RISK ASSESSMENT OF OPEN PIT SLOPE DESIGN AT PT ADARO INDONESIA

PENILAIAN RISIKO KESTABILAN LERENG TUNGGAL TAMBANG TERBUKA DI PT ADARO INDONESIA

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ABSTRACT

Risk assessment of open pit slope stability is an important aspect to be considered in a decision making of slope design. The risk of slope failure that occurred on the slopes of the mine affect two factors namely the failure probability (FP), and consequences (C) of slope failure. FP is obtained from the collection of the value of Safety Factor (SF) $\leq$ 1 compared to the total value of SF, while the consequences is estimated from the sectional area multiplied by the width of slope failure. Physical and mechanical properties of sandstone was collected from PT Adaro Indonesia, and tested by “Kolmogorov-Smirnov (K-S)” fitting method to obtain an assumed theoretical distribution that be sued with the character of the original distribution data. “Monte Carlo (MC)” and “Latin Hypercube (LH)” sampling method is used as a tool to generate sample data, and both methods were compared. Finally Validation is conducted in order to propose an acceptable criteria of FP for single slope of sandstone.

Keywords: risk, open pit, failure probability, slope stability

SARI

Penilaian risiko kestabilan lereng tambang terbuka merupakan aspek penting yang perlu dipertimbangkan dalam pengambilan keputusan suatu disain lereng. Risiko longsor yang terjadi pada lereng tambang dipengaruhi 2 faktor, yakni probabilitas kelongsoran (PK) lereng tersebut akan longsor, dan seberapa besar dampak yang ditimbulkan bila lereng tersebut benar-benar longsor. Probabilitas Kelongsoran (PK) diperoleh dari kumpulan nilai FK $\leq$*1 dibandingkan dengan total nilai FK, sedangkan dampak kelongsoran ditentukan dari estimasi luas penampang disain lereng dikalikan dengan lebar pengaruh longsoran. Penelitian ini menggunakan data sifat fisik dan mekanik batu pasir yang berasal dari PT Adaro Indonesia. Uji suai (*fitting test*) terhadap data sifat fisik dan mekanik menggunakan metode Kolmogorov-Smirnov (K-S) guna memperoleh distribusi yang paling cocok dengan karakter data aslinya. Untuk memperbanyak data hasil uji suai digunakan 2 metode* sampling*, yakni metode Monte Carlo (MC) dan metode Latin Hypercube (LH). Hasil dari kedua metode tersebut dibandingkan. Validasi dilakukan guna mengusulkan ambang batas PK yang aman untuk lereng tunggal batu pasir.*

Kata kunci: risiko, tambang terbuka, probabilitas kelongsoran, stabilitas lereng

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INTRODUCTION

For the last three decades the Indonesian coal production tends to be increased up to the level of above 400 million tons in 2013 (ESDM, 2014). That is due to the increasing needs of the world's coal and coal prices are quite favorable. As a result, most of the domestic coal mines are competing to raise their production level, which indirectly increase the dimensions of excavation, the use of heavy equipment with large capacity, as well as the frequency and amount of explosives used in rock destruction. This of course increases the potential risk of slope failure. On the other hand, high rainfall in Indonesia also affect the detoriation of rock strength in slope.

When the above factors are not well managed, then it raises the potential risk of overall slope failure. Some events of slope failure have often occurred on the smallest scale (single slope) up to the large-scale (overall slope), that are caused by one or more of these factors.

Risk of slope failure is the result of the multiplication of the failure probability (FP) or (Likelihood) and the consequences of slope failure (C). FP is the chance that caused slope failure due to one or more factors affect the slope stability. C is impacted due to slope failure that can be fatal and/or injury, loss and/or damage of property and mine infrastructure, loss of potential reserve, loss of revenue, rehabilitation cost, as well as the environmental impact.

Based on these facts, the research related to risk assessment of open pit mine slope design may become a very important problem to be solved.

Research on consequences analysis of slope failure has been performed by several researchers (Terbrugge et al, 2006; Steffen et al, 2008; Chiwaye, 2010) which includes safety and economic impact analysis. Case studies on the consequences analysis of Batu Hijau mine has proven slope failure that occurred at a pre-estimated, so that production operations are not conducted in the span of the potential failure (S.Kramadibrata et al, 2012).

METHODOLOGY

Fitting Test

If a theoretical distribution has been assumed, then the validity of the assumed distribution could be confirmed or refuted by a statistical test with goodness of fit. There are several methods to test the goodness of fit of some assumed distribution functions, i.e. Chi Square method, Kolmogrov-Smirnov (K-S) method, and Anderson-Darling method. This paper only discusses the K-S method. The basic procedure of this method includes a comparison between experimental and theoretical cumulative frequency distribution of the types of assumed distributions. If the difference of both frequencies is higher than those of a certain sample size, the assumed theoretical distribution will be rejected. We used cumulative distribution function as input parameter for getting F^* (x) theoretical distribution function. The equation of this cumulative distribution function is as follows:

$$S_n\,(x) = \begin{cases} 0 & x < x_1 \\ \frac{k}{n} & x_n = x < x_{k+1} \\ 1 & x = x_n \end{cases} \qquad [1]$$

$x_1, x_2, ..., x_n$ are the values of the sample data that is already set, and n is the sample size.

In the K-S test, to examine if the data support the null hypothesis, we compared F* (x) against the experimental distribution function F(x). The maximum difference of both distributions can be written as follows:

$$D_n = \max_x |F(x) - F^*(x)| \qquad [2]$$

Theoretically D_n is a random variable where the distribution depends on n. To a certain significance level α, the K-S test compares the maximum difference of the observations in the above equation with the critical value D_n^α. Thus with a significance level α, the null hypothesis is rejected if D_n is higher than the critical value.

When two non-nested models are compared, the larger model with more parameters have the advantage of being able to fit the in-sample data with more flexible function and thus possibly a larger log-likelihood. To compare models on more equal terms, penalized log-likelihood may be adopted. The Akaike information criterion (Tse, 2009), denoted by AIC, proposes to penalize large models by subtracting the number of parameters in the model from its log-likelihood. Thus, AIC is defined as:

$$AIC = \log L\,(\hat{\theta};x) - p \qquad [3]$$

Where $\log L(\hat{\theta};x)$ is the log-likelihood evaluated at the MLE $\hat{\theta}$ and p is the number of estimated parameters in the model. Based on this approach the model with the largest AIC is selected.

The above problem of the AIC can be corrected by imposing a different penalty on the log-likelihood. The Schwarz information criterion (Tse, 2009), also called the Bayesian information criterion, denoted by BIC, is defined as:

$$BIC = \log L(\hat{\theta};x) - \frac{p}{2}\log n \qquad [4]$$

The details of these methods can be seen in Tse (2009); Azizi (2013) and Pramuditya et al (2013).

Using Sampling Method

The fact that the SF depends upon a number of random variables such as the unit weight (γ), the cohesion (c) and the internal friction angle (ϕ). The values of these variables are distributed about their means in a manner which can be described by one of the assumed theoritical distribution functions such as normal, lognormal, beta, and gamma. The question is how to use this information to determine the distribution of SF values and the FP.

The Monte Carlo method (Abramson et al, 2000; Baecher et al, 2003; Hoek, 2007) used random or pseudo-random numbers to sample from probability distributions and, if sufficiently large numbers of samples are generated and used in a calculation such as that for a safety factor, a distribution of values for the end product will be generated. The Latin Hypercube sampling technique (Imam et al, 1980 & Startzman and Watterbarger, 1985 in Hoek, 2007; Abramson et al, 2000) was relatively recent development which gives comparable results to the Monte Carlo technique with few samples. The method was based upon stratified sampling with random selection within each stratum. Typically an analysis using 1000 samples obtained by the Latin Hypercube technique would produce comparable results to an analysis using 5000 samples that was obtained using the Monte Carlo method. Both techniques were incorporated in the program Slide version 6.

Both the Monte Carlo and the Latin Hypercube techniques require that the distribution of all the input variables should either be known or that they should be assumed. When no information on the distribution is available it is usual to assume a normal or a truncated normal distribution.

Determine Failure Probability (FP)

In recent years probabilistic methods have been more frequent to be used in slope design. These methods are based on the calculation of FP of the slope. A probabilistic approach requires a deterministic model exists. In this case the input parameters are described as probability distributions rather than point estimates of the values. By combining these distributions within the deterministic model used to calculate the SF, the probability of failure of the slope can be estimated (Steffen et.al., 2008).

Figure 1 describes a Probability Density Function (PDF) and Cumulative Distribution Function (CDF). Probability density functions explains area in which the relative probability of a random number can be assumed to be a unique value compared to the other values. Failure probability (FP) is determined from the distribution of the safety factor. The area under the curve (FK <1) is defined as a failure probability value.

In this research, the function of FP depends on cohesion (c) and internal friction angle (ϕ), and SF was determined by "Bishop" limit equilibrium method using Slide program (rocscience).

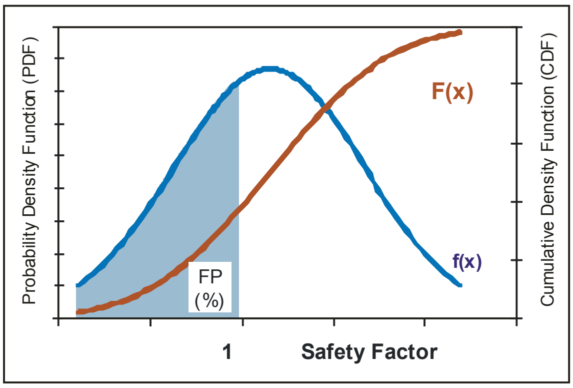

Figure 1. Failure Probability Concept

Experimentation

Generally rainfall has a contribution to decrease the rock strength, especially in Indonesia. Two experiments had been conducted in relation to rainfall effect,i.e: induction of sandstone under rainfall and direct shear test based on the first experiment.

There were three sandstone samples placed in an open space on a rainy day, the first sample was taken at 15 minutes, the second sample taken at 20 minutes and the last sample was taken at the time after raining cease over. Then each sample was determined using the highest water levels induced by the difference in weight before and after induced by rain. Induction time with the highest water content will be used as a reference in the direct shear test. Sandstone samples with a 20-minute induction has the highest water content on 14 mm.

The second experiment was the direct shear test in two conditions namely natural and saturated conditions. the natural condition is the condition of the actual sample, while the saturated condition is the condition of the samples immersed for 20 minutes based on the first experiment.

Based on direct shear test concluded that the cohesion of sandstone decreased about 7.1% in peak condition, and 9.5% in the residual condition, while the internal friction angle decreased about 7.4% in peak condition, and 14.4% in residual condition. Consider the induction test was conducted in Bandung, the realistic application of which can be done in the same way at the mine site PT Adaro Indonesia.

RESULT AND DISCUSSION

The Results of Fitting Test and Experiments

Table 1 is a fitting test result that indicates the use of custom parameters, and provides the cohesion as a lognormal distribution (Lnormal) to both peak and residual conditions, the internal friction angle has a normal distribution in both the peak and residual conditions. Table 2 shows the input parameters of the physical and mechanical properties of sandstone. The parameters without rainfall was obtained from fitting test results, while input parameter under rainfall was obtained from the experimentations. By considering that unit weight have uniform distribution with a single value.

Table 1. Fitting Test Results of Mechanical Properties of Sandstone

Parameter	Peak		Residual	
	cohesion	Internal friction angle	cohesion	Internal friction angle
Dnmax	0.018	0.097	0.019	0.023
Nilai Kritis	0.248	0.248	0.248	0.248
Log-likelihood	35.19	-101.1	49.59	-94.28
AIC	33.19	-103.1	47.59	-96.28
BIC	33.71	-102.5	48.12	-95.76
Distribusi	Lnormal	Normal	Lnormal	Normal

Table 2. Input Parameter of Physical and Mechanical Properties of Sandstone

Statistical parameter	Unit weight (kN/m^3)	No rainfall		rainfall	
		cohesion (kPa)	□ (0)	cohesion (kPa)	□ (0)
Mean	20.5	106	18.8	96	16.1
Std.Deviation	-	57	5.7	52	4.9
Minimum	-	77	13.1	70	11.2
Maximum	-	134	24.5	121	21.0
Distribution	-	L-normal	Normal	Lnormal	Normal

Relationships Between Slope Angle vs. Safety Factor

Figure 2 shows the results of SF calculations obtained from “MC” sampling method is relatively the same as a “LH” sampling method of both SFdet and SFr. From the calculation results it can be concluded that the higher slope angle would provide the value of SF decreases. These fact reinforces the concept that the higher slope angle, the lower the slope safety factordue to the smaller load detained in geometry.

Relationships Between Slope Angle vs. Failure Probability

Figure 3 presents the results of the FP calculation at 16 meters and 24 meters in height using “MC” and “LH” sampling method. FP results of “MC” sampling methods are found relatively similar to“LH” sampling method. The figure also concluded that the higher slope angle causes the FP value increases.

These fact reinforces the concept that the higher is the slope angle, the higher the failure probability

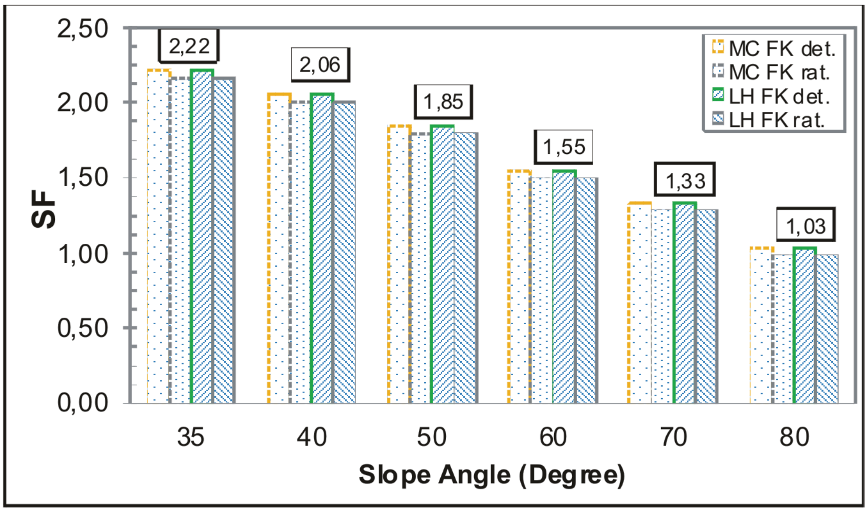

Figure 2. Relationships between angle of slope versus SF of single of slope (sandstone with 16 meter in height)

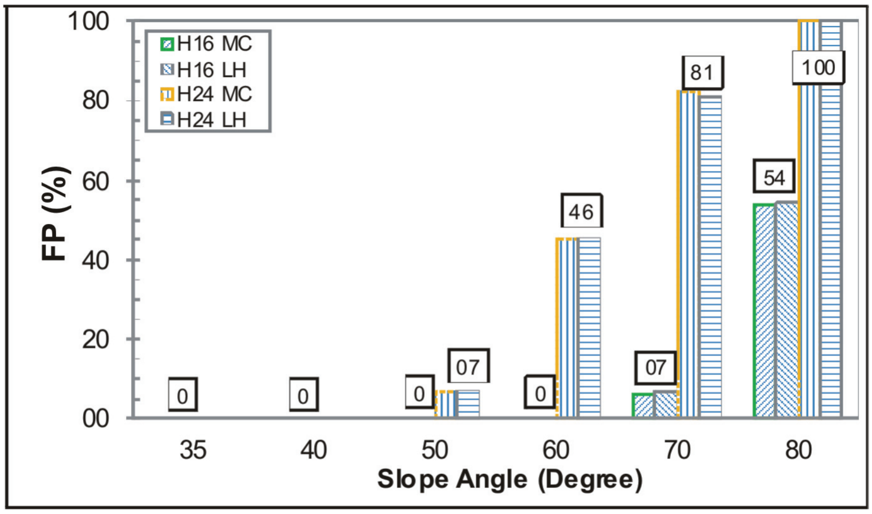

Figure 3. Relationships between angle of slope versus FP of single slope of sandstone

of slope because of the greater load detained in geometry.

As an example from the graph above, i.e. the slope angle with 700 and a 16 meters in height is stable, while the slopes with 24 meters in height is unstable (based on FP Acceptable criteria in Read & Stacey, 2009). Hence the acceptable maximum FP value is 25% for low risk consequences and 50% for high risk consequences.

Slope Design Graphics

Figure 4 describes a stability line of sandstone single slope with Acceptable FP= 25% (green line) and FP = 50% (brown line) using "MC" and "LH" sampling method. The difference between stability line of "MC" and "LH" sampling method is about 0.7% (FP Acceptable = 25%) and is about 0.9% (FP Acceptable = 50%). Furthermore, the stability line of FP acceptable = 25% is more pessimistic FP acceptable = 50%. As an example for a 16 meter in height, the maximum slope angle is about 750 (FP acceptable = 25%) and is about 790 (FP acceptable = 50%).

Figure 5 describes a comparison of single slope design of sandstone single without rainfall (yellow line) and due to rainfall (blue line) with FP acceptable about 25% using "MC" sampling method. On the other hand, the figure also indicates the stability line with FP accepts about 25% is more pessimistic than FP acceptable about 50%. As an example for a 16 meter in height, the maximum slope angle is about 700 (without rainfall) and is about 750 (due to rainfall).

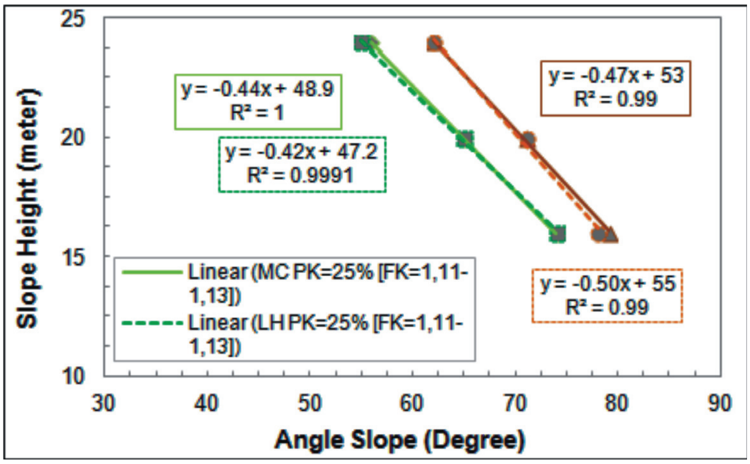

Figure 4. Relationships between slope angle versus height of sandstone without Rainfall

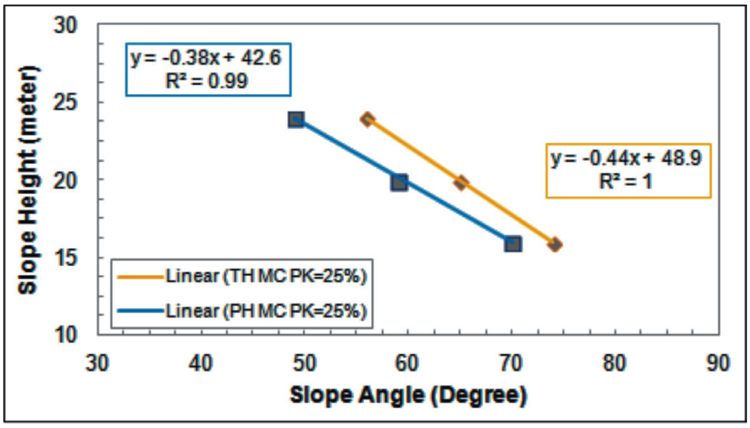

Figure 5. Comparison of sandstone single slope design without (TH) and due to (PH) rainfall

Relationships between SF and FP vs. Volume of Failure Material

Volume of failure material is estimated by multiplying between the area of failure (design) and width of failure based on historical data, i.e. 15 meters in width.

Figure 6 describes higher SF would increase the volumes until SF=1.16 which yield the volumes about 2321 m^3 ("MC" sampling method), then the more higher SF will decrease the volumes.

Figure 7 shows higher FP, increase volumes until FP=27.4 which yield volumes about 2320 m^3 ("MC" sampling method), then higher FP decrease volumes.

This is caused by a volume of failure will increase inline with an increase in the dimensions of the slope untill optimal condition which is an indication of the amount of the biggest failures.

Validation

Monitoring data of 4 failed sandstone slope movement shows the displacement range from 0.03 to 0.77 meters at a distance of tension crack to crest about 11-20 meters (Saptono, 2012), thus back analysis was conducted using the limit equilibrium method in which result cohesion and internal friction angle under the critical limit (Table 3).

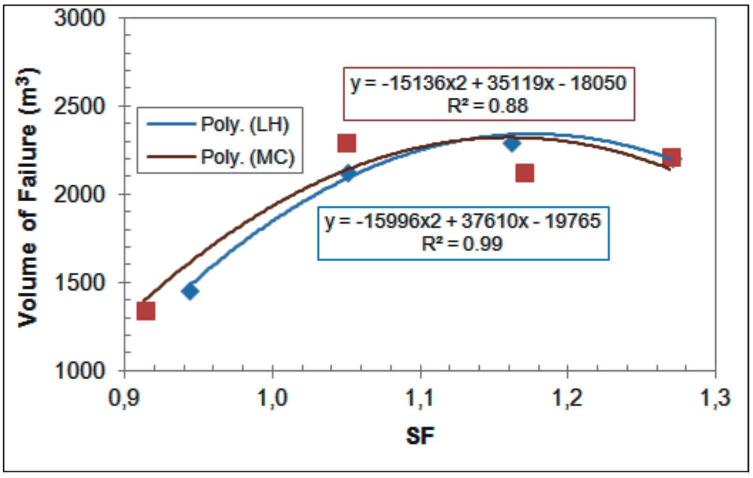

Figure 6. Relationships between SF versus volume of failure sandstone

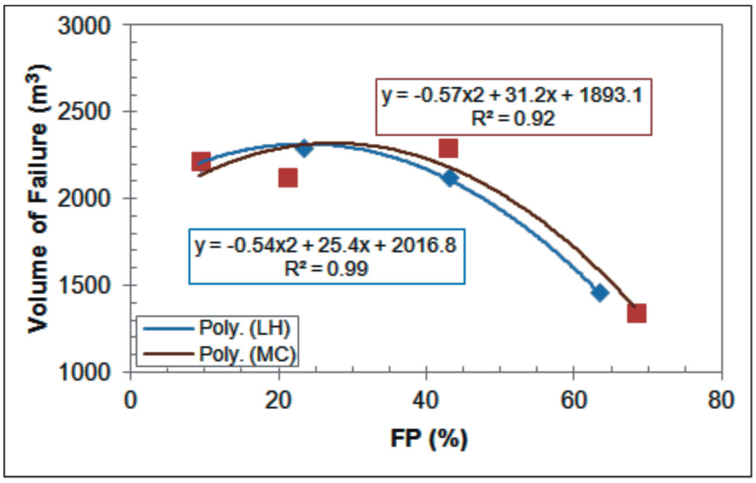

Figure 7. Relationship of FP versus volume of failure sandstone

Table 3. Monitoring data of sandstone single slope failure (Saptono, 2012)

No	Unit Monitoring	Height (meter)	Slope Angle (0)	Displacement (m)	Distance Crest to Tension Crack (m)
1	PRA 52	30	34	0.53	11
2	PRA 123	30	50	0.48	20
3	PRN 17	35	35	0.03	20
4	PRA 136	17	30	0.77	12

Based on back analysis show deterioration of cohesion and internal friction angle about 60.4% and 14.9% respectively, so to determine the long term strength of slope using this analysis (Table 4). Long term slope stability of sandstone gives all slopes stable, except 2 failed slopes give FP greater than 45% (Table 5). According to Read & Stacey (2009), the acceptable criteria for single slope was about 25-50%.

Table 4. The results of back analysis for sandstone single slope

Statistical parameter	Design		Back analysis	
	C kPa)	ϕ (°)	C (kPa)	ϕ (°)
Mean	106	18.8	42	16
Std.deviation	57	5.7	4	2

CONCLUSIONS

Some of the conclusions that can be gleaned from this paper is as follows:

a. Characterization data is an important process that used in open pit slope design, and it can explain the level of uncertainty of the input parameter data.

Table 5. Deteroriation of SF for Longterm Single Slope of Sandstone

Section	Dimension		SF Design		SF Longterm		FP design	FP long term	Time (days)	Condition
	H (m)	β (0)	Det.	Mean	Det.	Mean				
1	12	30	2.94	2.86	1.54	1.54	0	0	90	Stable
2	12	40	2.67	2.59	1.34	1.34	0	0	90	Stable
3	12	40	2.67	2.59	1.34	1.34	0	0	90	Stable
4	12	56	2.2	2.13	1.05	1.05	0	8.2	90	Stable
5	12	40	2.67	2.59	1.34	1.34	0	0	90	Stable
6	12	50	2.38	2.31	1.17	1.17	0	0	90	Stable
7	12	40	2.67	2.59	1.34	1.34	0	0	90	Stable
8	12	37	2.74	2.65	1.38	1.38	0	0	90	Stable
9	12	42	2.59	2.51	1.29	1.29	0	0	90	Stable
10	24	25	1.87	1.83	1.06	1.06	0	5.4	90	Stable
11	12	35	2.81	2.73	1.43	1.43	0	0	90	Stable
12	12	40	2.67	2.59	1.34	1.34	0	0	90	Stable
13	12	38	2.71	2.63	1.37	1.37	0	0	90	Stable
14	12	45	2.51	2.43	1.25	1.25	0	0	90	Stable
15	12	43	2.55	2.47	1.27	1.27	0	0	90	Stable
16	24	55	1.18	1.15	0.59	0.59	25.8	100	90	Failed
17	24	50	1.29	1.25	0.67	0.67	6.7	100	90	Failed

b. The results of fitting test using the Kolmogorov-Smirnov method as follows:
   - Cohesion has a lognormal distribution either peak or residual condition.
   - The internal friction angle has normal distribution either peak or residual condition.

c. Based on direct shear test concluded that the cohesion of sandstone decreases about 7.1% in peak condition and 9.5% in the residual condition, while the internal friction angle decreases about 7.4% in peak condition and 14.4% in the residual condition.

d. Failure probability can be an alternative in assessing the open pit slope stability, and become an important tool in decision making.

e. Long term slope stability of sandstone gives all slopes stable, except twofailed slopes give FP greater than 45%

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