

# Empirical Modeling on the Spatial Variation of Soil Thickness in Mountain Slopes for Large Scale Landslide Hazard Mapping with GIS Application

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## ABSTRACT

Soil thickness is one of the important parameters in the stability of mountain slopes. However, determination of its spatial distribution especially for large scale landslide hazard assessment is cumbersome, costly and time consuming. To address the problems of laborious field investigation, efforts have been done by many researchers to arrive at a reasonable prediction of this parameter over large areas. This study aimed to establish an empirical correlation model of the soil thickness with the slope angle. The data were gathered from 30 sampling points and 60 probed points within the study area with Pliocene-Pleistocene geology. The corresponding slope map was generated through a processed Digital Elevation Model (DEM) in Geographic Information System (GIS) platform particularly the ArcGIS software. Slope angles were confirmed in the site through actual measurement using the clinometer. The soil thickness was measured from the ground surface down to the interface of soil and the weathered bedrock. The regression analysis revealed that the soil thickness in the study area has good correlation to the slope angle with  $R^2$  of 0.9284. The resulting empirical model was validated from ten different sites with similar geology.

**Keywords:** Empirical model, Landslide, Slope stability, Slope angle, Soil thickness

## I. INTRODUCTION

In the Philippines, landslides are among the major geologic hazards that have caused socio-economic damages over the years. With the growth of population, the demand for suitable and necessary infrastructure and other services increases. Therefore, in a country that is mostly hilly and mountainous, utilization of land on slopes is inevitable. It is therefore very important to map out unstable areas in order to ensure the safety of the people by delineating suitable areas for development [1].

One of the most widely used methods in landslide hazard assessment or mapping is the physical-based models (deterministic). The landslide susceptibility is determined using slope stability models, which are based on Limit Equilibrium Method (LEM), resulting in the calculation of factor of safety [2]. Deterministic models provide the best quantitative information on landslide susceptibility that can be directly used in engineering works. Ho et al. [3] and Pachri et al. [4] confirmed that the soil thickness on hillslope, which often coincides with the failure depth, is a critical parameter in

performing a slope-instability analysis. The soil thickness can vary as a function of many different and interplaying factors, such as underlying lithology, climate, gradient, hillslope curvature, upslope contribution area, and vegetation cover, making the distributed estimation of soil thickness challenging and often unreliable [5]. Soil is the surficial material mantling the underlying weathered or fresh bedrock and lacking relict rock structure [6]. Kim et al. [7] added that soil thickness is of particular importance to the mechanical and hydrological properties related to hydraulic conductivity, transmissivity, and the angle of internal friction.

Furthermore, researches have been made to predict soil thickness over large areas in order to minimize, if not eliminate, expensive and laborious field investigations. Shallow landslides and debris flows are dangerous phenomena responsible for a large number of casualties and economic losses [8, 9]. Segoni et al. [10] added that soil thickness is a well-known factor controlling shallow landslides. However, its spatial variation over large areas is poorly understood. When trying to predict or model shallow landslides in a distributed way over large areas, one of the main problems is not the stability model itself, but the uncertainty in the spatial variability of the input parameters such

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as the soil thickness [11, 12, 13]. Therefore, attention should be given to choosing the right criterion to enter this parameter in slope stability models. Many authors rely on straightforward and simplistic solutions, such as considering a spatially constant value in the whole studied area [14, 6, 11, 12], using soil thickness classes [15], assigning a constant value for each geological formation encountered in the analyzed site [12], or deriving a distributed soil thickness map from a single known topographic attribute such as the elevation [16] or the slope gradient [17, 18]. More complex methods that make use of multivariate statistical analyses [19, 20, 21] or that employ process-based models [22, 23] are less frequently used in large scale slope stability analyses because they are very site specific and require some efforts to be correctly applied and calibrated over large areas. Kim et al. [7] also stated that some researchers included sparse soil thickness sampling data in the analysis of shallow landslides. However, Lee and Ho [24] adopted the wetness index to determine the spatial distribution of soil thickness for slope instability analysis. Ho et al. [3] also applied uniformly distributed soil thicknesses to assess the success rate for physically based shallow landslide prediction using different soil thickness assumptions for comparison. These methods presented in the literature will make the application of infinite slope model possible, yet it will not lessen the uncertainties of the input parameters particularly the soil thickness. To address this challenge, Obasi & Anyaegbunam [23] stated that there is now a tendency in countries all over the world towards building up correlation equations between soil properties in order to speed up the design process. This is most pertinent in third world countries where up-to-date testing equipment are lacking and the trained manpower needed to operate them.

While data on soil thickness are hardly determined, the data on slope angles can be obtained through the DEM from government agencies that are conducting government projects like Phil-LIDAR (Light Detection and Ranging). Slope map of the municipality can also be obtained from Municipal Planning and Development Office (MPDO) of the Local Government Unit (LGU). Moreover, slope angles can also be obtained through actual measurement in the site by using the clinometer. Hence, using this slope attribute to correlate with soil thickness will result in a model

that will enhance the present deterministic method of landslide hazard assessment.

On the other hand, Akayuli and Ofosu [26] stated that many researchers in the field of geotechnical engineering have used linear regression to establish empirical models between soil parameters. Yoon et al. [27] proposed best regression models for predicting compression index using natural water content, liquid limit and void ratio for Korean coastal area. Recently Abasi et al. [28] used regression analysis to predict the compression behavior of normally consolidated fine grained soil and concluded that the proposed empirical models predict the compression index accurately in comparison with the existing equations. Yildirim and Gunaydin [29] also estimated the California Bearing Ratio (CBR) of soils from different parts of Turkey using regression analysis. They concluded that the correlation equations obtained as a result of regression analyses are in satisfactory agreement with the test results and recommended that the proposed correlations will be useful for a preliminary design of a project where there is a financial limitation and limited time. It is evident in the literature that using regression analysis in correlating geotechnical parameters has been proved to be successful and widely accepted. Tan et al. [30] stated that although the soil thickness is related to many effect factors including the vegetation cover, the underlying lithology, the climate, the angle and curvature of slope, the land use and so on, it is more convenient to simply assume that the soil thickness decreases with the increasing slope angle for the engineering objectives. They assumed that there is a function relationship between the soil thickness and the slope angle. The correlation between soil thickness and slope angle from the field surveys and the other researches related to this issue are presented in the literature by Delmonaco et al. [31] and Salciarini et al. [18]. **Table 1** shows the summary of empirical relationships of soil thickness with slope angle from previous studies but using the same regression analysis.

**Table 1- Correlations of soil thickness with the slope angle from previous authors**

Authors	Empirical Correlation
Tan et al. (2008)	$H = 10.91 e^{-0.0515\alpha}$
Salciarini et al. (2006)	$d_{fb} = 14e^{-0.0693\alpha}$
De Rose (1996)	$Y = 5380\exp^{-.124X}$

Where  $H$ ,  $d_{lb}$  and  $Y$  are soil thickness and  $a$ ,  $\alpha$  and  $X$  are slope angle, Dietrich et al. [6] added that soil thickness strongly affects relative slope stability, yet the spatial variation in soil thickness in landslide-prone areas is rarely estimated, but with the exceptions of Okimura [32] and DeRose et al. [33]. Soils are typically thin to absent on sharply defined ridges and thickest in unchanneled valleys.

In addition, the assessment of regression relationships can be done through estimation of coefficient of determination, ( $R^2$ ). For example an  $R^2$  value of 0.5 means that 50 percent of the variation in the independent variable is being explained by the dependent variable. The values of  $R^2$  range between 0.0 and 1.0. An  $R^2$  value of 0.0 means that there is no correlation between the variables; an  $R^2$  value of 1 means that there is a perfect correlation between the variables. Haan [34] added that the quality of a regression relationship depends on the ability of the relationship to predict the dependent variable for observation on the independent variables that were not used in estimating the regression coefficients.

## II. METHODS AND MATERIALS

### The Study Area

The area of the study is located at New Kidapawan and Kiorao, Kibawe, Bukidnon as shown in **Figure 1**. The geographical coordinates of the municipality is  $7^{\circ}34'7''$  North latitude,  $124^{\circ}59'16''$  East longitude. Based on the geology map of the Philippines, the site has Pliocene-Pleistocene geology. Most the deposits associated with the Plio-Pleistocene glaciation are only 10,000 to 15,000 years old, largely because most of the earlier Plio-Pleistocene deposits were eroded by subsequent ice advances, and they are generally unconsolidated. Most were deposited in areas that were under ice or under water, but are now exposed on dry land because the ice and its associated water bodies are gone. Because glacial deposits are exposed on land (as steep cliffs in some cases) and because they are unconsolidated, they are especially prone to failure such as slumps and slides [35]. It was observed in the past decades that most landslide events in the entire municipality had occurred in this type of geology.

### Slope Angle from Digital Elevation Model (DEM)

The parameter necessary in deriving the empirical model in this study is the slope angle. The values of the slope angle were derived from digital elevation model (DEM) which was acquired from the Phil-LiDAR Central Mindanao University. The processed DEM was used in producing the slope map which was used as the working map showing the specific locations of sampling points. The slope map of the two barangays is shown in **Figure 1** which is generated from the ArcGIS software.

### Field Investigation

Field exploration was conducted to obtain actual measurements of slope angle and soil thickness as well as to obtain soil samples for the laboratory tests. Soil sampling was equally important as soil testing since these samples represent the characteristics of the soil found in the field. Sampling locations were selected based on the programmed slope angle ranges. The soil thickness was measured from the soil surface down to the interface between the soil and the weathered bedrock by auger and probe holes. The 30 boreholes were equally distributed to 10 different slope angle ranges. The actual slope angles in the

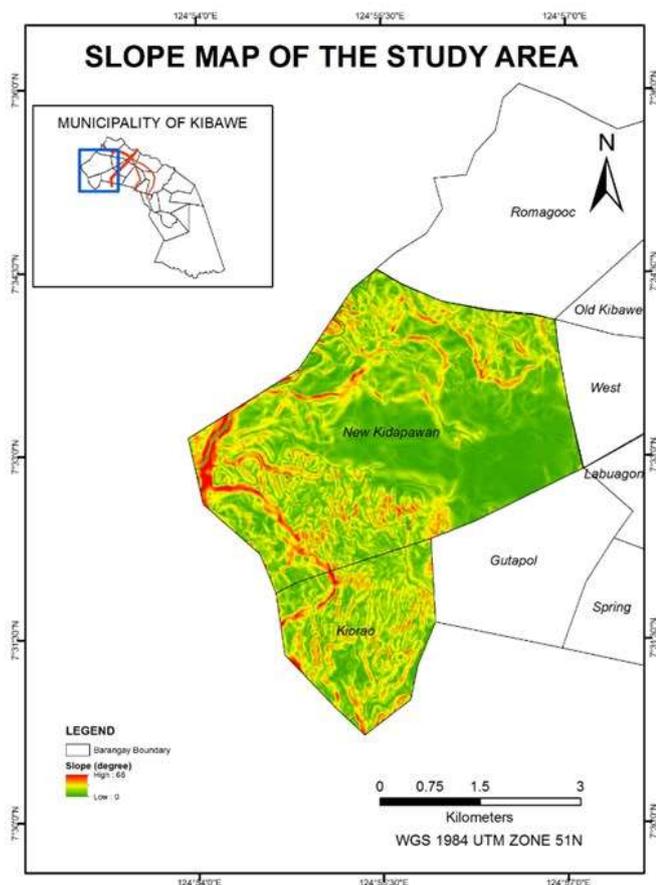


Figure 1. The location of the study area with its slope map

site were measured using the clinometer. In addition to the 30 boreholes, another 60 probed points were also established to obtain more data of soil thickness. A GPS was used to identify the location (latitude, longitude – elevation included) of the sampling points.

### Laboratory Tests

Physical properties and index tests were conducted to determine the engineering properties and classifications of soil under study. The physical properties of soil are considered as the most important preliminary phase for every type of civil engineering work. These are essential in understanding the behavior of soil which are needed in the analysis of earth structures such as structural foundations, dams and retaining walls. The physical properties such as: moisture content was determined based on ASTM D 2216 - Standard Test Method for Laboratory Determination of Water (Moisture) Content of Soil, Rock, and Soil-Aggregate Mixtures; particle size distribution was based on ASTM D 422 - Standard Test Method for Particle-Size Analysis of Soils; and total unit weight was determined from measuring the density in the field. Index tests were conducted by means of Atterberg Limits test. The index properties of the soil are liquid limit (LL), plastic limit (PL), plasticity index (PI), and liquidity index (LI) which are obtained via fall cone method.

### Regression Analysis

Regression analysis was used to establish the empirical model between the soil thickness and the slope angle. The coefficient of determination  $R^2$  was used to determine the quality of the relationships; the higher the value of  $R^2$ , the higher the quality of the relationship between the variables.

## III. RESULTS AND DISCUSSION

### Soil Classification and Characterization

Based on the results of index property tests, the plastic limit ranges from 13.15% - 39.88% or an average of 24.73%, which indicates that soils are from silt to clay. The liquid limit varies from 41.65% - 94.17%, which is within the range of 40% -150% for clay. The plasticity index varies from 14.11% - 71.28%, which is within the range of 10% to greater than 40%, indicating that it has medium to very

high plasticity. The liquidity index of the soil varies from 0.12 to 0.96. This range is within 0 to 1.0 which means that the soils at its in-situ water content are in the plastic state of intermediate strength and can be deformed like a plastic material. Based on USCS, there are four soil types in this geology, namely: High Plasticity Clay (CH), High Plasticity Silt (MH), Low Plasticity Clay (CL), and Low Plasticity Silt (ML). Among the soil samples, 13.33% has medium plasticity, 30% has high plasticity and majority or 56.67% resulted in very high plasticity. Considering the entire geology, the average PI is 40.83% which indicates that on the average the soil in the area has very high plasticity. On the other hand, based on AASHTO soil classification system, the soil belongs to A-7-5 and A-7-6 groups, which have moderate and high plasticity, respectively. There are two soil types in the area based on the Soil Type Map from Bureau of Soil and Water Management or BSWM (2004), namely, the Kidapawan Clay and Macolod Clay. These engineering properties of soil must have primarily affected the topography of soil in the area which is the primary indicating factor of soil thickness.

### Correlation of Soil Thickness with the Slope Angle

Regression analysis of soil thickness and slope angle of this study is presented in **Figure 2** with its coefficient of determination ( $R^2$ ). The results show that the soil thickness at the study area yielded good exponential correlation with the slope angle, with  $R^2$  of 0.9284. This finding agreed to the observation of Tan et al. (2008), Salciarini et al. (2006) and De Rose (1996).

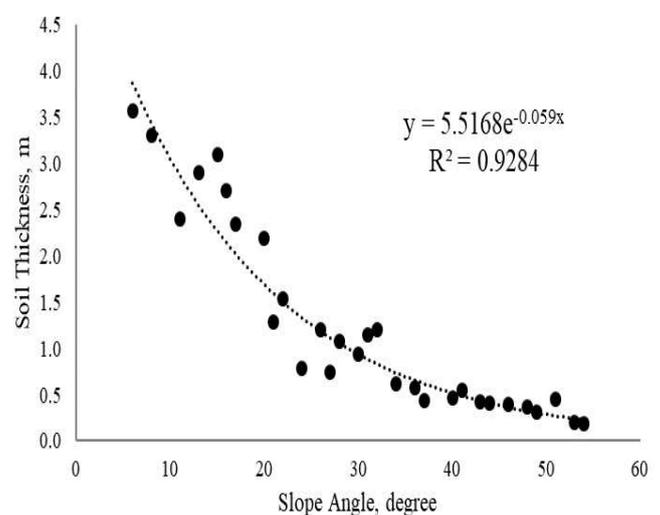
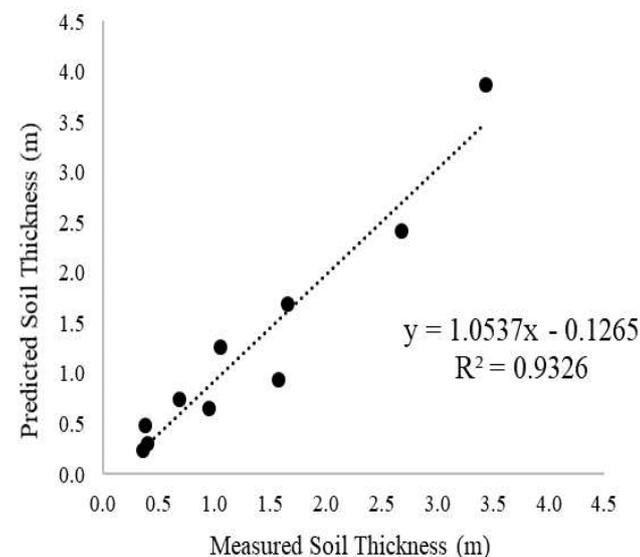


Figure 2. Empirical model of soil thickness with the slope angle

Moreover, this finding conforms to the general fact cited in the literature that soil thickness decreases with increasing slope angle. The average depths are 2.16 m for gentler slopes ( $< 28^\circ$ ), decreases to about 1.0 m for the modal class slopes ( $28^\circ - 32^\circ$ ), and to more or less 0.5 m for the steepest slopes ( $> 32^\circ$ ). The high coefficient of determination  $R^2$  of 0.9284 of the empirical model presented simply indicates that the spatial distribution of the soil thickness in the study area of Pliocene-Pleistocene geology can be mapped with reasonable degree of accuracy using the derived correlation equation together with the DEM using GIS platform.

The good correlation of soil thickness and slope angle is attributed to the fact that steeper slopes have accelerated erosion. If rate of erosion is greater than rate of soil development it will result in thin or no soil. On the other hand, soil in low-lying areas have higher water content and more weathering resulting in thicker soils.

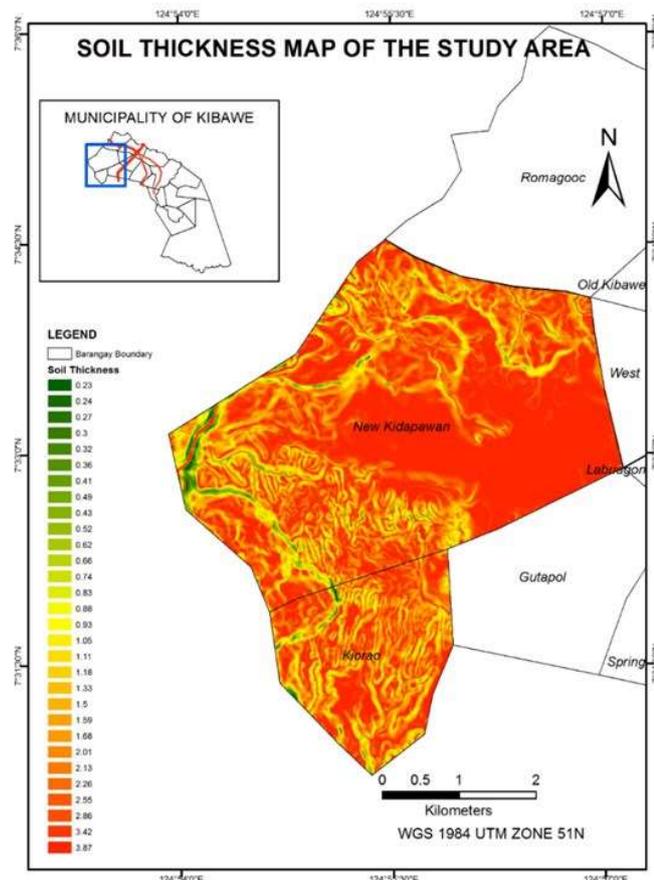
In order to verify the derived empirical equation between the slope angle and the soil thickness, the empirical equation derived was validated by predicting the soil thicknesses of other 10 sampling points outside the study area but of the same geology. The sampling site used for the validation was Barangay Katipunan, Arakan, North Cotabato. **Figure 3** shows the relationship of the predicted and measured soil thickness. The resulting relationship has high value of  $R^2$  of 0.9326, which indicates that the



**Figure 3. Validation of the model**

established equation is statistically reasonable and can be used to predict soil thickness of slopes located in the same geology.

**Figure 4** shows the soil thickness map in the area which is generated from ArcGIS platform using the established empirical model. As to reference to Figure 1, the output map shows that steeper slopes have thinner soil thickness, in contrast to gentler slopes with thicker soil.



**Figure 4. Soil Thickness generated using the derived empirical model**

## IV. CONCLUSIONS

The correlation of soil thickness with the slope angle is best described by an exponential function:  $y = 5.5168e^{-0.059x}$ , where  $y$  is the soil thickness (in meters) and  $x$  is the slope angle (in degrees). The equation has  $R^2$  of 0.9284, indicating high correlation between the two parameters. Furthermore, for the model validation, the predicted and the observed or measured values of soil thickness yielded a high  $R^2$  of 0.9326. The high correlation of empirical model of soil thickness with the slope angle means that it can be used to predict the spatial

variation of soil with less uncertainty. Since the empirical model was successfully validated at another site outside the study area, it can be used to predict soil thickness of other locations of the same geology. Finally, the derived empirical model can be used as input function in large scale deterministic landslide hazard assessment and mapping using slope stability analysis that employs Limit Equilibrium Method.

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