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DEVELOPMENT OF A NON-EXPERT TOOL FOR SITE-SPECIFIC EVALUATION OF LANDSLIDE SUSCEPTIBILITY

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Abstract

The development of simplified procedure for evaluating susceptibility of slope to rainfall induced, shallow-depth landslides is presented. The procedure is based on the concept that for extended slopes, the shear strength of the slope material should be greater than the applied load on the slope. The concept is extended to include all types of slope materials including rocks and intermediate geomaterials by developing an empirical shear strength rating system. The proposed system does not require expensive and sophisticated laboratory or in situ field tests and can be performed using improvised tools for estimating slope angle and material strength. This approach makes it suitable for preliminary landslide susceptibility screening by non-experts. A system of empirical weighting factors to take into consideration the effects of vegetation, prior slope failures and ground deformation, land use, drainage and artesian flow are presented. Comparison of the proposed procedure with existing procedures for estimating landslide susceptibility shows good agreement in results.

Keywords: *Landslide, slope stability, risk rating, land use planning.*

1 Introduction

The Philippines is one of the most disaster-prone countries in the world because of its geographic location and geologically active environment. It is characterized by high seismicity and active volcanism as it straddles three major tectonic plates; additionally, the Philippine Fault cuts across the eastern length of the archipelago. Moreover, a third of the country's land area comprises of steep slopes. An average of 30 typhoons visits the country every year because it lies along the path of tropical cyclones. All of these combine to make the country highly susceptible to landslides. Landslide is a general term used to describe the down-slope movement of soil, rock and organic materials under the influence of gravity. It is a normal landscape process in mountainous areas, but becomes a problem when it results in serious damage that often approach disaster proportions. As cities and towns grow, roads and highways and other amenities progressively encroach onto steeper slopes and mountainsides. Subsequently, these infrastructures attract further built-up environments. Landslide hazards become an increasingly serious threat to life and property. Recent major landslide occurrences have claimed hundreds of lives and caused significant property damage: Cherry Hills-Antipolo (1999), Panaon Island-Surigao (2003), Aurora-Quezon (2004), St. Bernard, Southern Leyte (2006), and more recently on 1 December 2006, mudflows triggered by tropical storm Reming (Durian) devastated the communities around Mayon Volcano, killing 753 people and destroying P1.7 billions worth of property. This paper describes a simplified procedure for site-specific evalua-

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tion of slope to susceptibility to shallow seated, rainfall-induced landslides. The proposed procedure is simple enough to be performed by a non-expert so that the potentially unstable slopes can quickly be identified, hence more detailed geotechnical studies and appropriate mitigation measures can be undertaken.

2 Theoretical framework of proposed procedure

The framework of the proposed procedure takes off from the simple notion that for extended slopes, the strength of material S should always be greater than the applied load L resulting in a ratio of S L $>$ 1 for a stable slope. For granular and frictional materials such as gravelly, sandy and silty soils, this ratio S L usually refers to the Factor of Safety Fs given by the expression

$$F_s = \tan\phi / \tan\alpha \qquad (1)$$

where ϕ is the angle of friction of the slope material and α, the slope angle. The expression tan ϕ essentially defines the shear strength of these materials and tan α is a representation of the load which is primarily due to gravity. The concept of the factor of safety F_s in Equation (1) is extended in this study to include all slope materials and is defined by the expression

$$F_s = \frac{SRating}{\alpha Rating} \qquad (2)$$

In the above expression, *SRating* is a numerical index ranging from 1 to 100 that characterizes the strength of the slope material whereas α Rating is also a numerical index that ranges from 1 to 100 and is proportional to the tanα. Rating system for slope angle α follows this rule: if slope angles were to be grouped as listed below, the *αRating* is the tangent of the mean of the range of the group, normalized such that the *αRating* for the range α = 75 is 100. The value of *αRating* for specific ranges in the slope angle α is assigned on the basis the guidelines shown in Table 1.

Ideally, the slope angle α for a given slope should be measured by using an angle measuring device such as tiltmeter, anglemeter, or protractor. In cases where such a device is not available, the angle can be estimated using the folded paper technique shown in Figure 1. In this procedure, it is assumed that the slope under consideration has only one slope angle α and a predominant slope material. If the slope angle varies, but the variation is within the range of angles corresponding to a single *αRating* and if the predominant material is uniform within the area, then the area is treated as a single area. If the slope angle varies, and the variation is outside the range corresponding to a single *αRating*, then the area should be subdivided into smaller areas with width of 10 m or longer.

Table 1: *αRating* for various slope angles. Slope Angle

Slope Angle α	*αRating*
75°	100
60° ≤ α < 75°	32
45° ≤ α < 60°	17
30° ≤ α < 45°	10
15° ≤ α < 30°	5
α < 15°	2

2.1 Basic strength index rating for slope materials

The value of the *SRating* is assigned by the usage of the following guidelines as summarized in Table 2. For rock slopes, the material classification can be performed in situ by using a Schmidt rebound hammer or through unconfined compressive strength tests performed on core samples. For such cases, the following scheme may be used for purposes of determining the material type for rock slopes:

HR-1: unconfined compression strength $\sigma_{ci} \geq$ 20 MPa, Schmidt hammer rebound value $HR \geq 30$, with crack or discontinuity spacing $s \geq 200$ cm, and Geological Strength Index 55 $\leq$ GSI $\leq$ 100.

HR-2: unconfined compression strength $\sigma_{ci} \geq$ 20 MPa, Schmidt hammer rebound value $HR \geq 30$, with crack or discontinuity spac-

Table 2: *SRating* for various slope materials.

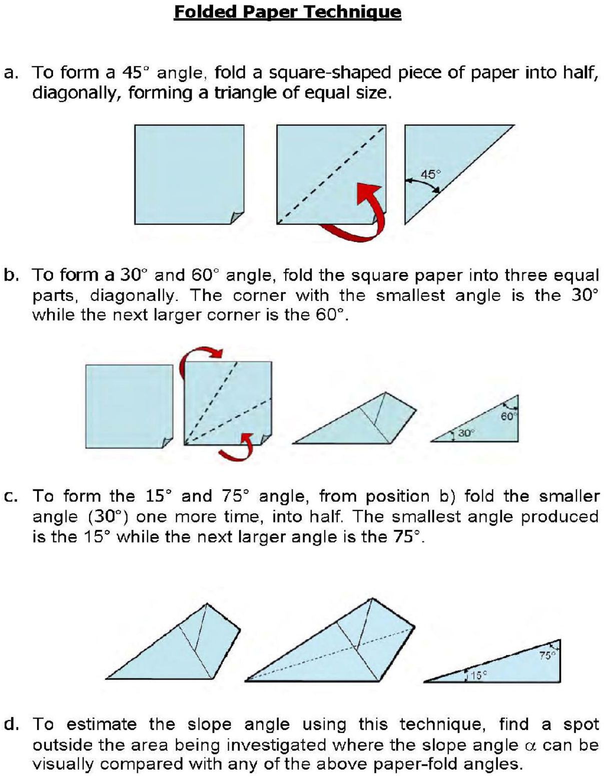
Material	Slope Material	*SRating*
HR-1	Massive and intact hard rock	100
HR-2	Blocky, well-interlocked hard rock, rock mass consisting mostly of cubical blocks	45
HR-3	Very blocky, disturbed hard rock with multi-faceted angular blocks formed by 4 or more discontinuity sets	25
HR-4	Disintegrated, unstable rocks and boulders, protruding rock fragments	13
SR-1	Massive and intact soft rock	30
SR-2	Very blocky and fractured soft rock	15
HS-1	Stiff, cemented and dense gravelly, sandy, silty and clayey soils	25
SS-1	Gravelly soil	10
SS-2	Sandy soil	8
SS-3	Clayey/silty soil	5

ing $s \geq 60$ cm, and Geological Strength Index $35 \leq \mathrm{GSI} \leq 55$.

HR-3: unconfined compression strength $\sigma_{ci} \geq 20$ MPa, Schmidt hammer rebound value $HR \geq 30$, with crack or discontinuity spacing $20\mathrm{cm} \leq s \leq 60\mathrm{cm}$, and Geological Strength Index $25 \leq \mathrm{GSI} \leq 35$.

HR-4: unconfined compression strength $\sigma_{ci} \geq 20$ MPa, Schmidt hammer rebound value $HR \geq 30$, with crack or discontinuity spacing, $10\mathrm{cm} \leq s \leq 60$ cm and Geological Strength Index $5 \leq \mathrm{GSI} \leq 25$.

SR-1: unconfined compression strength $\sigma_{ci} < 20$ MPa, Schmidt hammer rebound value $HR > 30$, with crack or discontinuity spacing, $s \geq 200$ cm and Geological Strength Index $55 \leq \mathrm{GSI} \leq 100$.



Folded Paper Technique

a. To form a 45° angle, fold a square-shaped piece of paper into half, diagonally, forming a triangle of equal size.

b. To form a 30° and 60° angle, fold the square paper into three equal parts, diagonally. The corner with the smallest angle is the 30° while the next larger corner is the 60°.

c. To form the 15° and 75° angle, from position b) fold the smaller angle (30°) one more time, into half. The smallest angle produced is the 15° while the next larger angle is the 75°.

d. To estimate the slope angle using this technique, find a spot outside the area being investigated where the slope angle α can be visually compared with any of the above paper-fold angles.

Figure 1: Folded paper folded technique for estimating slope angle.

SR-2: unconfined compression strength $\sigma_{ci} < 20$ MPa, Schmidt hammer rebound value $HR < 30$, with crack or discontinuity spacing, $s \leq 200$ cm and Geological Strength Index $5 \leq GSI \leq 35$.

In cases where the shear strength cannot be estimated either by Schmidt hammer or through laboratory testing of core samples, the SRating can be estimated by driving a 4-inch wire nail into the outcrop as shown in Figure 2. For hard rocks (HR-1 through HR-4), it is not possible to penetrate the rock mass given that the material has a shear strength in excess of that of concrete (21 MPa). In the case soft rocks, 4-inch nail can be driven into the rock mass because the shear strength is less than that of concrete.

For soil materials, the SRating for each of the slope material can be obtained by using geotechnical parameters of conventional in situ tests or by laboratory shear strength tests performed on undisturbed samples collected from the field. Table 3 summarizes the various geotechnical parameters corresponding to each

Figure 2: Hammer and nail test for estimating material classification in rock slopes.

slope material type. In cases where access to a study site is limited, to prevent mobilization of drilling rig, the Swedish weight sounding test (SWST) as shown in Figure 3 can be used, given the portability of the apparatus. The test was developed and standardized by the Swedish State Railways and has been in use since 1914. The apparatus consists of a screw point, sounding rods, rotating handles and 10 individual weights of 10 kg each making a total of 100 kg. In addition to the geotechnical parameters previously described in Table 3, the SRating for soil slopes should be estimated based on the following qualitative descriptions for each material type:

HS: can be easily penetrated by a 4-inch wire nail; a fist size will crumble or deform with hand pressure but will not crumble or deform with finger pressure. The thumb will not indent sample, but can be easily indented by thumbnail.

SS-1: Gravelly soil with most particles between 5mm to 75mm in diameter. Fist size sample or smaller containing 5 or more particles will crumble under finger pressure.

SS-2: Sandy soil with particles size of no more than 5 mm in diameter and grains can be distinctly felt with fingers. Sample crumbles under finger pressure.

SS-3: Clayey or Silty soil in which particles cannot be felt with finger, especially when wet. Thumb can indent and will crumble with finger pressure.

Table 3: Geotechnical parameters for estimating material classification for soil slopes

Material	SPT N	SWST N_{sw}	S_u (KPa)	ϕ
HS	> 15	≥ 80		35°- 45°
SS-1	≤ 20	≥ 80		30°- 45°
SS-2	≤ 10	≤ 80	≤ 80	15°- 35°
SS-3	≤ 5	≤ 60	≤ 70	5°- 25°

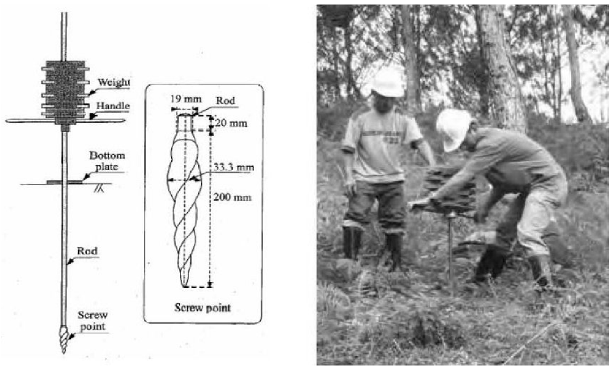


Figure 3: Swedish weight sounding test (SWST).

2.2 Additional factors

In addition to the strength factor and slope factor, the following factors as summarized in Table 4 are considered in this study to influence the stability of the slope.

2.3 Vegetation cover

The effect of vegetation cover on the shear strength of slope is taken into consideration by multiplying vegetation factor / *vFactor* to the modified *SRating* of the slope. Table 5 summarizes the numerical value for *vFactor* for different vegetation types.

Table 4: Other factors that affect the stability of the slope.

Factor	Shorthand name
Vegetation	*vFactor*
Occurrence or frequency of Failure	*fFactor*
Presence of springs	*sRed*
Conditions of drainage system	*dRed*
Land use	*lFactor*

2.4 Frequency of failure and deformation

The presence and frequency of previous failures and visible signs of ground deformation is used to reduce the modified $SRating$ by multiplying with the factor $fFactor$ together with the $vFactor$ previously described. Table 6 summarizes the numerical value for fFactor corresponding to different types and occurrences of slope failure and deformation.

Table 5: Types of vegetation and corresponding numerical values for vFactor.

Type	*vFactor*
No Vegetation	1.0
Predominantly grass or vegetation with shallow roots	1.1
Coconut, bamboo, or vegetation with moderately deep roots	1.3
Tress with age less than or equal to 20 years	1.5
Trees with age more than 20 years	2.5

Table 6: Geotechnical parameters for estimating material classification for soil slopes.

Frequency & occurrence of failure	*fFactor*
Once a year or more than once a year	0.5
Presence of past failure, but occurrence not yearly	0.7
Presence of tensile cracks in ground	0.7
If retaining wall present, wall is deformed	0.7
None	1.2

2.5 Presence of springs

The effect that springs have on the stability of the slope is incorporated into the rating system through the factor sRed which is subtracted from the SRating. Table 7 summarizes the numerical values of sRed different durations of artesian or spring flow.

Table 7: Geotechnical parameters for estimating material classification for soil slopes.

Duration	*sRed*
Yearlong	2
Only during rainy season	1
No flow/spring	0

Table 8: Geotechnical parameters for estimating material classification for soil slopes.

Condition	*dRed*
No drainage system	2
Totally clogged, filled with debris	2
Partially clogged or overflows during heavy rains	1
Water leaks into the slope	1
Good working condition	0

2.6 Drainage conditions

The effect of drainage conditions on the stability of the slope is incorporated into the rating system through the factor $dRed$ which is subtracted from the $SRating$. Table 8 summarizes the numerical values of $dRed$ in different drainage conditions. The spring $sRed$ and drainage condition $dRed$ factors are subtracted from the unmodified $SRating$ to obtain the modified $SRating$. It is then further modified by multiplying by $vFactor$ and $fFactor$.

2.7 Land use

The effect of land use on the stability of the slope is incorporated multiplying the $\alpha Rating$ with $lFactor$ to reduce F_s. Table 9 summarizes the numerical value for $lFactor$ for different land use types. The overall factor of safety F_s, taking into consideration all the modification factors previously described, is then computed using the following expression:

$$F_s = \frac{[vFactor \times sFactor \times (SRating - sRed - dRed)}{\alpha Rating \times lFactor} \tag{3}$$

The level of stability or susceptibility is then assessed as follow: $F_s > 1.2$ is considered stable; $1 \leq F_s < 1.2$ is considered marginally stable; 0.7 $\leq F_s < 1.0$ is considered susceptible; and $0.7 < F_s$ is considered highly susceptible.

If $F_s < 1.0$, and life, limb and property are stake, then the following precautions are further recommended:

1. Evacuate the area whenever a strong rain is forecasted or expected within the area;
2. Report the situation immediately to concerned local government officials with a request for further and more detailed evaluation to be carried out by a competent geotechnical engineer or engineering geologist; and
3. If the affected area is a private property, the owner should take the initiative to consult a geotechnical engineer or engineering geologist for appropriate mitigation measures.

In cases where failure of the slope would affect several households or a community, a more detailed geotechnical site investigation should be undertaken even if the slope is marginally stable ($1.0 \leq F_s < 1.2$).

2.8 Validation of rating procedure

More landslide surveys were carried out after Typhoon Pepeng, which caused tragic landslides in Baguio City, Benguet and Mt. Province. Included in the database were twenty-three (23) sites, among which are the Little Kibungan landslide in La Trinidad, Benguet where the fatalities were 146 and the Kayan East Landslide in Tadian, Mt. Province where 47 people were buried. When grouped according to FS, the results as shown in Table 10 were obtained. When the same sites were evaluated using the Japan Road Association (JRA, 1988) Procedure and the procedure proposed by the Japanese Ministry of Construction (MOC, 1997), the results contained in Tables 11 and 12 were obtained respectively. Results of the preceding analysis shows that the proposed procedure, despite its very simple nature, is capable to accurately estimate the susceptibility of slopes to failure, and gives results that are comparable to existing methods for estimating landslide susceptibility such as the JRA 1988 and MOC 1997 procedures. It should be noted that for the proposed procedure, reliable results for slopes in which a factor of safety $F_s < 0.7$ is obtained.

Table 9: Geotechnical parameters for estimating material 10classification for soil slopes.

Land use	*vFactor*
Dense residential area with closely spaced structures < 5m apart	1.4
Commercial with buildings having 2 storeys or more	1.4
Residential area with building having 2 storeys or less spaced at ≥ 5m apart.	1.25
Road/highway with heavy traffic (1 truck or more every 10 mins)	1.4
Road highway with light traffic (less than 1 truck every 10 mins)	1.25
Agricultural area, grasslands and bushlands	1.0
Uninhabited and no vegetation	1.0

Table 10: Summary of evaluation using the proposed procedure.

	Sites	Failed	Failure
$F_s \geq 1.2$	13	0	0
$1.0 \leq F_s \leq 1.2$	10	1	10%
$0.7 \leq F_s \leq 1.0$	71	47	66%
$0.7 < F_s$	142	134	94%
Total	238	182	77%

3 Conclusions

The development of simplified procedure for evaluating susceptibility of slope to rainfall induced, shallow-depth landslides is presented. The procedure is based on the concept that for extended slopes, the shear strength of the

Table 11: Summary of evaluation using JRA 1988 procedure

Risk Rating	No. of Sites	No of Sites Failed	% Failure
Slope failure likely	229	179	78%
Slope failure probable	7	3	43%
Slope failure unlikely	0	0	0

Table 12: Summary of evaluation using the MOC 1997 procedure

F_s	No. of Sites	No of Sites Failed	% Failure
Very High	27	22	81%
High	178	146	82%
Moderate	31	14	45%

slope material should be greater than the applied load on the slope. The concept is extended to include all types of slope materials including rocks and intermediate geomaterials by developing an empirical shear strength rating system. The proposed system does not require expensive and sophisticated laboratory or in-situ field tests and can be performed using improvised tools for estimating slope angle and material strength, making it suitable for preliminary landslide susceptibility screening by non-experts. A system of empirical weighting factors to take into consideration the effects of vegetation, prior slope failures and ground deformation, land use, drainage and artesian flow are presented. Comparison of the proposed procedure with existing procedures for estimating landslide susceptibility show good agreement in results.

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