful information to study the physical changes and the latest geological assessment of their vulnerability. It quantifies all the information for any complex phenomenon. In these studies, landslides were classified in terms of types, materials involved, estimated volumes and velocities, degrees of activity, and return periods; and distinctions are made between source and depositional areas. Approximately about 2,119 landslide locations have been identified through an extensive review of literature, aerial photograph interpretations and field studies (Figure 5). The landslides were classified into several types; 20% of fall, 30% of translational, 20% of rotational, 15% of flow, and 15% of complex (a combination of fall, slide and/or flow). In terms of landslide scale, the study area consists of small (<50 m^3) (20%), medium (50 m^3 - 500 m^3) (60%) and large (> 500 m^3) (20%).

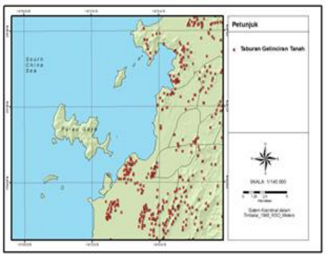


Figure 5. Landslide distributions map (LDM)

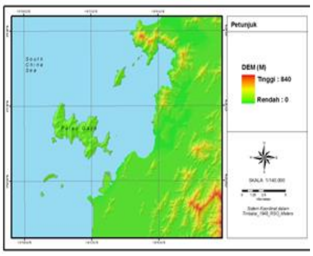


Figure 6. Digital elevation model (DEM)

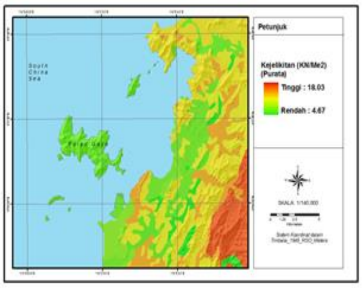
D. Digital elevation model (DEM)

A digital elevation model (DEM) of the slope conditions provided by raster datasets on morphometric features (altitude, internal relief, slope angle, aspect, longitudinal and transverse slope curvature and slope roughness) and on hydrologic parameters (watershed area, drainage density, drainage network order, channel length, etc.) were automatically extracted from the DEM (Figure 6). In addition, the slope angle is also considered as an index of slope stability caused by the presence of a digital elevation model (DEM) which is evaluated numerically and is illustrated by the spatial analysis (Yalcin & Bulut, 2007). In terms of slope gradient, the results suggest that 48.37% of the area can be categorized as 00 - 50, 28.45% as a 60 - 150, 22.41% as 160 - 300, 0.75% as 310 - 600 and 0.01% in excess of 600. Areas with slope angles in excess of 300 represent a very steep slope segment in the study area where the steeper a slope, the higher the LSA value.

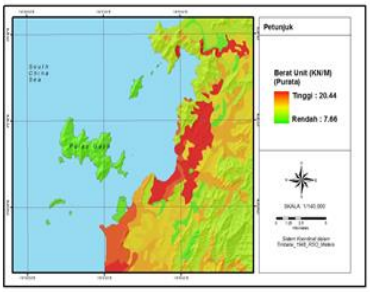
E. Geological Engineering Properties

Geotechnical engineering properties are closely related to the mechanical behaviour of soil and rock, and their equilibrium. Since different geotechnical engineering properties have different LSL values they are very important in providing data for susceptibility studies. For this reason it is essential to group the geotechnical engineering properties properly (Carrara et al., 1991; Dai et al., 2001; Cevik & Topal, 2003; etc.). Soil and rock shear strength is an important engineering property. It is a fundamental property that governs the stability of natural and constructed slopes. It is not a unique value, but is strongly influenced by loading, unloading, and especially by water content. The shear strength is basically described as a function of normal stress on the slip surface (σ), cohesion (c), and internal angle of friction (φ). The relationship of these properties to other characteristics of natural soil has been given by Terzaghi and Peck (1967), and Fredlund and Rahardjo (1993).

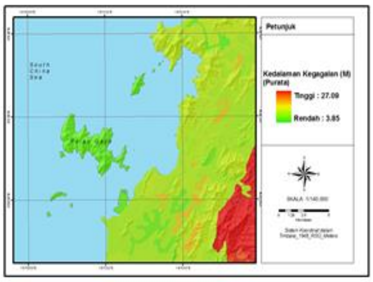
Geotechnical engineering properties of seventy two (72) soil samples indicated that the soil materials mainly consist of poorly graded to well graded materials of clayey, silty to sandy soils, which are characterized by low to high plasticity, effective cohesion (c’) ranges 4.67 kPa to 18.03 kPa, unit weight of soil (γ) ranges from 7.66 kN/m3 to 20.44 kN/m3, depth of failure surface (Z) ranges from 3.85 m to 27.09 m, height of ground water table (Zw) ranges from 0.00 m to 2.93 m, Zw/Z dimensionless (m) ranges from 0.00 to 11.30, effective angle of shearing resistance (ϕ) ranges from 1.700 to 26.070, tanϕ ranges from -5.540 to 2.280, slope surface inclination (β) ranges from 00 to 67.570 and sinβ, cosβ and cos2β ranges from -10 to 10 (Figure 7 and 8).



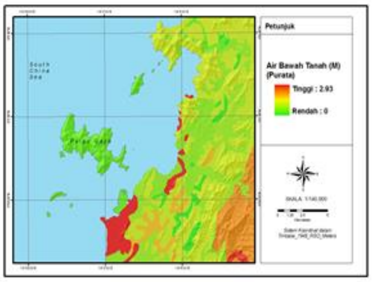
Effective cohesion (c’)



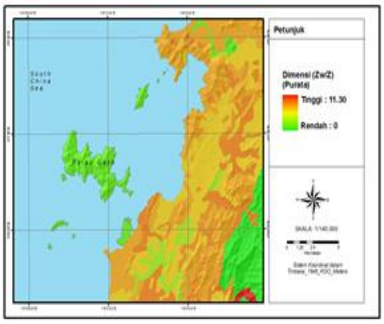
Unit weight of soil (γ)



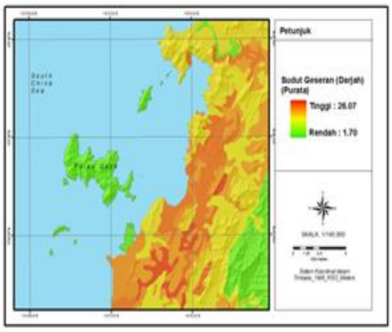
Depth of failure surface (Z)



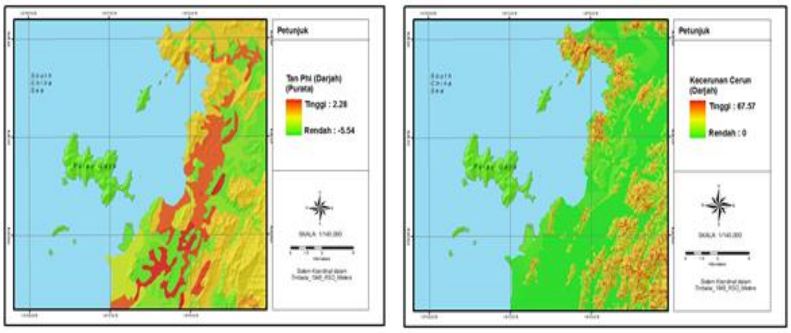
Height of ground water table (Zw)



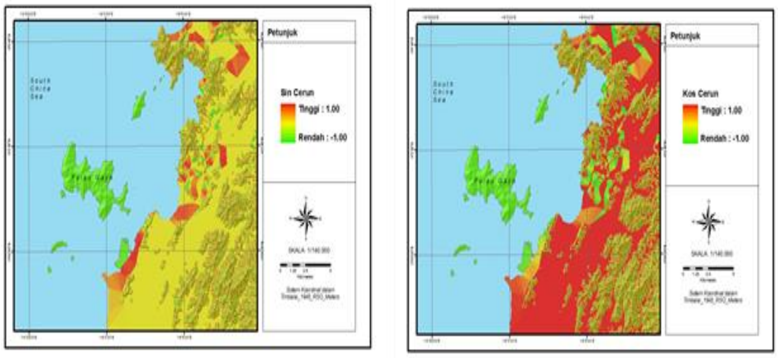
Zw/Z dimensionless (m)



Effective angle of shearing (ϕ)



tanϕ Slope surface inclination(β)



sinβ cosβ

Figure 7. Thematic maps for landslide hazard identification phase (LHIP) using Normal Polygon Geotechnical Deterministic Analysis (NPGDA)

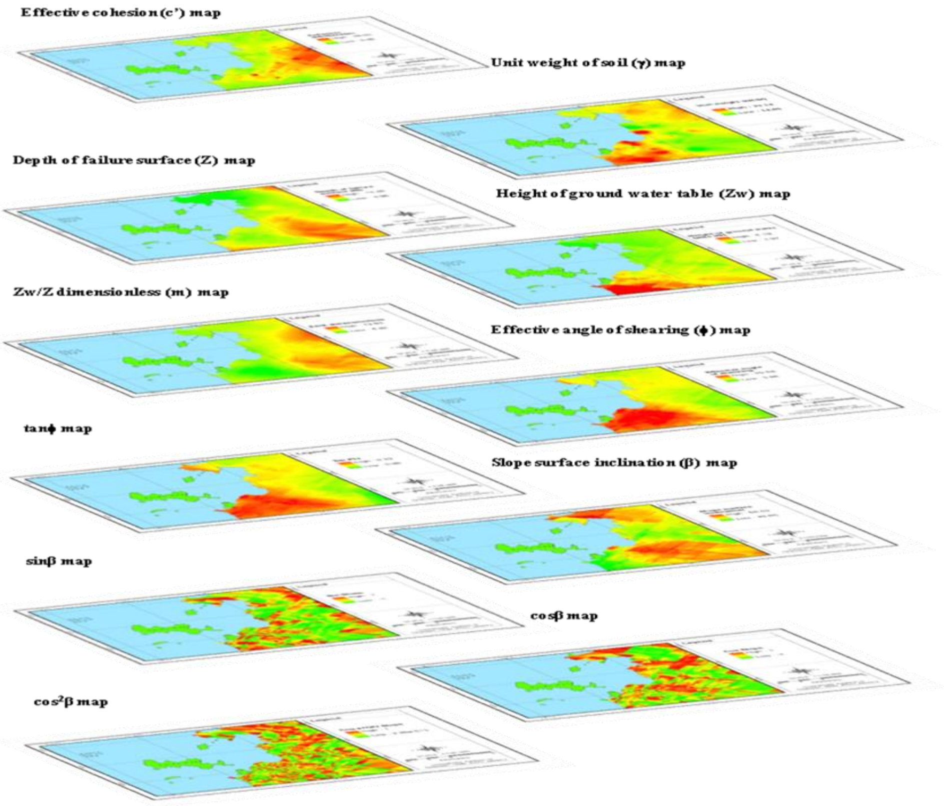


Figure 8. Thematic maps for landslide hazard identification phase (LHIP) using GEOSTAtistical INterpolation Techniques (Kriging) (GEOSTAINT-K)

F. Landslide Susceptibility Analysis (LSA)

After all thematic maps in phase 1 (LHIP) were produced, all of these parameters are compiled and compute according to the equation (1) and reanalysed together with LDM to generate a new thematic map known as "Landslide Susceptibility Analysis (LSA) maps" (Figure 9 and 10).

The resultant LSA maps provided a relative assessment of the landslide area using the FOS. The LSA for Normal Polygon Geotechnical Deterministic Analysis (NPGDA) suggests that areas of VLS to LS were 33% and 12%; and areas of MS to EHS were 29% of MS, 8% of HS, 8% of VHS and 10% of EHS (Figure 8). While the LSA for GEOSTAtistical INterpolation Techniques (Kriging) (GEOSTAINT-K) suggests that 38% of the area can be categorised as Very Low Susceptibility (VLS), 14% as Low Susceptibility (LS), 28% as Moderate Susceptibility (MS), 6% as High Susceptibility (HS), 6% as Very High Susceptibility (VHS) and 8% as Extremely High Susceptibility (EHS) (Figure 9).

A comparison of LSA-NPGDA and LSA-GEOSTAINT-K indicate that β and Zw parameter factors have the highest influence on landslide instability. This is evidenced by the changes in the percentages of MS to EHS, which increased about 1 % to 2% and decreased from 2 % to 5% in the LS and VLS. In general, VLS to MS areas (FOS = > 1.00) refer to the stable conditions with flat to moderately steep slopes with pasture and this area is highly recommended for any future development planned (Table 2). In contrast, HS to EHS areas (FOS = < 1.00) represent unstable conditions with steep slope segments. HS to VHS areas are basically not recommended to be developed due to geological, hydrological and geotechnical constraints. However, if there is no alternative or the developer or the local authorities really want to develop this area, some procedures to be observed are asstated in Table 2. EHS areas are strictly not recommended to be developed and should have provisions, and suitable non-structural works planning control as shown in Table 2 are recommended.

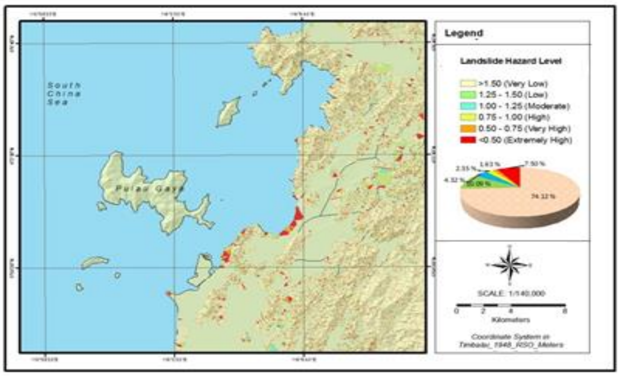


Figure 9. Landslide Susceptibility Analysis (LSA) map using Normal Polygon Geotechnical Deterministic Analysis (NPGDA)

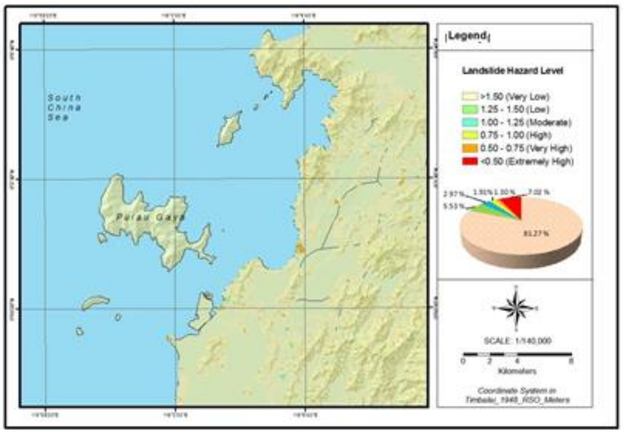


Figure 10. Landslide Susceptibility Analysis (LSA) map using GEOStatistical INterpolation Techniques (Kriging) (GEOSTAINT-K)

Table 2. Land use suitability classes from FOS value

Susceptibiity Degree	Requirements for development procedure
Very low (VLS)	- Development highly recommended. - Environmental Impact Assessment (EIA) must be conducted followed by suitable procedural guidelines or acts available (Handbook of EIA Guidelines, 2001 (DOE), Pindaan Akta Perancangan Bandar dan Desa, Akta A933 (1995), Garis Panduan DBKK, etc). - Detailed engineering geological and geotechnical reports. - Conduct landslide hazard assessment (LHA) – hazard identification & hazard analysis.
Low (LS) to Moderate (MS)	- Development slightly recommended. - Environmental Impact Assessment (EIA) must be conducted followed by suitable procedural guidelines or acts available (Handbook of EIA Guidelines, 2001 (DOE), Pindaan Akta Perancangan Bandar dan Desa, Akta A933 (1995), Garis Panduan DBKK, etc). - Detailed engineering geological and geotechnical reports. - Suitable structural control works planning (stabilization and mitigation). - Conduct landslide risk analysis (LRAn) – LHA, consequence analysis & risk estimation.
High (HS)	- Development to be allowed. - Environmental Impact Assessment (EIA) must be conducted followed by suitable procedural guidelines or acts available (Handbook of EIA Guidelines, 2001 (DOE), Pindaan Akta Perancangan Bandar dan Desa, Akta A933 (1995), Garis Panduan DBKK, etc). - Detailed engineering geological and geotechnical reports. - Suitable structural control works planning (stabilization and mitigation). - Conduct landslide risk assessment (LHAs) – LHA, LRAn & risk evaluation.
Very high (VHS)	- Basically development is not recommended. However, if there is no alternative or the developer or the local authorities really want to develop this area, some procedures to be observed

	are as follows: - Environmental Impact Assessment (EIA) must be conducted followed by suitable procedural guidelines or acts available (Handbook of EIA Guidelines, 2001 (DOE), Pindaan Akta Perancangan Bandar dan Desa, Akta A933 (1995), Garis Panduan DBKK, etc). - Detailed engineering geological and geotechnical reports. - Suitable structural control works planning (stabilization and mitigation). - Conduct landslide risk management (LRM) – LHA, LRAn, LRAs & risk treatment.
Extremely high (EHS)	- Development is not recommended. - Suitable non-structural control works planning: Regulatory measures, public awareness, disaster preparedness, behavioral modification and early warning system)

G. Verification of Landslide Susceptibility Map

For validation of landslide susceptibility calculation models, two basic assumptions are needed: (1) landslides are related to spatial information, such as topography and geology, and (2) future landslides will be precipitated by a specific impact factor such as rainfall or earthquake (Brabb, 1984; Chung & Fabbri, 1999; Varnes, 1978).

In this study, the two assumptions are satisfied because the landslides were related to the spatial information, and the landslides were precipitated by heavy rainfall in the study area. The LSA results were validated using known landslide locations. Verification was performed by comparing the known landslide location data (Figure 5) with the LSA maps (Figure 9 and 10).

Figure 11 illustrates how well the estimators perform with respect to the landslides used in constructing those estimators. To obtain the relative ranks for each prediction pattern, the calculated index values of all cells in the study area were sorted in descending order. The success rate validation results were divided into 100 classes with accumulated 1% intervals, according to the landslide susceptibility index value.

As a result, considering all the factors used in the study area, the 90–100% (10%) class, with the highest possibility of landslide, contains 38% and 62% of the landslide grid cells in success rate using the LSA-NPGDA and LSA-GEOSTAINT-Kmodels and continuously untilthe calculation of0% -100% (100%) of 100% of the total area in the rates obtained in this model, respectively.

To compare the result quantitatively, the areas under the curve were re-calculated with the total area assumed to be one, which means perfect prediction accuracy (Lee & Dan, 2005; Hyun et al., 2010).

Hence, the area under a curve can be used to assess the prediction accuracy qualitatively. The area ratios were 0.88 and 0.81, which indicate prediction accuracy of 88% and 88 %, respectively. Overall the cases where both factors and maximum LSA-NPGDA model was used showed a higher accuracy than cases where the LSA-GEOSTAINT-Kmodel were used.

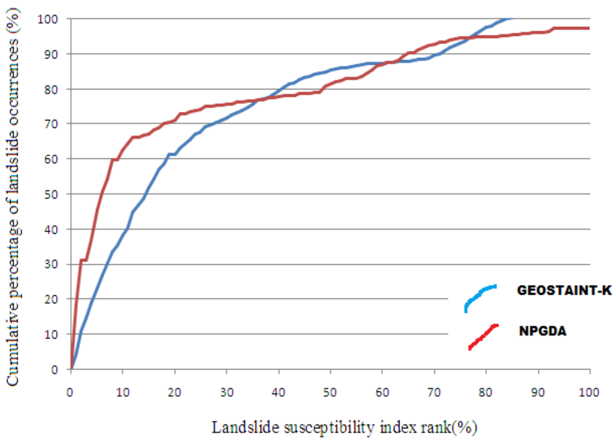


Figure 11. Illustration of cumulative frequency diagram showing landslide susceptibility index rank (y-axis) occurring in cumulative percentage of landslide occurrence (x-axis)

VI. CONCLUSION

In light of available information, the following conclusion may be drawn from the present study:

a. LSA maps indicate that slope surface inclination (β) and height of ground water table (Zw) parameter factors have the higher influence on landslide instability.

b. The benefit of a NPGDA and GEOSTAINT-K models is to provide insight and options for decision-making in practical problems. The benefits include:

  - It encourages a rational, systematic approach for assessing the safety of slopes, and a framework to put uncertainties and engineering judgment into a system and allows comparison of hazard and risk for different slopes.
  - LSA study allows collecting, management, analysis and dissemination of a large amount of data, widespread in the region. All of these actions, based on continuous scientific and technologic research, with a strong multidisciplinary component and the involvement of local, regional, and interregional authorities, allow effective regional land-use planning.

c. The verification result showed that LSA-NGDA (88%) performed better than LSA-GEOSTAINT-K (81%) for the study area.

GIS geospatial technology capability of LSA provides a valuable tool for gaining susceptibility level estimates at the regional scale. This result highlights the importance of the potential effects of landslides in the study area. The resulting LSA can be used by local administration or developers to locate areas prone to landslide area, determine the land use suitability area, to organize more detailed analysis in the identified “hot spot” areas and can manage the impact of landslide disaster that may affect the regional economy (loss and damage to property) or welfare of the community (deaths and homeless) (risky areas).

VII. ACKNOWLEDGMENT

Deep gratitude to Universiti Malaysia Sabah (UMS) for providing easy access to laboratories and research equipment. Highest appreciations also to the UMS for the fundamental research grant award Analisis Bencana Geologi di Kawasan Kota Kinabalu, Sabah (Geological Hazards Analysis at the Kota Kinabalu area, Sabah) (SBK0335-2017) and Pemetaan Geobahaya Kawasan Kota Kinabalu, Sabah (Geohazards Mapping at the Kota Kinabalu area, Sabah (UMSGreat: GUG0077-STWN-2/2016) to finance all the costs of this research.

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