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Reliability Analysis of Block Sliding in Large Brown Coal Open Cuts

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ABSTRACT

The probabilistic analysis of block sliding of a large brown coal open cut slope in Australia is presented. Probabilistic and reliability based analysis is performed considering the variation of random variables. Monte Carlo Simulation is employed to investigate the effect of friction angle, buoyance force and number of slices on the reliability index of a typical slope in a open cut. It was found that with more understanding of ground information, further dividing of the sliding block into slices and by considering the variation of the soil properties in each slice as non-correlated variables, a higher reliability index of a design can be obtained.

1. INTRODUCTION

Slope stability in large open cuts is critical issue for the safe operation of open cut mines. Unexpected failure of slopes causes damage to the industries, loss of lives, passive social and economical impacts. The impacts are hard to evaluate depending on the size and location of the failure. Yet the cost for the remediation of mass displacement alone can be easily over millions of dollar (Harries et al., 2009). Due to the failure of Yallourn open cut, VIC, Australia in 2007, the power station of TruEnergy lost two-thirds of its 1450MW capacity for weeks, besides the huge damage to the mine infrastructure (Herald Sun, 2011). Also in the USA, the incident rate in the open-cut mining industry is 164 injuries out of 1000 workers during the period 1986 to 1988 (Leigh et al., 1990).

In the design of large slopes in the open cuts, either deterministic or probabilistic method is adopted. In deterministic analysis, the Factor of Safety

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(FOS) is calculated with the assumption that the materials along the critical slip surface have the same specification and FOS. Thus the choice of the FOS and the material properties are much affected by the knowledge and experience of the designer. The slopes in the large open cuts ranges from tens of meters (bench scale) to hundreds of meters (overall slope) and the properties of the materials vary too much in space. Therefore using a unique value of FOS to describe the stability of such a big slope may not be sufficient and realistic.

Not similar to deterministic method, the probabilistic based design considers the variation of ground condition and soil properties. The method has been used by researchers to study the reliability of soil slopes (Babu and Murthy, 2005; Xue and Gavin, 2007). In this method, the stability of a slope is evaluated using probability of failure or reliability index. Priest and Brown (1983) suggested to consider both FOS and probabilistic of failure to evaluate the stability of rock slopes. This theory has also been recommended into the practice of open pit design (Raed and Stacey, 2009).

Block sliding is one of the most common failure modes in open cuts. Such failure normally takes place along existing weak plane and can be triggered by the increase of water pressure in deep vertical faults or cracks. Deterministic method is often used in the analysis of such failure, however in order to use a more reliable technique, this paper describes the probabilistic analysis of block sliding of a typical slope in large brown coal open cuts in Australia.

2. SLOPE PROFILE AND MATERIAL PROPERTIES

Brown coal deposit in Latrobe Valley, Victoria, Australia hosts 23% of the world's brown coal reserves which can last for 500 years on the production level of 2008 (Australia Mineral Resources, 2011) and is the largest brown coal deposit in the world. Three open pit mines are under operation in the region. The deepest cut is now at the depth up to 120m below the ground level. Brown coal in this region is a light material (11.5kN/m^3) with high water content (up to 200%). Research showed that the material has high tensile strength (Trollope *et al.*, 1965), high friction angle and cohesion as shown in

Table **1**. With such high strength and light weight, the slopes can be cut vertically up to 400 meters high without failure (Brown, 1969). Below the coal seam, lies a layer of interseam material. The interseam materials are weak in strength as shown in

Table **1** (Suchnicka and Honderla, 1993; Rosengren and Krehula, 1967). Significant difference between shear strength of coal and interseam material, makes the failure happen along the coal-interseam interface. The failure mechanism is shown in Fig. **1** (Rosengren and Krehula, 1967).

Table 1: Physical and mechanical properties of the materials

Material	Unit weight (kN/m^3)	Friction angle (°)	Cohesion (kPa)
Brown coal	11.5	37	200
Interseam	18	13	0

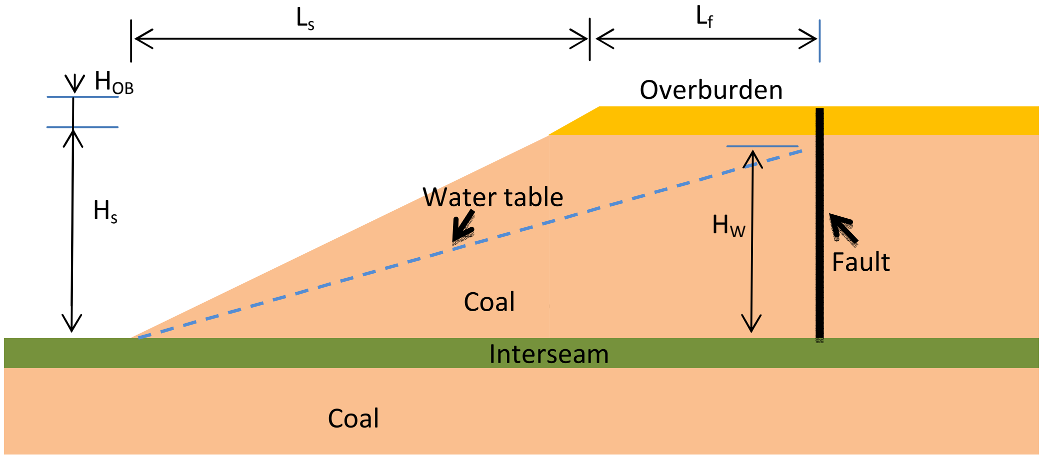


Fig. 1. A typical slope in brown coal open cut

3. DETERMINISTIC ANALYSIS

As seen in Fig. **1**, by analysing the equilibrium of the block, the factor of safety of the block (FOS) can be described as:

$$FOS = \frac{C(L_s + L_f) + (\gamma_C * (0.5 * H_s * L_s + H_s * L_f) + \gamma_{OB} * H_{OB} * L_f - U) * \tan(\phi)}{0.5 * \gamma_W * H_W * H_W} \quad (1)$$

in which γ_C is the unit weight of brown coal, γ_{OB} is the unit weight of over burden material, *C* and ϕ are the cohesion and friction angle of coal-interseam interface, and *U* is the buoyancy force at the bottom of the block due to water pressure, which can be calculated using the equation below for the situation described in Fig. **1**.

$$U = 0.5 * \gamma_W * H_W * (L_s + L_f) \quad (2)$$

Take a typical slope in the Victorian brown coal open cut as an example. The material properties of the brown coal and interseam material are shown in Fig. **1.** A typical slope in brown coal open cut

3. DETERMINISTIC ANALYSIS

. The friction angle between the interseam and the brown coal layer are taken as 13 degree as recommend by Suchnicka and Konderla (1993). The water table in the slope is assumed as a straight line as shown in Fig. **1**. Taking $H_{slope}=100m$, $H_{OB}=15m$, $L_s=300m$, assuming that water level in the crack is just at the surface of brown coal layer, which is about 15m below the ground surface, the crictical distance of the fault from the crest (L_f) of the slope for FOS=1, can be obtained using equation 1, which is about 202m. This means that for cracks or existing faults that are fully developed through the brown coal seam layer, and the crack is filled with water up to the top of brown coal seam, then the critical distance of the crack / fault from the crest of the slope is about 202m for this situation. For a safety of factor of 1.2, the distance is about 247m.

In the above analysis, deterministic values for the material properties, such as unit weight and friction angle, and water table profile are adopted. But for slopes in such a large scale, most of the above parameters are random variables in natural. So a probabilistic analysis method is required to evaluate the reliability of the slopes.

4. RELIABILITY BASED ANALYSIS

Instead of using FOS as the stability index of a slope, probability of failure or reliability index is used in a probabilistic analysis, by considering the variation of random variables.

In slope stability analyses, where the shearing resistance of the soil (C') is compared to the applied disturbance (D) along a failure surface, the limit state is indicated when the limit state function is less than zero:

$$g(X) = C' - D < 0 \quad (3)$$

The limit state function can also defined as:

$$g(X) = FOS - 1 < 0 \quad (4)$$

The probability of failure (P_f) of the slope is defined as the probability that the demand will equal or exceed capacity:

$$P_f = P(g(X) < 0) \tag{5}$$

The probability of failure can be obtained by:

$$P_f = \int_{g(X)<0} f(X)\, dX \tag{6}$$

where *[X]* is the vector of random variables, and *f(X)* is the probability density function (likely range of values) of the random variables. To find the probability of failure of a slope, the direct integration of equation () is rarely analytically possible. In practice, the probability of failure can be solved using Monte Carlo simulation. Apart from probability of failure, reliability index is another parameter to evaluate the stability of slopes. The reliability index can be obtained using First Order and Second Moment (FOSM) method. The methods of Monte Carlo simulation and FOSM are explained in detail below.

4.1. FOSM method

In order to find the reliability index, the limit state function may be approximated by a Taylor series expansion. Using only first order (linear terms) the reliability index for uncorrelated variables (Harr,1987), can be expressed as equation 7.

$$\beta = \frac{E[g(X)]}{\sigma[g(X)]} = \frac{g(\bar{X})}{\sqrt{\sum_{i=1}^{n}\left(\frac{\partial g(X)}{\partial X_i}\right)^2 \sigma^2[X_i])}} \tag{7}$$

Where *E[g(X)]* and *σ[g(X)]* are the mean and standard deviation of the Factor of Safety respectively. And $\bar{X}$ and $\sigma(X_i)$ are the mean value and standard deviation for a number (*N*) of variables (X_i).

4.2. Monte Carlo Simulation

The Monte–Carlo method is based on the idea of random simulation. It has been used by many researchers to analyse the stability of soil slopes with deterministic methods, Malkawi et al. (2001), and probabilistic methods (El-Ramly et al. (2005), Hsu and Nelson (2006); Malkawi et al. (2000)). In the method used by Malkawi et al. (2000), soil properties are randomly produced according to the distribution of the soil samples (Fig. **2** a). Factor of safety of the slope is then calculated using the random numbers, thus the distribution of the factor of safety of the slope can be obtained (Fig. **2** b). The probability of failure can be found by simply finding the ratio of the number of FOS that is less than one and the total number of simulations.

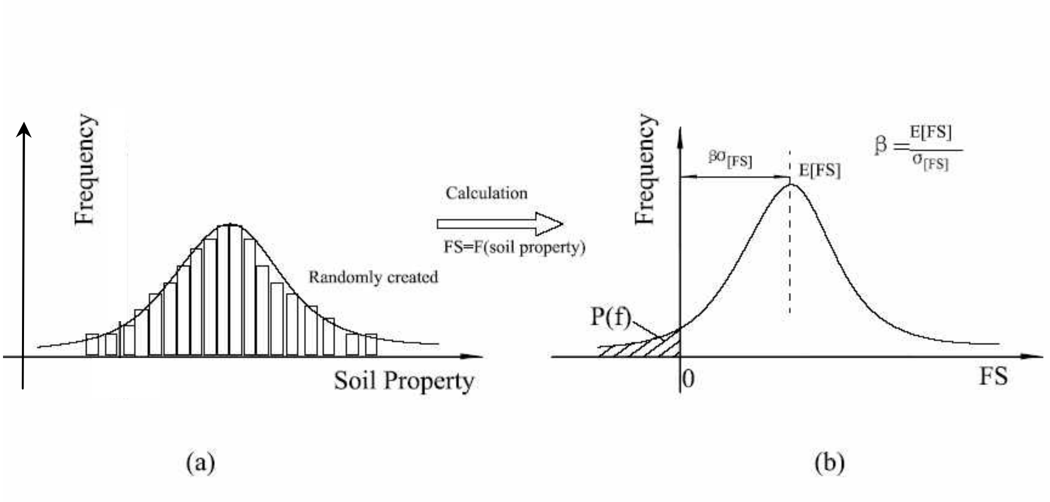


Fig. 2. Basic idea in Monte-Carlo simulation

Assuming that the soil properties and the factor of safety are normally distributed, the reliability index of the slope can be calculated using equation 8.

$$\beta = \frac{E(FS)-1}{\sigma(FS)} \qquad (8)$$

5. RELIBILITY MODEL OF BLOCK SLIDING

In equation (1), soil properties such as cohesion and friction angle are highly varied in nature, and the water table profile can seldom be described as a straight line due to variation of ground and local hydrogeological conditions and transient seepage. Considering this, the following parameters are assumed as random variables in the reliability analysis: cohesion (*C*), friction angle (ϕ) and buoyance force (*U*). The limit state function of the slope is defined as:

$$LES = \frac{C(L_s+L_f)+(\gamma_C*(0.5*H_s*L_s+H_s*L_f)+\gamma_{OB}*H_{OB}*L_f-U)*\tan(\phi)}{0.5*\gamma_W*H_W*H_W} - 1 \qquad (9)$$

As discussed in the previous session, for a safety factor of 1.2, the critical distance of the fault from the crest of the slope is 247m for the slope shown in Fig. **1**. For the sake of simplification, the fault is assumed to be 240m away from the crest of the slope in the following reliability analysis, which gives a FOS of 1.17 for ϕ=13°. The values 0.05 and 0.1 are assumed in the analysis for the coefficient of variation of friction angle (ϕ) and buoyance force (U), respectively.

By using FOSM and Monte Carlo simulation, the reliability of the slope can be obtained as presented in Table 2. The results show that FOSM and Monte

Carlo simulation give comparable results. It seems that the reliability of the slope is more sensitive to the coefficient of variation of buoyant force. The reliability index decreases from 1.975 (CovPhi=CovU=0.05) to 1.26 (with CovPhi=0.1 and CovU=0.05), and to 1.236 (with CovPhi=0.05 and CovU=0.1) respectively.

Table 2: the reliability index and probability of failure of the slope

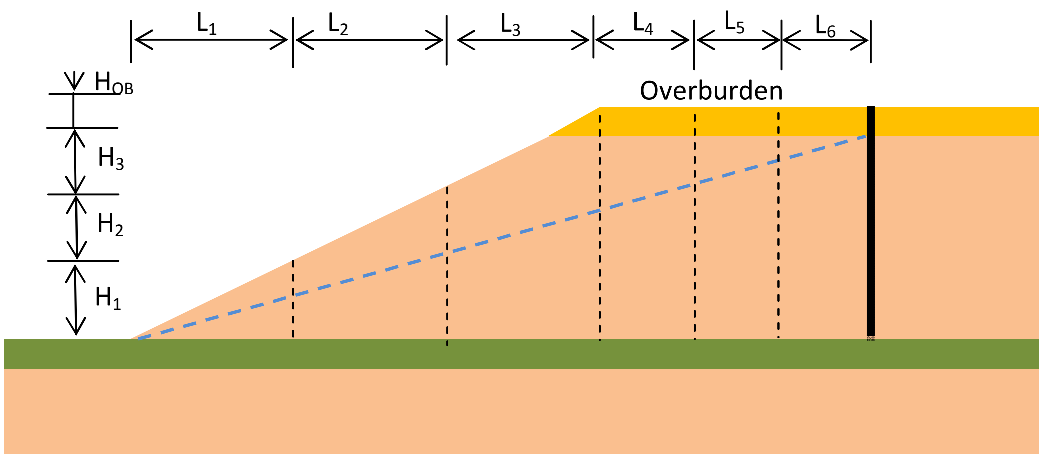
CovPhi	CovU	Reliability index (β)		Probability of failure (P_f)
		FOSM	MC	
0.05	0.05	1.975	1.991	2.03%
0.1	0.05	1.26	1.268	10.01%
0.05	0.1	1.239	1.236	10.55%

6. EFFECT OF NUMBER OF SLICES ON RELIABILITY

In the previous section, one block was assumed in the analysis. Is it a too simple assumption for such a big slope. Along the coal-interseam interface, the soil properties and water table may be affected by the local geological condition. Considering this, the block can be further divided into *n* slices when more ground information is available. The limit state function in equation(9) can be rewritten as equation 10.

$$LES = \frac{\sum_{i=1}^{n} C_i L_i + (W_i - U_i) * \tan(\phi_i)}{0.5 * \gamma_W * H_W * H_W} - 1 \quad (10)$$

In this equation, W_i is the weight of the i[th] slice, and U_i is the buoyance force at the bottom of the i[th] slice. Therefore, the soil properties or water pressure in each slice can be considered as correlated / non-correlated random variables, e.g. soil friction angle in each slice can be treated as non-correlated variables. The effect of the number of slices on the reliability or factor of safety of slope will be discussed here.



By using Monte Carlo simulation, and assuming that the random variables are non-correlated. Two mean values of the friction angle of the interface material were adopted in the simulation for comparison: 12° and 13°. Different values (0.05 and 0.1) for coefficient of variation were adopted for friction angle and buoyance force. By increasing the number of slices, the factor of safety of the slope does not change. The results from Monte Carlo simulation are shown in

Table 3 and Fig. 4. Variation of reliability index by number of slices.

Table 3: variation of reliability index of the slope with number of slices

CovPhi	CovU	Reliability index (β)							
		Number of blocks							
		2		6		9		18	
		ϕ=13°	ϕ=12°	ϕ=13°	ϕ=12°	ϕ=13°	ϕ=12°	ϕ=13°	ϕ=12°
0.05	0.05	2.799	1.431	4.499	2.362	5.196	2.613	7.414	3.674
0.1	0.05	1.769	0.928	2.9	1.518	3.326	1.702	4.751	2.4
0.05	0.1	1.71	0.893	2.852	1.442	3.221	1.605	4.641	2.295

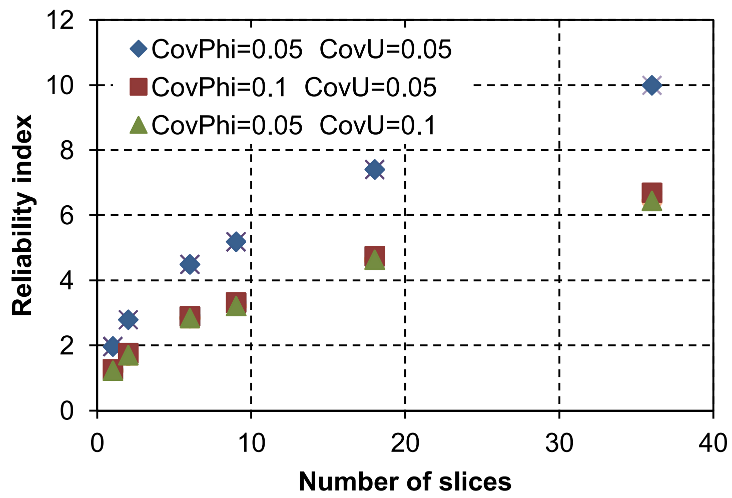


Fig. 4. Variation of reliability index by number of slices

The results showed that with increasing number of slices and the more understanding of soil properties in each slice, the reliability index of the design increases. For example, for ϕ=13° and CovPhi=CovU=0.05, by having two slices in the block and more information about the ground condition in the slices, the reliability index of the design will increase from 1.976 (one slice) to 2.799. This means that with more confidence of the material properties, the design of the slope would be more reliable. It is worthwhile to note that, the reliability index of the slope won't increase by solely increasing the number of slices without further understanding of the ground conditions.

The results suggested that with more understanding of the ground conditions, a lower factor of safety can be adopted with higher reliability. For example, for ϕ=12°, the FOS of the slope reduces to 1.076 comparing to 1.17 for ϕ=13°. Yet by increasing the understanding of the ground condition and therefore dividing the slope into 6 slices, the reliability index of the slope can be increased to 2. 362 (for CovPhi=CovU=0.05) from 1.976 (for one slice, ϕ=13 and CovPhi=CovU=0.05).

7. SUMMARY

Reliability analysis of block sliding using FOSM and Monte Carlo simulation revealed that both methods estimate very similar reliability index and calculated index is more sensitive to the coefficient of variation of buoyant force rather than the shear strength parameter.

Also, reliability analysis of limit equilibrium based analysis showed that the reliability index value is highly sensitive to the number of assumed slices and increases with increasing number of slices. This gives the meaning that: if each slice represents a field measurement data point (i.e. investigation borehole), the design of the slope would be more reliable if more field investigation data are available.

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