Slope Stability Analysis for Deterministic Shallow Landslide Assessment and Mapping: A Case Study in Kibawe, Bukidnon

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Abstract

The slope's stability in mountainous or hilly region is significantly important for the safety and protection of the people and the environment. Intensive field sampling was carried out in the study sites at Kibawe, Bukidnon, Philippines and soil samples were subjected to laboratory tests. The study applied the deterministic method through slope stability analysis to calculate the factor of safety (FOS) for landslide assessment. It also used Geographic Information System (GIS) particularly the ArcGIS software for FOS mapping. The results revealed that the study sites have mostly inorganic but highly expansive fine-grained soils. The values of the FOS varied in each steady-state condition. For fully-saturated and dry conditions, the values ranged from 1.54-9.98 and 1.94-12.66, respectively. For partially-saturated condition where m = 0.75, m = 0.5 and m = 0.25, the values of FOS ranged from 1.65-10.65; 1.74-11.32; and 1.84-11.99, respectively. In general, the FOS values signified that the study area was stable against sliding; however, there was a considerable decrease in FOS values when the slope changed from completely dry to fully-saturated condition. The created set of FOS maps lay out a visual impression and the variation of slope stability condition in the study area. The findings provide a baseline reference study for the area's slope stability that is essential in planning or further assessment of the study area. Furthermore, this can be directly used by the local government for land-use planning and future development.

***Keywords**:* GIS, slope stability, landslide, factor of safety, soil

1. Introduction

Landslide separates a mass of earth including rocks and soil from the mountainside or a slope, plunging the debris to the bottom and resulting in deep failure, debris flows or avalanches. Earthquake and excessive amount of rainfall are identified as some of the hazards making the slope vulnerable to a landslide (Dumlao and Victor, 2015). Landslide is considered as one of the most hazardous natural disasters, resulting in continuous road obstruction, infrastructural damage, loss of agricultural land, loss of buildings, and in some cases, loss of lives (Nandi and Shakoor, 2006; Roopnarine *et al*., 2013). The continuous development and urbanization, particularly in mountainous areas, have increased slope instability resulting in landslide. For this reason, this phenomenon has drawn global attention and needs to be seriously studied due to the vast damage it causes to the people and the environment.

Soil is the main material in slope stability structures. The geotechnical properties of soil differ in different locations; hence, it must be extensively analyzed and understood. The analysis will provide an insightful literature in categorizing its significant effect on the slope stability problem. Engineers primarily use the factor of safety (FOS) values in assessing the stability of the slope (Hossain and Islam, 2016). According to Rouaiguia and Dahim (2013), when the FOS value is close to 1.0, shear strength of the soil is nearly equal to shear stress. Thus, the slope is close to failure. On the other hand, if the FOS value is less than 1.0, the slope should have already failed.

Deterministic quantitative method is one of the approaches in assessing a landslide-prone area, which mainly depends on soil mechanics principles in terms of the slope stability analysis. This physically-based slope stability model properly analyzes existing or potential failure mechanisms using in-situ and laboratory test results (Ciurleo *et al*., 2017) and does not rely on the observation of past landslide events. This method is site-specific (Terlien *et al*., 1995) and is based on mathematical models (Alkhasawneh *et al*., 2012) which provides a high degree of accuracy. One of the advantages of this method is its capability in staging the practical details of the initial motion and the system leading to drive slope failure. Thus, landslide hazard researchers and civil engineers utilize this model to ascertain existing stability conditions, generate new slope designs, and assess possible landslide occurrences (Almeida *et al*., 2017).

Meanwhile, the Geographic Information System (GIS), a computer-based technique, can capture, store, analyze and display geographically referenced information such as the data identified according to a particular location or region (Mhaske and Choudhury, 2009). Many studies have been carried out on landslide susceptibility evaluation using GIS. For instance, Ayalew and Yamagishi (2005) conducted a study on the application of GIS-based logistic regression for landslide mapping in Japan. The results revealed that by using a predicted map of probability, 8.87% of the total study area was classified under medium and high susceptibility zones. Wang *et al.* (2009) assessed the susceptibility of landslides around the area of Guizhou Province in China by applying a qualitative map combination model to produce a landslide susceptibility zonation map using GIS. The findings disclosed that 66.14% of the landslides that occurred in total fall into the very high and high susceptibility class, while 28.36% and 5.50% of the landslides fall into moderate and low susceptibility classes, respectively. Moreover, GIS methods for modeling slope instability have been employed by different investigators throughout the world (Ray and Smedt, 2008). These include Aleotti and Chowdhury (1999), Guzzetti *et al.* (1999), Gorsevski *et al.* (2003), Mergili *et al.* (2014), Bouajaj *et al.* (2016) and Sanders (2017).

Kibawe is one of the municipalities of Bukidnon located in Region X of Northern Mindanao, Philippines. The said municipality is classified by Mines and Geosciences Bureau (MGB) as one of the areas with high susceptibility to landslides. According to the report documented by the National Disaster Risk Reduction and Management Council, the municipality experienced continuous occurrence of rains which caused multiple incidents of landslide and flooding on June 1 to 10, 2014. A total of 762 families were affected by the incident.

It is not advisable to locate communities or build infrastructure in areas identified by MGB as susceptible to landslides; however, relocation causes displacement of people from their communities and consequent loss of their source of livelihood which would have great social implications (Alejandrino *et al.*, 2016). It is a huge challenge to the government to create a detailed and accurate landslide hazard map, based on the mechanics of slope which can be easily adopted by the local authorities and engineering agencies for land-use planning and slope instability monitoring. Therefore, an attempt was made to conduct a study on the application of deterministic methods for landslide assessment and to produce landslide susceptibility maps of the study area through slope stability analysis.

2. Methodology

The study area is situated in the Municipality of Kibawe, Bukidnon, particularly barangay New Kidapawan and barangay Kiorao. The center of barangay New Kidapawan is geographically situated at 7° 33' 24.12" N latitude and 124° 55' 18.12" 41 E longitude with an elevation of 347.8 m above mean sea level. The center of 42 barangays, Kiorao is geographically situated at 7° 31' 42.24" N latitude and 124° 55' 43 8.76" E longitude with an elevation of 303.0 m above mean sea level.

The research methodology was divided into several stages. A reconnaissance survey was conducted to evaluate the accessibility of the study area. Using the Digital Elevation Model (DEM), the working map with predetermined 20 slope ranges was obtained from the slope map of 5m x 5m cell size. This application is commonly used in generating a slope map using GIS software.

Figure 1 shows the process of the ArcGIS in generating the working map. Based on the predetermined slope ranges, a total of 20 boreholes for soil sampling were identified on the working map. Handheld GPS was used to track the actual location of the 20 boreholes in the site and to fit the corresponding coordinates acquired from the GIS. Appropriate measures were undertaken to ensure that the correct amount of soil samples was taken from each borehole, bearing in mind its depth and thickness or depth of the residual soil. The collected soil samples were delivered to the Qualitest Solutions and Technologies, Inc. (QSTI) soil laboratory and subjected to various soil analyses such as density, moisture content, fall cone and direct shear tests, and grain size analysis. In the analysis, the research deemed it necessary to add 10 soil exploration reports made by Daleon and Lorenzo (2017) to supplement the data in order provide a broader picture of the area under study.

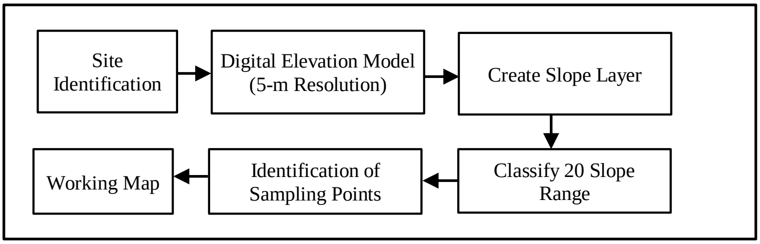

Figure 1. Steps in generating the working map in GIS

Figure 2 shows the procedure using ArcGIS in generating thematic maps.

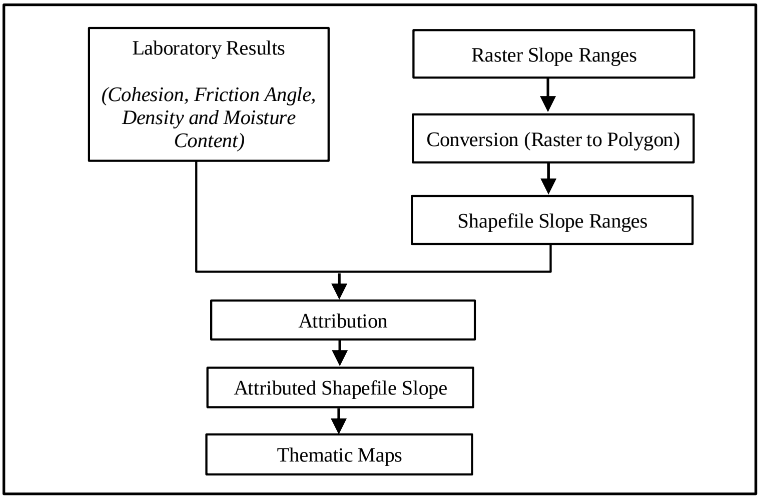

Figure 2. Steps in generating the thematic maps in GIS

Figure 3 shows the actual location of the 30 boreholes. The field and laboratory data were interpreted and used as an input parameter into GIS, particularly ArcGIS software, to provide interactive maps that show the spatial distribution of the variables and identify the soil characteristics and slope stability conditions.

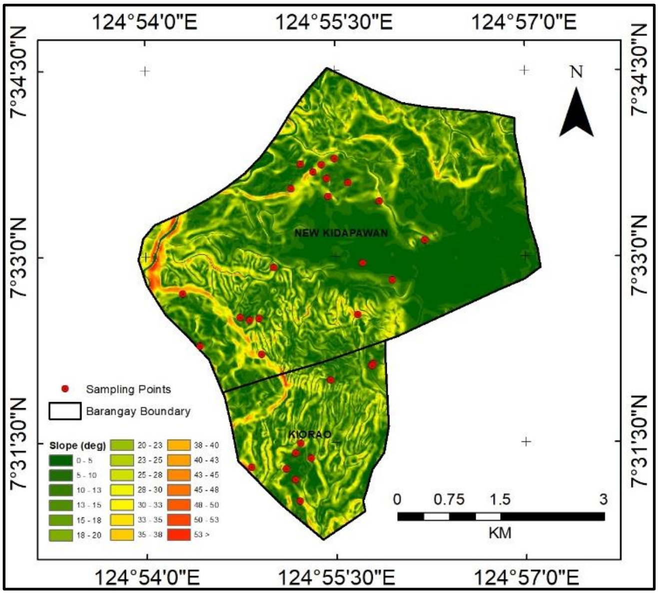

Figure 3. Actual location of the sampling points

In this study, the FOS was introduced as an indicator to quantitatively evaluate the state of stability of the slope. Three possible failure conditions were analyzed, namely: case 1– fully-saturated condition (the ratio of z_w and z or the value of m is 1.0); case 2– partially-saturated condition (the ratio of z_w and z or the value of m ranges from 0.25-0.75); and case 3– completely dry condition (the ratio of z_w and z or the value of m is 0).

The FOS was calculated using Equation 1 according to Brunsden and Prior (1979) as illustrated in Figure 4. The *FOS* is the slope stability factor of safety (adimensional), *c'* is the soil cohesion (kPa), ϕ' is the angle of internal friction of the soil (º), γ is the unit weight of soil (kN/m3), γw is the unit weight of water (kN/m3), and *ß* is the slope angle (º). The parameter m is the wetness index and relatively expressed in terms of the position of the water table, z_w/z (adimensional), in which z_w is the height of the water table above failure surface (m), and *z* is the sliding surface depth (m).

$$FOS = \frac{c' + (\gamma - m\gamma_w)z\cos^2\beta\tan\phi}{\gamma z\sin\beta\,\cos\beta} \tag{1}$$

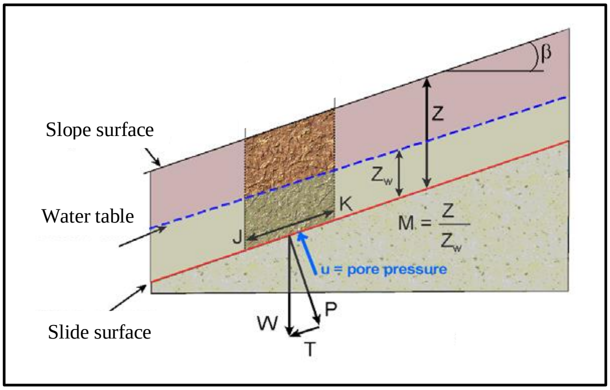

Figure 4. Analysis of infinite slope (Brunsden and Prior, 1979)

The FOS values were interpreted based on the presented slope stability classes elucidated by Ray and De Smedt (2008) as shown in Table 1. The slopes were denoted as unstable when the FOS is smaller than 1.0, quasi-stable when FOS is between 1.0 and 1.25, moderately stable if FOS is between 1.25 and 1.5, and stable when FOS is larger than 1.5.

Table 1. Slope stability classes (Ray and De Smedt, 2008)

Safety Factor	Slope Stability Class	Remarks
FOS > 1.5	Stable	Only major destabilizing factors lead to instability
1.25 < FOS < 1.5	Moderately Stable	Moderate destabilizing factors lead to instability
1.0 < FOS < 1.25	Quasi Stable	Minor destabilizing factors lead to instability
FOS < 1.0	Unstable	Stabilizing factors are needed for stability

3. Results and Discussion

3.1 Physical, Index and Mechanical Properties

The data on soil properties based on laboratory tests are summarized in Table 2. The ranges of the values are based on the laboratory results from the 30 soil samples. The results of the particle size distribution test showed that soil samples from the respective sites were generally fine-grained soil, with more than 50% of the material passing the 0.075 mm sieve. Classification of soils based on the Unified Soil Classification System (USCS) is presented in Table 3. The description is based on the laboratory results of the physical property and the degree of plasticity. This study had three types of soil, namely CH, MH, and CL-ML.

Table 2. Soil properties data

Soil properties	Value ranges	
	From	To
Gravel (%)	0.00	45.83
Sand (%)	0.48	58.52
Clay and Silt (%)	36.57	99.52
Moisture Content (%)	15.57	62.97
Density (kg/m^3)	1,264.70	1,684.20
Liquid limit, LL (%)	40.54	94.17
Plastic limit, PL (%)	11.33	46.82
Plasticity index, PI (%)	13.38	71.28
Cohesion (kN/m^3)	4.60	52.90
Friction Angle (°)	8.00	31.00

Table 3. Soil classification

Soil Classification	Slope Ranges	Cohesion (kPa)	Friction Angle (°)	Textural Class
CH	0 - 5	52.90	19.90	Dark reddish brown, silts
	5 - 10	20.00	20.95	Dark yellowish brown, silts with few sands
	15 - 18	14.10	22.35	Dark reddish brown, clays with few sands
	25 - 28	21.10	16.95	Dark yellowish brown, silts with little sands
	28 - 30	14.10	26.20	Dark reddish brown, silts with little gravels and traces of sands
	33 - 35	20.60	24.20	Dark reddish brown, silts with little sands and traces of gravels
	45 - 48	16.00	24.10	Very dark gray, silts with few sands and traces of gravels
	48 - 50	14.60	23.60	Dark brown, silts with some sands and few gravels
	50 - 53	29.00	14.85	Dark brown, silts with little gravels and few sands
	> 53	16.90	26.00	Dark brown, silts with traces of sands
MH	10 - 13	21.60	20.00	Dark brown, clays
	18 - 20	20.20	22.10	Dark brown clays, with few sands
	20 - 23	25.90	15.90	Dark yellowish brown, silts with some sands
	35 - 38	26.30	14.30	Strong brown, clays with little sands
	38 - 40	32.70	15.30	Dark reddish brown, clays with traces of sands
CL-ML	13 - 15	22.80	27.00	Dark brown, silts with some sands and traces of gravels
	23 - 25	22.60	21.10	Dark yellowish brown, gravelley clays with few sands
	30 - 33	22.60	17.80	Dark yellowish brown, sandy clays with little gravels
	40 - 43	20.30	15.95	Strong brown, clayey sands with some gravels
	43 - 45	17.60	15.90	Yellowish brown, clayey sands with some gravels

The Atterberg limits such as liquid and plastic limits, and plasticity index are normally used to assess the engineering properties of fine-grained soils. In this study, the liquid limit and plasticity index results were used to determine the expansiveness of the soil based on the IS 1498 degree of expansion criteria. The result revealed that most of the samples were inorganic but highly expansive fine-grained soils. Also, the clay and silt content in all the soil samples ranged between 36.57 and 99.52% which exceeds 32%, indicating extremely high expansive potential.

The shear strength parameters of soil are the cohesion and friction angle. These are the two important parameters of the soil in calculating the factor of safety. The values of cohesion and friction angle range between 4.6 kPa and 52.9 kPa, and 8.0°-31.0°, respectively.

3.2 Factor Safety Data

The values of the calculated factor of safety using Brunsden and Prior's proposed equation and their slope stability classification are summarized and presented in Table 4. Five conditions were analyzed including fully-saturated, completely dry, and three partially-saturated, i.e. with wetness index of 0.75, 0.50 and 0.25. The value of FOS varies in every slope range depending on the type of conditions. Under completely dry condition, the stability of a slope is governed by the parameters such as slope angle, soil cohesion, and angle of internal friction of the soil. The FOS values derived for this condition range from 1.94-12.66 which indicate that the slopes in the study were in stable condition.

Meanwhile, under partially-saturated and fully-saturated conditions, the stability of slope is governed by slope angle, soil cohesion, angle of internal friction of the soil, and the wetness index. Although it is very unusual to encounter partially-saturated and fully-saturated conditions especially in a mountainous area with steep slopes, these conditions are considered to evaluate the effect of the presence of the water table on the slope due to rainfall events and to determine the areas where landslides are more likely to occur. The partially-saturated condition results showed that the FOS values with wetness index of 0.25, 0.50, and 0.75 ranged from 1.84 to 11.99, 1.74-11.32, and 1.64-10.65, respectively. Although the values denote that the slope is stable against sliding, decreasing values of FOS were noticed.

Table 4. Factor of safety values

Slope Ranges	Factor of Safety				
	m = 0	m = 0.25	m = 0.50	m = 0.75	m = 1.0
0 - 5	12.66	11.99	11.32	10.65	9.98
5 - 10	5.48	5.06	4.64	4.22	3.81
10 - 13	5.04	4.62	4.21	3.79	3.37
13 - 15	3.21	3.01	2.80	2.59	2.39
15 - 18	2.34	2.15	1.95	1.75	1.55
18 - 20	2.79	2.61	2.43	2.26	2.08
20 - 23	3.53	3.41	3.28	3.16	3.04
23 - 25	4.88	4.74	4.59	4.45	4.31
25 - 28	2.71	2.61	2.51	2.41	2.31
28 - 30	3.09	2.93	2.77	2.61	2.44
30 - 33	3.57	3.49	3.41	3.33	3.25
33 - 35	4.52	4.41	4.30	4.19	4.08
35 - 38	5.49	5.43	5.38	5.33	5.27
38 - 40	8.94	8.89	8.85	8.80	8.75
40 - 43	4.06	4.01	3.96	3.91	3.87
43 - 45	4.13	4.05	3.96	3.87	3.79
45 - 48	5.09	5.03	4.97	4.90	4.84
48 - 50	1.94	1.84	1.74	1.64	1.54
50 - 53	9.12	9.09	9.05	9.01	8.97
> 53	7.42	7.35	7.28	7.22	7.15

Moreover, the fully-saturated condition gave the lowest values of FOS among the five conditions which ranged from 1.54 to 9.98. The FOS values for the slope range 15-18 and 48-50 were 1.55 and 1.54, respectively, which can be considered as very near to moderate stability under this condition. These slope ranges have CH type of soil. This scenario implies that the stability of a slope is greatly influenced by the presence of water. According to Bidyashwari *et al.* (2017), as the water content increases, the stability of the slope decreases thus, the factor of safety.

3.3 Factor of Safety Maps

The computer-simulated factor of safety maps for the completely dry, partially-saturated and fully-saturated conditions are presented in Figures 5 to 9.

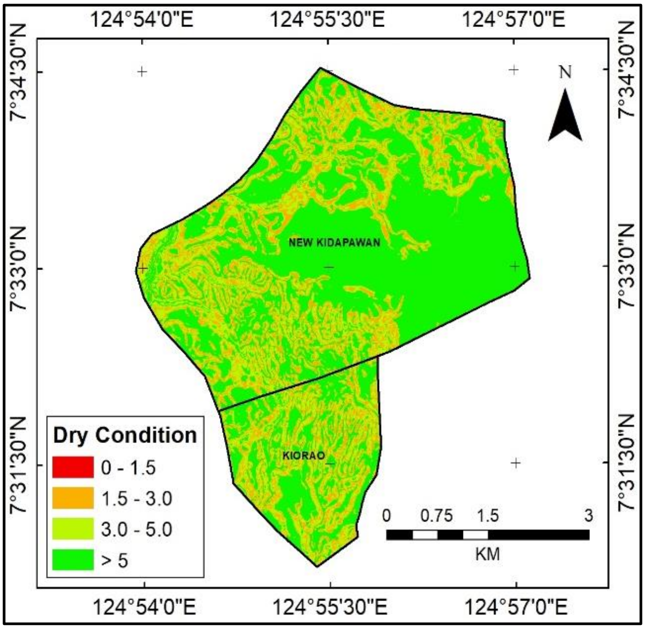

Figure 5. Completely dry condition where m = 0

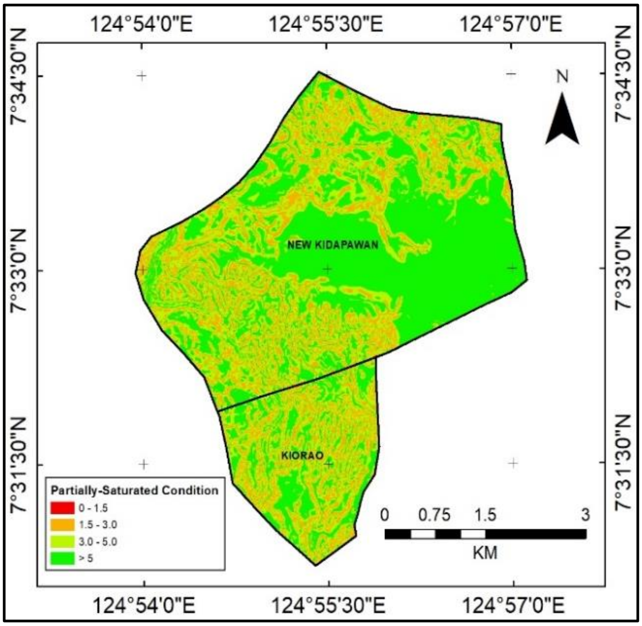

Figure 6. Partially-saturated condition where m = 0.25

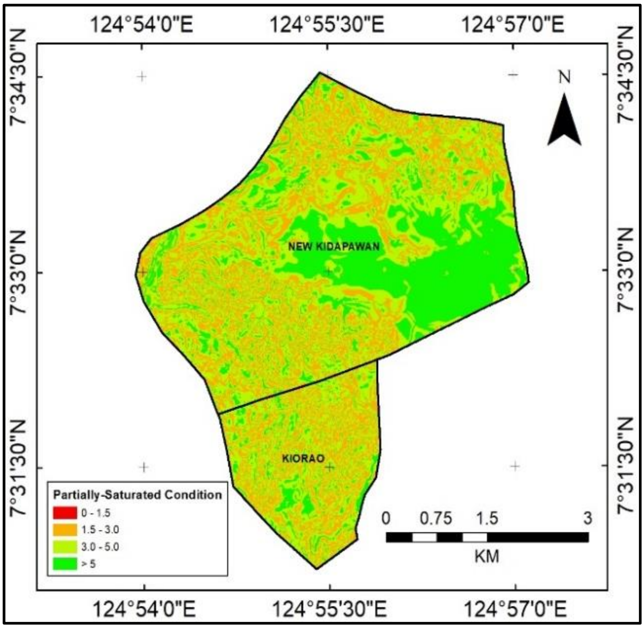

Figure 7. Partially-saturated condition where m = 0.50

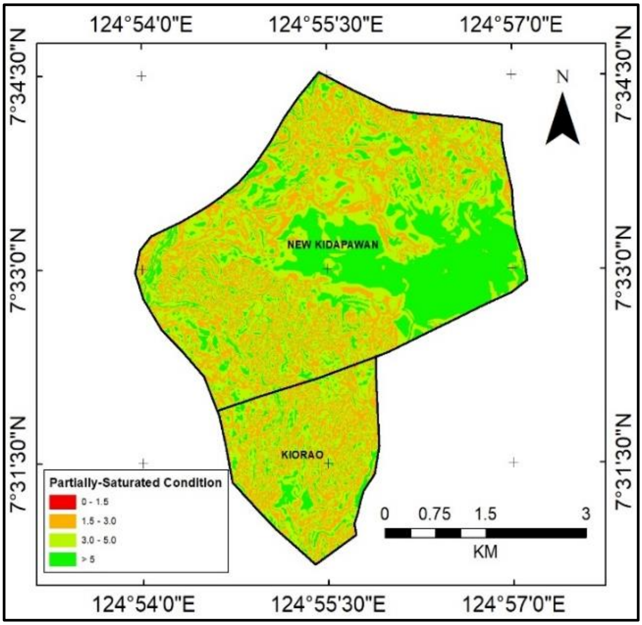

Figure 8. Partially-saturated condition where m = 0.75

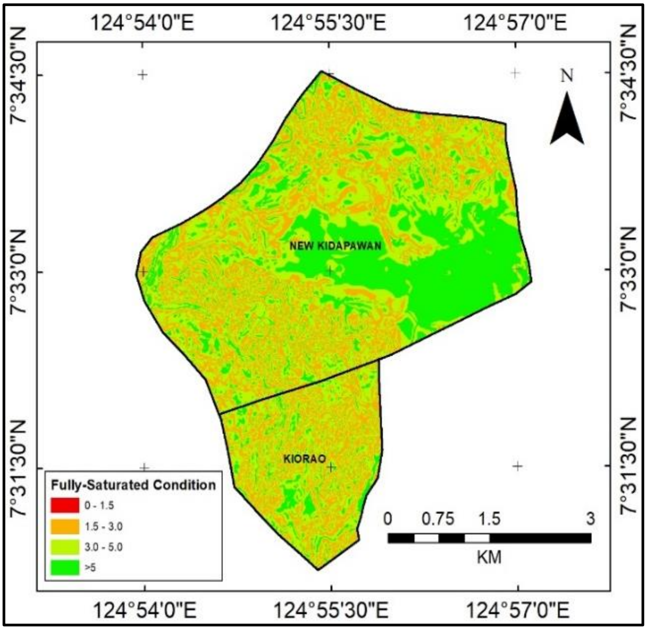

Figure 9. Fully-saturated condition where m = 1.0

As can be seen in the figures, the distribution of the colors in terms of its stability is not relatively dependent on the slope ranges or slope angle of the terrain although it is a usual expectation that a steeper slope is prone to sliding or will have smaller FOS values. This is mainly because the FOS values vary in every slope range since it depends on the in-situ and laboratory results of the soils. Furthermore, the stability of the slope is generally affected by the presence of the water table or pore pressure. Under completely dry condition, it is observed in the map that the study area is covered with green, light yellow and yellow color which implies that the slopes are stable against sliding. However, an increase in the wetness index values in the equation changes the dispersal of the colors in the maps as displayed in partially and fully-saturated maps. This signifies that an increase in the wetness index values may lead to instability of the slope in the study area.

The Mines and Geosciences Bureau (MGB) hazard map of Kibawe, Bukidnon is shown in Figure 10. Comparing the MGB hazard map with the produce FOS maps, the generated FOS maps are more detailed in terms of the degree of hazard or slope instability in the study area. Also, it is more accurate since it is based on the concept of slope stability analysis, unlike MGB-produced map which is descriptive and subjective. However, the FOS map can be improved by integrating the seismic acceleration factors, land cover to rainfall infiltration and root cohesion to the equation.

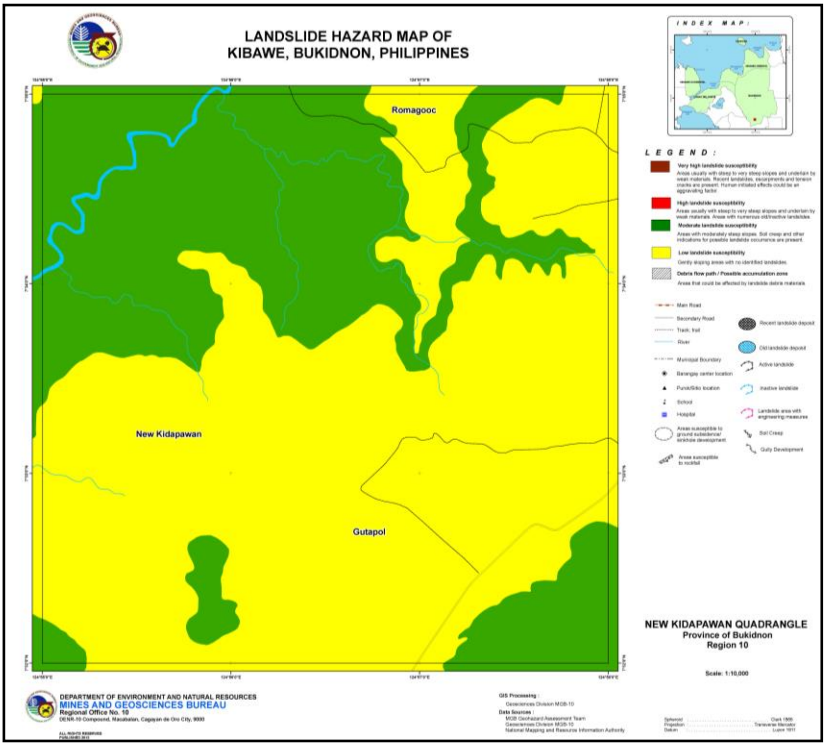

Figure 10. Landslide hazard map of Kibawe, Bukidnon (Department of Environment and Natural Sciences, Mines and Geosciences Bureau, Region 10, 2013)

4. Conclusion

The FOS values signify that the study area was stable against sliding. However, it can be noticed that there was a considerable decrease in FOS values when the slope changed from completely dry to fully-saturated conditions. The presence of water affected the stability condition of the slope. The created set of FOS maps provide a visual impression and the variation of slope stability condition in the study area. Thus, this paper lays out a baseline reference study for the slope stability that is essential in planning or further assessment of the study area. Moreover, the study provides the local government the critical information necessary in land-use planning and future development of the area.

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