Slope Stability Analyses using Probabilistic Approach (A Case study in Grobogan, Central Java)

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ABSTRACT: Naturally, soil parameters are uncertain random phenomena in a certain range. This uncertainty is also caused by the process of soil testing. In a slope stability analyses, the probabilistic approach may become an alternative method to take into account this uncertainty. The safety factor is optimized with the probability of failure (Pf) that is matching with the soil parameter distribution function using Chi-Square, Kolmogorov-Smirnov and Anderson-Darling methods. In this study, a number of slopes in Grobogan, Central Java, were analyzed using Monte Carlo simulation and simplified Bishop with the available soil parameters from laboratory tests. The result indicates that the greater the safety factor, the smaller the probability of failure. In this study, category of high risk impact (maximum Pf = 25%) produces a safe slope angle recommendation for maximum slope reaches 5 m with a slope angle up to 55°. The category of low risk impact (maximum Pf = 50%) produces a safe slope angle recommendation for maximum slope reaches 6 m with a slope angle of less than 60°.
Keywords: Monte Carlo, parameter uncertainty, probability of slope failure.

1. INTRODUCTION

The stability of the slope is influenced by soil parameter, which consist of the unit weight, cohesion, and friction angle. The value of these parameters are uncertainty with the random phenomena causing random variables. In this situation, the value of paramaters cannot be determined with certainty and tend to be in a certain range of values (Ang, 1976). The slope stability analysis is generally conducted deterministically.

However, this method cannot answer what is the probability of failure occurance due to the uncertainty of the parameters. Optimization is needed in the deterministic analysis, so that safety factor can increase the level of confidence in the calculation. With probabilistic approach, the uncertainty of soil parameters are taken into consideration as random variables.

This paper presents a case study of slope stability analyses using probabilistic approach. Slopes and soil properties of the slopes were taken from a Soil Investigation Report in Project of Electric Transmission in Mojoagung village to Warukaranganyar along 30 km, Grobogan, Central Java (Fig. 1).

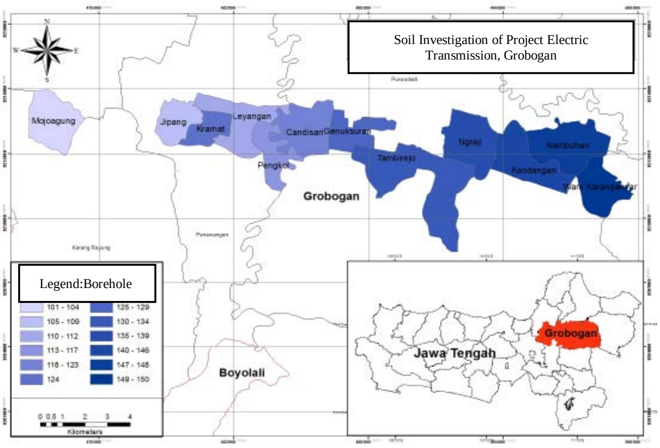


Figure 1. Location of study

2. SCOPE AND OBJECTIVES

The soil parameters in this study are unit weight (γ), cohesion (c), and friction angle (φ). Based on the data, between a depth of 1 m to 8 m, no groundwater was found. To find the best fit of soil parameter distribution function, in this study used Chi-Square, Kolmogorov-Smirnov and Anderson-Darling methods. Slope stability analysis was conducted using simplified Bishop method with the Entry and Exit procedure. Monte Carlo simulation for probabilistic calculation used 2000 trial (Malkawi et al in Khan (2013). The probability of failure is defined as probability of safety factor less than 1 (Pf = P (SF<1)). The probability of failure standard of slope failures is referred to SRK 2010 (Arif, 2016).

According to this standard, slope can be categorized as a high risk impact with allowed Pf up to 25% and a low risk impact with allowed Pf up to 50%. Output besides Pf is the reliability index (β) which has the formula $\beta = (\mu_{SF} - 1) / \sigma_{SF}$, with μ_{FS} is mean of SF and σ_{SF} is standard deviation of SF. The standard value β used for slope stability is 2 (US Army, 1999).

3. METHODOLOGY

The sequence of the study as follows: data validation, fitting model distribution, geometry modeling, and slope stability analysis with probabilistic approaches. According to the laboratory report, each soil properties have 100 data. The soils were categorized as clay with very soft to medium consistency. Those data are presented in Table 1.

Table 1. Summary of Data

Parameter	γ (kN/m^3)	c (kN/m^2)	φ (°)
n	100	100	100
minimum	14,27	4	3
maximum	21,14	70	24

Based on the Table 1, each soil parameter has minimum and maximum value. The value of each parameter must be validation with typical value for very soft to medium consistency. Typical view of slope failure in Grobogan is presented in Figure 2.

Figure 2. Typical view of slope failure in Grobogan

3.1 Data Validation

Firstly, soil properties validated with typical value of each soil parameter for clay soil with very soft to medium consistency. The result is shown in Table 2.

Table 2. Soil Properties

Parameter	γ (kN/m^3)	c (kN/m^2)	φ (°)
data $_{\text{(before validation)}}$	100	100	100
data $_{\text{(after validation)}}$	90	99	98
minimum	14,27	4	3
maximum	18,79	26	19

3.2 Fitting distribution

The smallest distribution value between the Chi Square (C-S), Kolmogorov-Smirnov (K-S), and Anderson-Darling (A-D) methods is the best fit distribution parameter. Fitting distribution used @RISK trial version program based on data are as follows:

a) Unit weight (γ)

The most suitable distribution for unit weight is lognormal that shown in Table 3.

Table 3. Distribution Value for Unit Weight (γ)

Method	Normal	Lognormal	Triangular	Uniform
C-S	9,9778	9,9778	12,4222	54,9556
K-S	0,0743	0,0934	0,1342	0,3222
A-D	0,5803	0,3984	1,5615	12,6980

In this study, lognormal distribution is utilized. Because the value of soil properties is always positive (Consolata, in Shen 2012). Lognormal distribution for unit weight is shown in Figure 3.

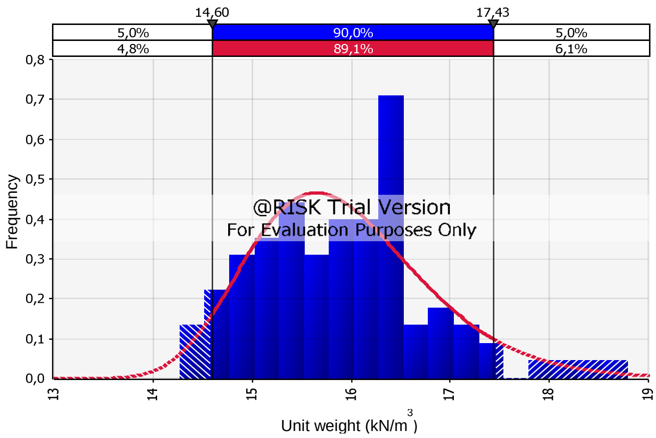


Figure 3. Lognormal distribution of unit weight

Based on figure 3, mean value = 15,92 kN/m^3, standard deviation = 0,91, skewness = 0,65 (+/tend to right).

b) Cohesion (c)

The most suitable distribution for cohesion is normal. Lognormal distributions for cohesion parameters cannot be analyzed because if plotted into data, the minimum relative value becomes too negative and does not meet the lognormal distribution requirements ($x > 0$). Distribution value of cohesion is shown in Table 4.

Table 4. Distribution Value for Cohesion (c)

Method	Normal	Lognormal	Triangular	Uniform
C-S	8,2222	N/A	13,7778	44,4444
K-S	0,0850	N/A	0,0710	0,3222
A-D	0,4814	N/A	0,5139	5,2086

Normal distribution for cohesion is shown in Figure 4.

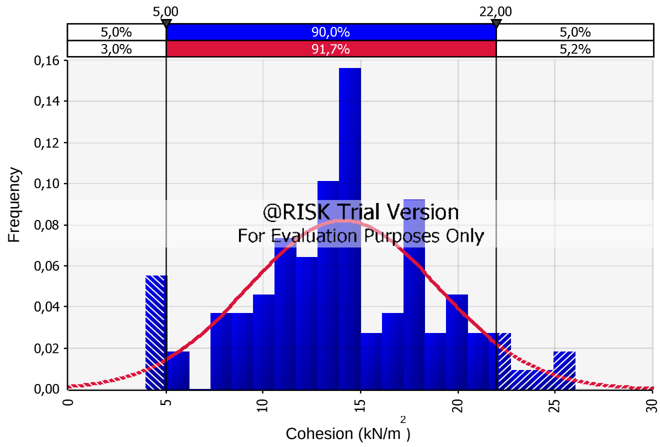


Figure 4. Normal distribution of cohesion

Based on figure 4, mean value = 14,11 kN/m^2, standard deviation = 4,86, skewness = 0 (center).

c) Friction angle (φ)

The most suitable distribution for the friction angle is lognormal that shown in Table 5.

Table 5. Distribution Value for Friction Angle (ϕ)

Method	Normal	Lognormal	Triangular	Uniform
C-S	109,2041	51,5102	48,5102	81,8163
K-S	0,2385	0,1051	0,2509	0,4184
A-D	7,5010	1,5259	-	24,4814

Normal distribution for cohesion is shown in Figure 4.

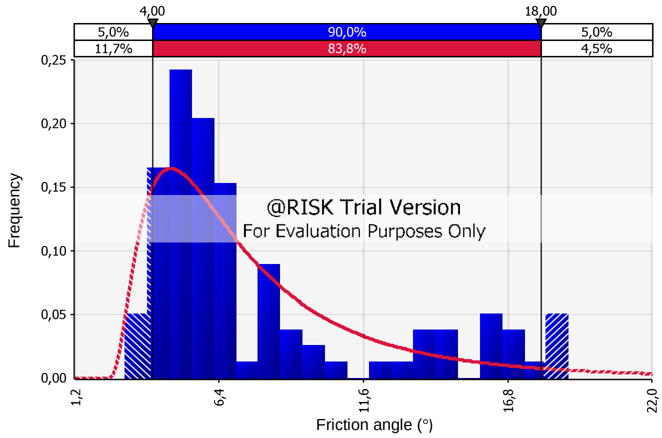


Figure 5. Lognormal distribution of friction angle

Based on figure 5, mean value = 8,02°, standard deviation = 5,17, skewness = 3,47 (+/tend to right).
The recapitulation of statistical parameter values based on the results of best fitting of distribution for each parameter that will be used for slope stability with probabilistic approach is shown in Table 6.

Table 6 Parameters for Probability Analyses

Parameter	γ (kN/m^3)	c (kN/m^2)	φ (°)
mean	15,924	14,11	8,29
distribution	lognormal	normal	lognormal
standard deviation	0,91	4,86	5,17
minimum	14,60	5,00	4,00
maximum	17,43	22,00	18,00

3.3 Geometry model

In this study used 36 variation geometry models.

- Slope height (H) : 2.5 m, 4.5 m, 5 m and 6 m,
- Slope angle (α) : 45° to 85°. (with range 5 °)

3.4 Slope Stability Analysis with Probabilistic Approach

The example result of slip surface obtained from slope stability analyses is shown in Figure 6. In the example is the result for slope with height is 6 m and angle is 45°.

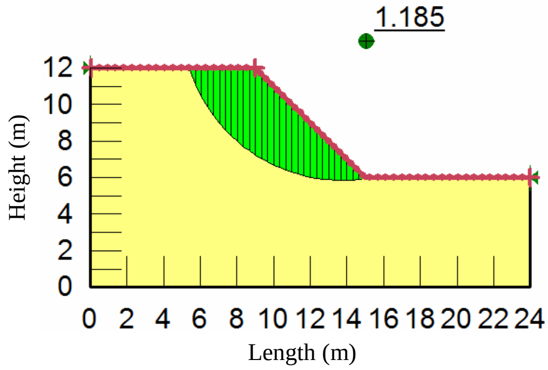
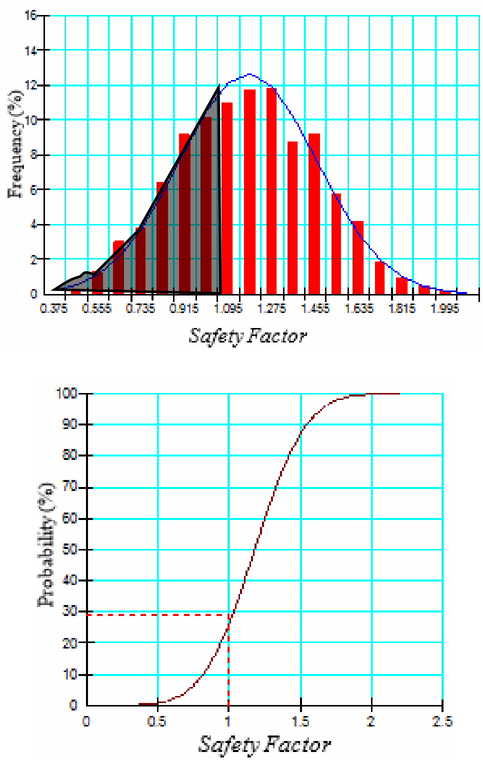


Figure 6. Slip surface deterministic analysis (H = 6 m, α = 45°)

Based on figure 6, the safety factor based on deterministic analysis with mean value of each parameter is 1,185. Then, the probability of failure from probabilistic analysis using 2000 trial of Monte Carlo simulation is shown in probability density function (PDF) and cumulative density function (CDF) in figure 7.



Mean F of S	1.1765
Reliability Index	0.621
P (Failure) (%)	28.800000
Standard Dev.	0.284
Min F of S	0.46653
Max F of S	2.0134
# of Trials	2000

Figure 7. Probability of failure (H = 6 m, α = 45°)

Based on figure 7, the slope have probability failure (Pf) about 28,8%. Its means that 28,8% x 2000 = 576 have SF < 1, and then the 2000-576 = 1424 have SF > 1. Reliability index (β) produced (1,176 - 1) / 0,28 = 0,62.

The probability of failure in all model variations is then plotted with low risk (Pf = 50%) and high risk (Pf = 25%) in the SRK 2010 standard, that shown in figure 8.

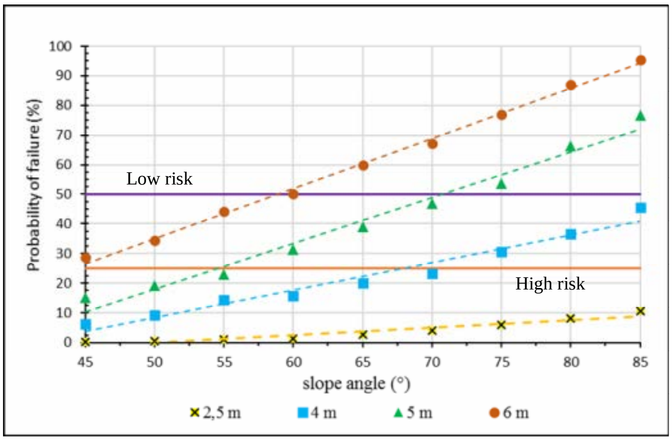


Figure 8. Probability failure for variations slope model that compared with SRK 2010

Figure 8 shows the variation of slope model based on the high risk impact category with allowed probability of failure up to 25%. Slopes with height 2.5 m are safe to an angle of slope of 85°. Slope with height 4 m are safe up to 70° slope angle. Slopes with height 5 m are safe up to of 55° slope angle. Slopes with height 6 m are not safe until the slope angle is 45°. From this result, it is indicated that the slope angle must be determined to be less than 45°.

For low risk impact category of slope with allowed probability of failure up to 50%, slopes with height 2.5 m and 4 m, are safe up to 85° slope angle. Slopes with height 5 m are safe up to 70° slope angle. Slopes with height 6 m are safe with slope angles of less than 60°.

The relationship between the mean safety factor and the probability of failure is shown in Figure 9 below:

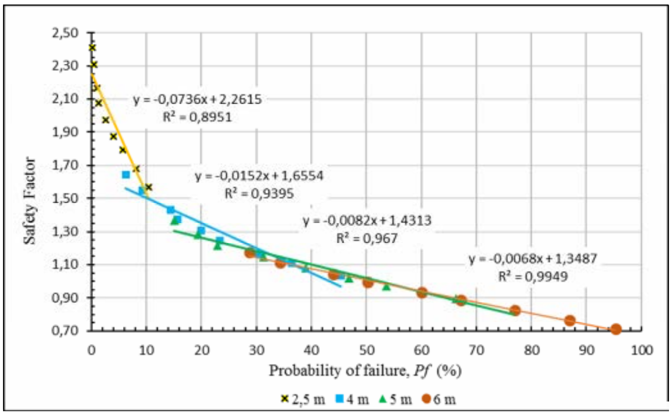


Figure 9. Safety factor and failure probability relationship

Figure 9 shows that the greater the safety factor, the smaller the probability of failure. According to Shen (2012), the relationship between safety factor and probability of failure (Pf) is influenced by the overlap that occurs between probability density function of resisting and forces in slope failure. The relationship between safety factor and Pf is inversely proportional. Figure 9 indicate that the higher the slope, the variation of the probability failure is greater than the variation in safety factor. The frequency of safety factor of less than 1.0 for 6 m slopes is greater than 5 m, 4 m and 2.5 m slope.

The relationship between the probability of failure and the reliability index on variations in research slopes is shown in figure 10 below.

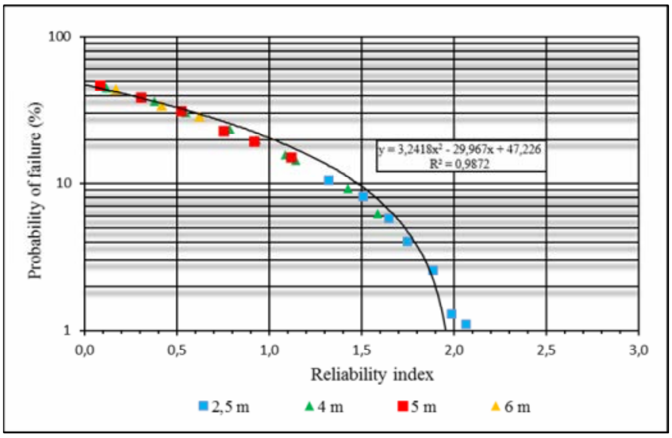


Figure 10. The relationship between reliability index and probability failure

Figure 10 is a scatter diagram between the reliability index as the x axis and the probability of failure as the y axis. Reliability and probability indexes are obtained from the results of slope stability analysis with a probabilistic approach on all variations of the slope. Then all the points are made trend line so that the trend line can be determined from the point of the plot of the reliability index and probability of failure of all variations. It is indicated that the reliability index and probability of failure have a relationship; that is the smaller the probability of failure, the greater the reliability index. This result is consistent with the theory of the relationship index of reliability index and probability of failure in Christian (1994). Trend line in the Figure 10 produces an empirical formula of the relationship between reliability index (x) and probability of slope (y) as y = 3.2418 x2 - 29.967 x + 47.2226 with a value of R^2 = 0.9872.

4. CONCLUSION

Based on this case study, it can concluded that:

1. The greater the safety factor, the probability of failure is getting smaller. The smaller the probability of failure, the greater the reliability index.
2. High risk slope category (SRK, 2010) with a permissible probability slope limit of 25% has a maximum slope recommendation up to a height of 5 m with a slope angle of 55°.
3. Low risk slope category (SRK, 2010) with allowable slope probability limits of 50% has a maximum slope recommendation up to 6 m high with a safe slope angle of less than 60°.

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