Probability of Failure based on Morphometric Characteristic of Slope in Padang Pariaman, West Sumatera, Indonesia

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Abstract

Infrastructure is needed to provide human's civilization. In the process of building an infrastructure, risk planning is needed in order to prevent disaster. Therefore, probability method is needed in order to retrieve the probability of slope failure, the studied natural phenomenon, as the morphometric used in order to simplify the process. Slope failure, in the context of natural slope, is very influenced by geological condition of the slope. Morphometric is a method that used in order to provide interpretation based on morphological condition of studied area. Probability method that commonly used in probability of failure analysis is Monte Carlo. The data then is used to create random variables for Monte Carlo calculation. By using factor of stability (FS) ≥1 as a threshold of safe slope or FS≤1 as a threshold of failure, the results from all of the tests are divided into two: the results that fulfill the requirement of safe slope and the results that fulfill the requirement of failure. Ratio between the results that fulfill the requirement of failure with test frequency becomes the probability of failure. Regions are divided by slope inclination, based on morphometric process. These regions have their own probability of failure (PF) range, which the lowest number is 0% and the highest number is 23.61%. According to the simulations, the PF range is always increased in wet condition. Furthermore, the PF from the result should be appropriate with the design criterion and aspect of natural situation based on literature for acceptable PF. If not, further analysis has to be done.

Keywords: Failure probability, morphometric analysis, Monte Carlo simulation

1. Introduction

As human become more civilized, their demand of needs is actually increased. Infrastructure indeed, is one of the needs that can support human's civilization. In the process of building an infrastructure, risk planning is needed in order to prevent disaster. The disaster in the context is a natural phenomenon that causes loss of life or property damage. In this study, we treat the phenomenon of slope failure and by knowing probability of failure, risk categories can be assessed. We have to accept that there will always be an uncertainty in the acquired data and even more of uncertainty if the study area is very big. The uncertainty of data cannot be solved by averaging their number as we know that averaging bias is cannot be accepted in any scientific analysis, the solution is probability method where the output is the chance of phenomenon to occur. Therefore, probability method is needed in order to retrieve the probability of slope failure, the studied natural phenomenon, as the morphometric used in order to simplify the process. While the orthodox failure analysis usually has a very detailed study area scale, this probability method can be applied into a wide area as long as the area said is in a same population. If we can apply this probabilistic method to a wide area, lots of time and expenses will be saved. And by all means, this study about probability of failure based on morphometric is only a small step to further risk assessment.

2. General

2.1 Slope Failure

Slope failure, in the context of natural slope, is very influenced by geological condition of the slope. If it causes loss of life or property damage, it can be categorized as geological hazard. As the failure may occur when the slope cannot hold the mass of its own, the causes of failure can be categorized into two i.e.: internal factor and external factor. Internal factor is its own technical characteristic of consisting material, while external factor is every other thing that not coming from the slope itself such as artificial load. In this study, these factors are termed as parameters. As the geological condition affect the failure, the type of failure is depends on it. Mathematically, a very simplified formula of factor of stability (FS) given by Wyllie et al. (1981) calculates ratio between driving force (D) and resisting force (R):

$$FS = R/D \quad (1)$$

Where, R and D could be affected by cohesion (c), internal friction angle (ϕ), weight of slope mass (W), water pore pressure (μ), length of sliding plane (L), and slope angle (α). Therefore, R and D can be written as:

$$R = c \times L + (W.\cos\alpha - \mu) \quad \tan\phi \quad (2)$$

$$D = W.\sin\alpha \quad (3)$$

2.2 Morphometric Analysis

Morphometric is a method that used in order to provide interpretation based on morphological condition of studied area. As the geometry of slope is one of the factors that affect the slope stability, morphometric analysis is taken as an approach to simplify the process. Taken as grid or contour, every point has its own elevation. Based on the elevation and contour interval, slope inclination can be determined by using a very simple tangential equation.

2.3 Monte Carlo Simulation

Probability method that commonly used in probability of failure analysis is Monte Carlo. Refer to Gibson (2011); the method is very simple compared to other elegant and complicated methods of probabilistic, yet powerful enough to provide proper analysis. The basic concept of Monte Carlo is to predict occurrence of a phenomenon which assumed by a threshold. The calculation formula of Monte Carlo depends on the threshold and the parameters that affect it, while the accuracy depends on frequency of test. The parameters are used to create random variables for test, where each test has random variable that differs with the other. Given 10000 of tests, the random variable that needed are 10000 sets.

In this study, where slope failure is the phenomenon, we use factor of stability (FS) as the threshold. Assumed that slope failure is occurs when the R (equation 1) of slope is lower than the D (equation 2). Therefore the threshold of failure is,

$$FS \leq 1 \quad (4)$$

While the threshold of safe slope is,

$$FS \geq 1 \quad (5)$$

Then by using the threshold, probability of failure (PF) is given by,

$$PF = (N-M)/N \quad (6)$$

Where (N-M) is the results of test that did not fulfill the threshold of safe slope, instead they fulfill threshold of failure. M, is the results that fulfill the threshold of safe slope and N is the total frequency of tests. Therefore, the PF will be given as percentage.

The frequency of test (N), however, is assumed to have correlation with standard deviation (d), error (α), and PF. The following shows the mathematical formula of N given by Gibson (2011):

$$N = \left(\frac{d}{\alpha}\right)^2 \frac{1-PF}{PF} \quad (7)$$

The equation can also be written as,

$$\alpha = d\sqrt{\frac{1-n}{n.p}} \quad (8)$$

As refer to Gibson (2011), standard deviation assumed based on a certain confidence level. The following table (Table 1) is the correlated standard deviation and confidence level. By using error number (α), PF range can be acquired as follow:

$$PF' = PF - (PF.\ \alpha) \quad (9)$$

$$PF' = PF + (PF.\ \alpha) \quad (10)$$

Table 1 Standard deviation based on confidence level, Gibson (2011)

Confidence Level (%)	Standard Deviation (d)
80	1.28
85	1.44
90	1.64
95	1.96
99	2.57

2.4 Acceptance Level of PF

Based on Read & Stacey (2010), a few recommendations exist in the literature for acceptable PF for design; one of them is Kirsten (1983) cited in

Table 2 PF design acceptance guidelines Kirsten (1983) in Read & Stacey (2010)

PF (%)	Design criteria			Aspects of natural situation	
	Serviceable life	Public liability	Minimum surveillance required	Frequency of slope failures	Frequency of unstable movements
50-100	None	Public access forbidden	Serves no purpose	Slope failures generally evident	Abundant evidence of creeping valley sides
20-50	Very very short-term	Public access forcibly prevented	Continuous monitoring with intensive sophisticated instruments	Significant number of unstable slopes	Clear evidence of creeping valley sides
10-20	Very short-term	Public access actively prevented	Continuous monitoring with sophisticated instruments	Significant instability evident	Some evidence of slow creeping valley sides
5-10	Short-term	Public access prevented	Continuous monitoring with simple instruments	Odd unstable slope evident	Some evidence of very slow creeping valley sides
1.5-5	Medium-term	Public access discouraged	Conscious superficial monitoring	No ready evidence of unstable slopes	Extremely slow creeping valley sides
0.5-1.5	Long-term	Public access allowed	Incidental superficial monitoring	No unstable slopes evident	No unstable movements evidence
<0.5	Very long-term	Public access free	No monitoring required	Stable slopes	No movement

Read & Stacey (2010), as follows (Table 2):

3. Methodology

First, we assume that soil in the study area is residual soil of weathered former rock. Based on that assumption, we can simplify soil's technical characteristic based on its lithological source. Morphometric process is taken in order to provide slopes geometric data, and then region are divided based on its morphometric properties. Soil samples are taken in some points in order to retrieve geotechnical data, which are cohesion and friction angle. The data then is used to create random variables for Monte Carlo calculation. By using FS≥1 as a threshold of safe slope or FS≤1 as a threshold of failure, the results from all of the tests are divided into two: the results that fulfill the requirement of safe slope and the results that fulfill the requirement of failure. Ratio between the results that fulfill the requirement of failure with test frequency becomes the probability of failure. The test will be done in two conditions which are wet condition and dry condition, each condition is assumed in an extreme condition. Therefore, the final output is PF ranges for each region in wet and dry condition, and then this PF ranges will be categorized based on their recommended acceptance level.

4 Result and Discussion

The study area consists of pumiceous tuff, mixed layer, and paleosol. Commonly, grain sizes vary from silt to silt with low plasticity. The properties of parameters and assumed slope geometry that will be used to create random variables are taken, peak cohesion and peak friction angle are taken by using direct shear test (Table 3).

The regions are divided based on its slope inclination (Figure 1). Each Monte Carlo test is done by using equation (1) to (3), where the mentioned thresholds are (4) and (5) in 10000 number of test. Assumed that the tests have 95% of confidence level, the given standard deviation for results is 1.96. The error can be retrieved by using equation (8). The result (Table 4) can be retrieved by using equation (6), (9), and (10). Therefore, by using literature for PF by Kirsten (1983) in Read & Stacey (2010), each region can be assessed based on its design criterion and aspects of natural situation (Table 5).

5 Conclusion

Regions are divided by slope inclination, based on morphometric process. These regions have their own PF range, which the lowest number is 0% and the highest number is 23.61%. According to the simulations, the PF range is always increased in wet condition. Furthermore, the PF from the result should be appropriate with the design criterion and aspect of natural situation based on literature for acceptable PF. If not, further analysis has to be done.

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Table 3 Parameter used to create random variables

Parameter	Min	Max	Average	Standard deviation
Peak cohesion (kg/m)	4000	340000	121833.3	110945.78
Peak friction angle (^{o})	23.91	39.42	31.91	5.85
Density (kg/m^3)	1172	1768	1395	261.69
Mass area (m^2)	42.55	54.48	48.52	8.44
Length of sliding plane (m)	86.80	88.34	87.57	1.09
Slope height (m)	57	76.50	66.75	12.79

Table 4 Results of Monte Carlo test

Region	Inclination (%)	PF dry (%)	PF wet (%)
1	0-2	0%	1.16%-1.63%
2	2-15	0%	2.46%-3.11%
3	15-70	1.6%-2.2%	11.78%-13.07%
4	70-100	10.39%-11.62%	21.96%-23.61%

Table 5 PF guidelines for study area

Region	Design criteria			Aspects of natural situation	
	Serviceable life	Public liability	Minimum surveillance required	Frequency of slope failures	Frequency of unstable movements
1	Very long-term up to medium Term	Public access free up to discouraged	No monitoring required up to conscious superficial monitoring	Stable slopes up to no ready evidence of unstable slopes	No movement up to extremely slow creeping valley sides
2	Very long-term up to medium Term	Public access free up to discouraged	No monitoring required up to conscious superficial monitoring	Stable slopes up to no ready evidence of unstable slopes	No movement up to extremely slow creeping valley sides
3	Long-term up to very short term	Public access allowed up to actively prevented	Incidental superficial monitoring up to continuous monitoring with sophisticated instruments	No unstable slopes evident up to significant instability evident	No unstable movements evidence up to some evidence of slow creeping valley sides
4	Very very short-term	Public access forcibly prevented	Continuous monitoring with intensive sophisticated instruments	Significant number of unstable slopes	Clear evidence of creeping valley sides

Figure 1 Map of the regions in study area