PROBABILISTIC SLOPE STABILITY ASSESSMENT FOR SUSTAINABLE MINING AT ANKPA COAL MINE, NIGERIA

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Abstract
The Ankpa Coal Mine plays a crucial role in meeting the energy demands of Dangote cement plants in Nigeria. However, mining activities at the site pose significant risks to slope stability, potentially impacting the sustainability and safety of mining operations. To ensure responsible and sustainable mining practices, this study conducted a probabilistic slope stability assessment of the mine. Samples of laterite, shale, and coal were collected from three distinct locations (A, B, and C) within the mine, and their physical and strength parameters were determined through laboratory tests. The slope's probabilistic assessment using the factor of safety (FOS) was implemented into numerical modelling utilizing the Point Estimate Method (PEM). The slope random shear strength parameters were used as inputs for the finite-element numerical simulations to determine the corresponding FOS for each location. This study also investigates the influence of slope angle on the probability of slope failure, providing valuable insights into potential instability triggers. The results indicated that location C exhibited higher susceptibility to slope instability compared to the other locations. Consequently, appropriate slope angle recommendations were proposed for each location to mitigate the risk of slope failure effectively.

Keywords: Probabilistic analysis, slope stability, Point estimate method, Finite element method, Reliability index, Factor of safety

Introduction

Assessing slope stability in mining operations has garnered substantial attention from researchers and practitioners, particularly in open-pit mining. Numerous methods have been employed for this purpose (Ducan and Norman, 1996; Akande and Idris, 2007; Eberhardt, 2003; Jiang et al., 2023; Idris, 2022; Griffiths and Fenton, 2004; Janbu, 1954; Bishop, 1955; Rabie, 2014). Slope stability is commonly assessed using the Factor of Safety (FOS). This assessment involves a delicate balance between the economic advantages of steeper slopes, which reduce waste excavation, and the heightened risks associated with decreased stability. Steeper slopes often yield improved mining economics due to reduced waste-to-ore ratios, although these benefits are countered by increased operational risks (Steffen et al., 2008).

Due to its simplicity, the Limit Equilibrium Method (LEM) has traditionally been a preferred choice for slope stability assessment. However, concerns regarding its general suitability have been raised by several researchers (Lorig and Stead, 2018; Krahn, 2023). Consequently, numerical methods relying on computer programs have been employed to overcome LEM's limitations. Various numerical codes, such as RS2 and FLAC/Slope, can be utilized for slope stability analysis. The selection of a particular numerical code may depend on the researcher's preferences and the specific problem (Idris, 2022).

The stability of soil or rock slopes is influenced by several factors, including shear strength parameters (cohesion and friction angle), unit weight, slope height, groundwater, and more (Idris, 2022). Geotechnical properties of soil and rock materials exhibit significant variability, making it challenging to determine their precise values (Idris, 2014; Phoon and Kuhawy, 1999). Despite acknowledging this complexity, conventional deterministic methods, which rely on mean values of geotechnical parameters, have been widely used to assess mining slope safety. However, these approaches tend to oversimplify the inherent variability in soil and rock properties, potentially leading to misleading conclusions regarding slope stability. It has been observed that slopes with the same safety factor can exhibit different failure

probabilities due to variability in soil parameters (Xiao et al., 2016).

In recent years, there has been a growing recognition of the limitations of deterministic methods, driving a shift towards probabilistic analyses (El-Ramly et al., 2002; Griffiths and Fenton, 2004; Zhang et al., 2022; Idris 2022). Probabilistic methods consider the inherent variability in geotechnical parameters, providing a more comprehensive understanding of the risks associated with slope stability. This paradigm shift is motivated by the need for more accurate risk assessment and decision-making in mining operations.

Dangote open-pit coal mine in Ankpa, Kogi State, Nigeria, plays a pivotal role in supplying essential raw materials for cement production within Nigeria. Any potential failure or instability at this mine could have far-reaching consequences on the production. Hence, there is a need to assess the likelihood of instability to prevent such occurrences proactively. Consequently, a probabilistic slope stability assessment has been conducted at the mine.

This assessment carefully considers the inherent variability in soil and rock properties, providing invaluable insights into the performance and safety of the mining slopes. In doing so, it underscores the importance of probabilistic methodologies in assessing slope stability, thereby enhancing the precision and reliability of risk assessment processes.

Material and Methods
Description of the Study Area
The Ankpa coal mine is situated in Kogi State, Nigeria, about 150 kilometres north of Enugu and 80 kilometres west of Makurdi. It's positioned at latitude 07°20'14"N and longitude 07°30'31"E. The area includes coal seam thickness ranging from 2.0 to 3.0 meters, averaging 2.5 meters. Figure 1 shows

the location of the coal mine. The main coal seam appears continuous from Ogboyoga to Okaba, offering favourable conditions for surface mining. The dominant lithology includes laterite, shale, and coal seam, with laterite forming a 15–20-meter overburden, followed by a shale layer of 20-45 meters, and the coal seam beneath, currently being extracted (Kolade, 2019).

Reports suggest that the coal quality is suitable for coal-fired power plants, with an average of 10,300 Btu, 8.8 percent ash, and 0.7 percent sulphur. The local demand, primarily from Dangote cement plants, is estimated at around 1.2 million tonnes per year. To meet this demand, a plant capable of producing 4,000 tonnes of coal per day is envisioned.

Determination of Physical and Mechanical Properties of Coal, Shale and Laterites
To assess the stability of the Ankpa coal mine, samples of laterite soil, shale, and coal were collected from three distinct locations within the coal mine, labelled as locations A, B, and C. The soil samples were collected from five different points along the study area's strike, using augers to reach a depth of 5cm. For shale and coal, sizeable boulders were selected from each location (A, B, and C) with great care, ensuring they were free from fractures. From each boulder, ten block samples were obtained, resulting in a total of 30 samples for each location.

The samples were tested for density, unconfined compressive strength, tensile strength, Young's modulus, shear strength (i.e., cohesion, and friction angle). All sample preparations and tests were carried out in strict accordance with relevant standards recommended by ISRM (1981) and ASTM (1999).
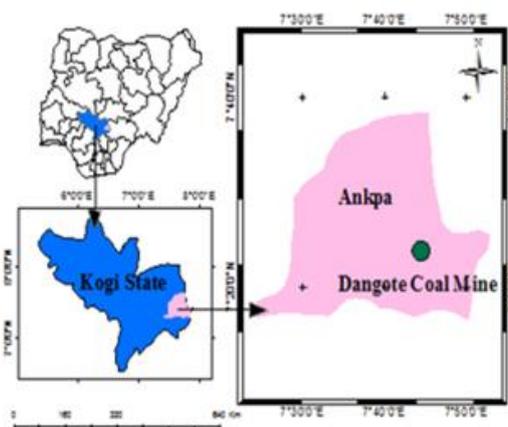
Figure 1: Location of Ankpa Coal Mine

Numerical Modelling of the Slope Stability

The RS², a finite element geotechnical software developed by Rocscience Inc, was used to model the slope stability of the coal mine. The elastic-perfectly plastic Mohr-Coulomb model was used to describe the behaviour of the slope materials. The RS2 conducts the slope stability analysis with simulations based on the shear strength reduction method (SRM). The SRM is used to calculate the critical shear reduction factor (SRF) by progressively reducing or increasing the shear strength of the material to bring the slope to state of limiting equilibrium (Zienkiewicz *et al.*, 1975). The critical SRF is identical to the Factor of Safety adopted by conventional limiting equilibrium method for slope stability analyses.

The geometry of the RS² model used for the numerical simulations is shown in Figure 2. The total slope height is 60 m, with three benches as is common practice at the coal mine. The upper bench height is 17 m, the middle bench height is 20 m, and the lower bench height is 23 m. Both the upper and middle benches have a slope angle of 75°, while the slope face of the lower bench is nearly vertical. The safety benches are 3 m wide. The average thickness of the laterite is 17 m, the shale is 40 m, and the coal seam is 3 m. The material below the coal seam was assumed to be shale to serve as the model boundary. The dimensions of the model are large enough to eliminate any boundary effects.
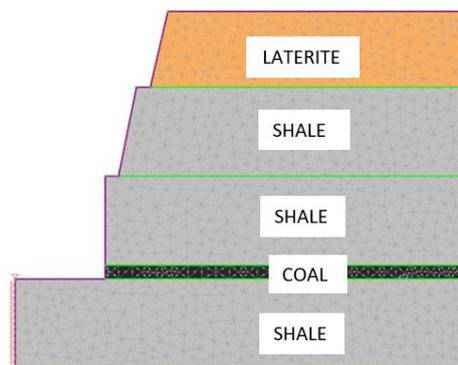
strength, density, and Young's modulus. However, only the cohesion and friction angle were considered in the probabilistic analysis; the tensile strength and Young's modulus were considered deterministic. This is because slope stability is mostly affected by the cohesion and friction angles (Hoek, 2007). The random variables were considered uncorrelated and normally distributed. Rosenblueth's Point Estimate Method (PEM) (Rosenblueth, 1981) was used together with the RS2 software for the probabilistic analysis.

The Rosenblueth PEM is a probabilistic method that uses only statistical parameters without reference to the spatial relationship between samples. In this case, only the mean and standard deviation were used to analyse the statistical relationship in the laboratory results because of the normal distribution used for modelling the data, which has a skew of zero.

The PEM requires 2^n realization points to obtain 2^n results in terms of the strength reduction factor (SRF) for the evaluation of the slope reliability. Since two random variables were considered for the laterite, shale, and coal, the total number of variables is eight (8); therefore, 2^8 (i.e., 64) numerical simulations were made for each location to determine 64 SRFs for each location.

The implementation procedures for the probabilistic analysis of the slope stability using PEM together with RS2 are summarized as follows:

Figure 2: The geometry of slope with its various lithologies

Probabilistic Analysis of the Slope Stability

The probabilistic analysis of the coal mine slope stability accounted for the uncertainty in the material properties of the slope. The random variables were the cohesion, friction angle, tensile

i. The values for the two points for the cohesion and the friction angle for the three locations were determined. The value for a variable is found from $x_i = \mu_x \pm \sigma_x$ where x_i is the

value for the variable at point *i*, μ_x is the mean and σ_x is the standard variation.

ii. A matrix of 64 different combinations of the random variables (cohesion and friction angles) for the laterite, shale, and coal was computed for the three locations.

iii. The combination of the random variables on each row of the matrix table, together with the mean value of tensile strength, unit weight, Poisson's ratio, and Young's modulus, were used as input parameters in the RS2 numerical simulation to get the corresponding SRF. This was repeated for all 64 combinations for each of the locations, and their corresponding 64 SRFs were obtained from the numerical simulations.

iv. The mean values (μ_{SRF}) and standard deviations (σ_{SRF}) for the 64 SRFs for each location were determined.

v. The reliability index (β) and probability of failure (P_f) for each location was calculated using Equations 1 and 2, respectively:

$$\beta = \frac{\mu_{SRF} - F_c}{\sigma_{SRF}} \qquad (1)$$

$$P_f = 1 - \phi(\beta) \qquad (2)$$

where ϕ is the cumulative density function (CDF) of the standard normal variable and F_c is the critical factor of safety for slope stability Various researchers and regulatory bodies have proposed different F_c values. For this study, considering the slope characteristics, mining method, and design life, an F_c value of 1.3 was chosen to reflect the consequence of failure falling within the range of low to medium based on the suggestion of Wesseloo and Read (2009).

Results and Discussion
Shear Strength Parameter of Laterite Soil, Shale, and Coal Samples
As mentioned in Section 2, the elastic-perfectly plastic Mohr-Coulomb model was used to describe the behaviour of the slope materials, so Tables 1, 2, and 3 present the mean and standard deviation (SDV) of shear strength parameters and density of the laterite soil, shale, and coal samples which are relevant to the numerical modelling. The tables show that the laterite soil shear strength parameters exhibit the highest variability at location A, the variability of the shear strength parameters for shale samples is the highest at location B, and the coal shear strength parameters exhibit the highest variability of all three locations.

Table 1: Density and shear strength parameters for laterite soil at different locations

Property	Location A		Location B		Location C	
	Mean	SDV	Mean	SDV	Mean	SDV
Density (kg/m³)	1980.6	-	1980.6	-	1980.6	-
Cohesion (kPa)	50.02	1.1	64.98	0.82	45.48	0.67
Friction angle (°)	32.7	0.64	34.3	0.49	34.6	0.61

Table 2: Density and shear strength parameters for shale sample at different locations

Properties	Location A		Location B		Location C	
	Mean	SDV	Mean	SDV	Mean	SDV
Density (kg/m³)	1921.7	37.6	2155.5	55.8	1629.3	30.5
Cohesion (kPa)	245.1	15.4	208.0	16.3	202.9	13.7
Friction angle (°)	34.3	1.93	31.6	1.87	31.9	0.98

Table 3: Density and shear strength parameters for coal sample at different locations

Properties	Location A		Location B		Location C	
	Mean	SDV	Mean	SDV	Mean	SDV
Density (kg/m^3)	989	4.74	952.6	2.38	944.8	1.70
Cohesion (kPa)	143.7	13.4	195.1	8.0	231.7	40.24
Friction angle (°)	30.7	1.62	30.2	1.36	27.5	2.98

Numerical Simulations of the Coal Mine Slope

The numerical simulation results for locations A, B, and C are shown in Figure 3. The input parameters were the mean values of the shear strength parameters for each location. The SRF (strength reduction factor), which is equivalent to the factor of safety (FOS), is indicated at the top of each plot. The results show that the slopes at locations A and B are stable while the slope at location C is likely to fail when the mean values of the shear strength parameters are considered. It is important to note that soil and rock are intrinsically variable in their properties, so the results of the simulations using the mean values as input parameters could be misleading and may not adequately quantify the likely risk of failure.

Reliability Index and Probability of Failure for the Coal Mine Slope

The point estimate method (PEM) was incorporated with the RS2 software for the probabilistic slope stability analysis. The variables considered for the analysis were cohesion and friction angle, which were assumed to follow a normal distribution. Their means and standard deviations were used to determine the estimation points as described in Section 2.4. Sixty-four (64) combinations of the input parameters were obtained for each of the three locations for the numerical simulations, and the corresponding SRFs were obtained from the simulations. The means and standard deviations of the SRFs for each location were determined.

Subsequently, the reliability index and the probability of failure for each location were calculated using Equations 1 and 2, respectively. The resulting reliability indices for locations A, B, and C were found to be 1.73, 0.54, and -21.90, respectively. Furthermore, the probability of failure for locations A, B, and C was determined to be 4%, 30%, and 100%, respectively.

The probabilistic slope stability analysis results show that the slope at location C is bound to fail with the considered geometry, while location B has a 30% probability of failure and location A has a 96% probability of stability. Based on the US Army Corps of Engineers (1997) Table 4, we can deduce that the performance level of the slope at location A is poor, while the performance level of the slopes at locations B and C is hazardous.
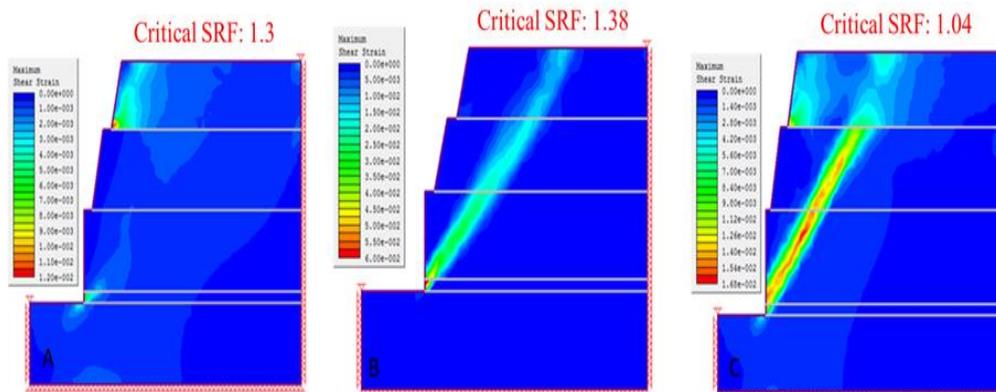

Figure 3: Numerical simulation plots for the 3 locations using mean values input parameters

Table 4: Reliability index, Probability of Failures, and their Performance Level

Reliability index	Probability of failure	Performance level
5	2.9E-7	High
4	3.2E-5	Good
3	1.35E-3	Above Average
2.5	6.21E-3	Below Average
2	0.023	Poor
1.5	0.067	Unsatisfactory
1	0.159	Hazardous

Sensitivity Analysis

Sensitivity analysis was conducted to investigate the effect of changing the slope angle of the upper and middle benches on slope stability. The overall slope height was kept constant because it is the average height of the deposit. Table 5 shows the slope's reliability indices and probability of failure for the three locations at different slope angles. The table shows that the reliability index decreases as the slope angle increases; therefore, the steeper the slope, the lower the reliability index and the higher the probability of failure. Slopes with angles below 50° have high performance at locations A and B, according to Table 4. Increasing the slope angle to 60° at locations A and B yields good and above-average performance, respectively. To reduce the overburden to be removed at locations A and B, the slope angle of the benches could be increased to 70°. Although the performance would be poor, the probabilities of failure are about 4% and 11%, respectively, which are acceptable. However, the slope angle for the benches at location C should be less than 50° to avoid a high probability of failure.

and their physical and mechanical properties were determined using standard procedures. These properties were used as input parameters for numerical simulations of the slope stability. The numerical simulation incorporated the PEM for the probabilistic analysis.

A probabilistic slope stability analysis of the Dangote open-pit coal mine in Ankpa, Kogi State, Nigeria, was conducted in this study by considering the variability of soil and rock properties. The coal seam is covered with laterite soil and shale layers. Samples of laterite soil, shale, and coal were collected from three different locations of the mine and their physical and mechanical properties were determined using standard procedures. These properties were used as input parameters for numerical simulations of the slope stability. The numerical simulation incorporated the PEM for the probabilistic analysis.

The results emphasize the importance of incorporating probabilistic methods in slope stability assessments, as relying solely on mean values may lead to misleading conclusions regarding the risk of failure.

Table 5: Reliability index and Probability of failure at different slope angles for the locations

Slope angle (°)	Reliability index			Probability of failure (%)		
	Location A	Location B	Location C	Location A	Location B	Location C
40	12.77	5.93	3.51	0.00	0.00	0.02
50	7.30	4.36	1.12	0.00	0.00	13.10
60	3.84	2.79	-0.22	0.01	0.26	58.70
70	1.75	1.22	-21.90	4.01	11.12	100.00

Conclusion

This study presents the results of a probabilistic slope stability analysis of the Dangote open-pit coal mine in Ankpa, Kogi State, Nigeria. The coal seam is covered with laterite soil and shale layers. Samples of laterite soil, shale, and coal were collected from three different locations of the mine

The findings indicate that location A exhibits a high probability of slope stability (96%), while locations B and C present varying degrees of vulnerability, with a 30% probability of failure at location B and an inevitable failure scenario at location C, based on the considered geometry. These results align with the performance classifications defined by the

US Army Corps of Engineers, characterizing location A as poor and locations B and C as hazardous.

Furthermore, sensitivity analysis revealed that increasing the slope angle of the upper and middle benches substantially impacts the slope stability. Steeper slopes are associated with lower reliability indices and a higher probability of failure, underscoring the need to carefully consider slope angles to balance performance and safety. At locations A and B, slope angles below 50° yield high performance, while modest increases to 60° can provide good and above-average performance, respectively. A steeper angle of 70° may be acceptable for locations A and B, albeit with lower performance, yet maintaining relatively low probabilities of failure (approximately 4% and 11%, respectively). Conversely, to mitigate the risk of failure, location C should maintain slope angles below 50°.

In conclusion, this study underscores the significance of probabilistic analysis in assessing slope stability, offering valuable insights into the geotechnical aspects of the Dangote open-pit coal mine and providing a foundation for informed decision-making and risk management in mining operations.

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