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Slope Design in Surface Mining with a Total Probability Methodology
[Diseño de Taludes en Minería Superficial con una Metodología de Probabilidad Total]

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Resumen

El presente estudio, tiene como objetivo proponer una metodología para el diseño de taludes óptimos en minería superficial, mediante la aplicación de la probabilidad de falla total en el proceso de determinar la geometría del banco berma de taludes rocosos. El macizo rocoso se caracteriza por ser un medio discontinuo, anisótropo y de naturaleza aleatoria. Por consiguiente, para diseñar taludes, no es suficiente un valor determinístico o Factor de Seguridad que represente la confiabilidad del diseño, sino que se debe incluir la incertidumbre inherente de las propiedades geotécnicas. La estabilidad de taludes a nivel de banco está en función de la calidad del medio rocoso y es controlada por la resistencia de la roca intacta, de las estructurales o por una combinación de ambas. Cuando el talud tiene un control estructural definido, se forman modos de falla planar, cuña o vuelco; estos, según las condiciones de estabilidad, generan eventos de desprendimiento de rocas. Por lo tanto, es necesario aplicar un método efectivo para establecer la geometría óptima del banco. El propósito del banco berma consiste en retener y mitigar el riesgo de caída de rocas y contener el material de derrame de taludes superiores debido a inestabilidades inherentes, con la finalidad de proveer un ambiente seguro para el personal y equipos que trabajan cerca a los taludes. La metodología propuesta considera la variabilidad del buzamiento, dirección de buzamiento, persistencia y fricción de las discontinuidades. El procedimiento inicia con la recopilación y análisis de la información geotécnica del macizo rocoso, con lo cual se definen dominios geotécnicos, sectores de diseño y familias principales de discontinuidades; luego, se realiza análisis estadístico, evaluación cinemática y se determina el ancho de berma conceptual; finalmente, se lleva a cabo el análisis cinético y de probabilidad de falla total validando la geometría del diseño. La investigación se enfocó en un dominio con 04 sectores de diseño geotécnico. Los resultados muestran que el ángulo de cara de banco de diseño aplicable está entre 53° y 71°, lo cual corresponde a un ancho de berma de 9.3m a 8.6m y a un ángulo interrampa geométrico entre 36° y 48° respectivamente. Asimismo, se obtuvieron probabilidades de falla planar total de hasta 31% y cuña total de 41% según las peculiaridades geotécnicas de cada sector. Se comprobó que, en los sectores con mayor probabilidad de falla, se tiene como diseño aceptable un menor ángulo de cara de banco y un ancho mayor de berma de diseño, debido a que se tiene una mayor probabilidad de pérdida de cresta. Por último, en los sectores con menor probabilidad de Falla, se tiene como diseño aceptable un mayor ángulo interrampa. En conclusión, mediante la metodología aplicada se ha demostrado que los resultados del proceso de diseño del banco berma cumplen con los criterios de aceptabilidad de la Probabilidad de Falla. Por lo tanto, el método desarrollado, el cual considera la variabilidad de los parámetros de las discontinuidades del macizo rocoso, permite diseñar taludes seguros y confiables validados mediante un nivel de probabilidad aceptable.

Palabras clave: Ángulo de Cara de Banco, Ángulo Interrampa, Factor de Seguridad, Probabilidad de Falla, Probabilidad de falla total y orientación de la discontinuidad.

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Abstract

The main goal of this research is to propose a methodology for the design of optimal slopes in surface mining, by applying the probability of total failure in the process of determining the geometry of the berm-bench of rock slopes. The rock mass is characterized by being a discontinuous, anisotropic and random medium. Therefore, to design slopes, a deterministic value or Safety Factor that represents the reliability of the design is not sufficient, and the inherent uncertainty of the geotechnical properties must be considered. The stability of slopes at bench level is a function of the quality of the rock mass and is controlled by the strength of the intact rock, the structural rocks, or a combination of both. When the slope has a defined structural control, planar, wedge or toppling failure modes are formed; These, depending on the stability conditions and generates rockfall events. Therefore, it is necessary to apply an effective method to establish the optimal geometry of the bench. The purpose of the berm-bench is to retain and mitigate the risk of rockfall and contain spill from upper slopes due to inherent instabilities, to provide a safe environment for personnel and equipment working near the slopes. The proposed methodology considers the variability of the dip, dip direction, persistence, and friction of the discontinuities. The procedure begins with the collection and analysis of the geotechnical information of the rock mass, which defines geotechnical domains, design sectors and main families of discontinuities; then, statistical analysis and kinematic evaluation are carried out and the conceptual berm width is determined; finally, the kinetic and probability of total failure analysis is carried out, validating the design geometry. The research focused on a domain with 04 sectors of geotechnical design. The results show that the applicable design bench face angle is between 53° and 71°, which corresponds to a berm width of 9.3m to 8.6m and a geometric interramp angle between 36° and 48° respectively. Likewise, probabilities of total planar failure of up to 31% and total wedge of 41% were obtained according to the geotechnical peculiarities of each sector. It was proven that, in the sectors with a greater probability of failure, a lower bench face angle and a greater catch bench of the design berm are considered acceptable designs, due to a greater probability of crest loss. Finally, in the sectors with a lower probability of failure, a greater interramp angle is considered an acceptable design. In conclusion, through the applied methodology it has been demonstrated that the results of the berm-bench design process meet the acceptability criteria of the Probability of Failure. Therefore, the developed method, which considers the variability of the parameters of the rock mass discontinuities, allows designing safe and reliable slopes validated through an acceptable level of probability.

Keywords: Bench Face Angle, Interramp Angle, Safety Factor, Probability of Failure, Total Probability of failure, discontinuity orientation.

1. Introduction

The main challenge of slope design is to provide an optimal geometric configuration of excavation taking into account safety, mineral recovery and return on investment considerations; However, during the design process an incomplete method can be conceived, which results in slopes without the retention capacity for rock fall events. This condition represents the potential to cause loss of human life, economic losses, environmental, social and legal impacts. Therefore, it is of vital importance to guarantee a certain degree of stability to the slopes from the design of the berm bank.

In the Peruvian mining industry, statistics show that the highest percentage of accidents that occurred between 2012 and 2020 are due to land collapses, falling masses of earth and rocks due to slope failure. According to the OSINERMING (2020), only from January to April 2020, accidents have occurred with 13 fatalities, of which 23% of the cases are due to rockfall (p.3).

Ojeda (2017) in his study about the bench-berm scale analysis methodology for determining design parameters applied to the La Alumbrera mine in the province of Catamarca in Argentina, explains that their objective is to carry out a bench berm analysis in order to to determine the geotechnical bases for the design of the final Pit slopes. According to the results of this analysis,

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the reliability of the bench face angles meets the adopted acceptability criteria, which correspond to 65% in a single bench and 70% in a double bench. The implementation of design parameters with a 75° bench face was recommended, with specific sectors with 65° and 70° designs (pp. 1-4,109-111).

Obregon and Mitri, (2019) carried out a slope study with a probabilistic approach in a Peruvian surface mining operation, whose objective was to evaluate stability at the bench scale. The methodology was based on performing a kinematic analysis according to stereographic projection techniques, followed by a kinetic analysis applying the limit equilibrium method, finally the kinetic and kinematic probabilities were combined to provide a global measure of the probability of slope failure at bench level. Monte Carlo simulation was used to calculate the kinetic and kinematic failure probability. The results obtained in the case study show that the probability density functions of the discontinuity parameters can be obtained from field measurements, laboratory tests and by applying engineering judgment. Probability of failure relates to the evaluation of slope performance from a geotechnical risk perspective and provides the basis for optimization of designs. (p. 629).

Deterministic analyzes do not consider the uncertainty due to the limited geotechnical information available, nor the inherent variability of the discontinuities of the rock mass; This means that an environment with reliable and safe slopes is not guaranteed. In this way, the need arises to develop a methodology that allows designing slopes at the Bank level validated by a certain degree of stability and reliability, applying a probabilistic approach that considers the uncertainty and dispersion of the geotechnical information of the discontinuities of the rock mass. with more realistic results regarding the stability of the slopes.

1.1. Bench-Berm Design

To determine the minimum effective berm width, the Ryan & Prior (2000) criterion was applied, cited by Hustrulid et al. (2001).

$$\mathrm{Be\ (m) = 0.17BH + 3.5m \ldots \ldots \ldots \ldots \ldots \ldots . . (Equation\ 01)}$$

Where:
Be: Bench width, in meters.
HB: Bench height, in meters.
Figure 1 shows the geometric parameters considered in the present study.

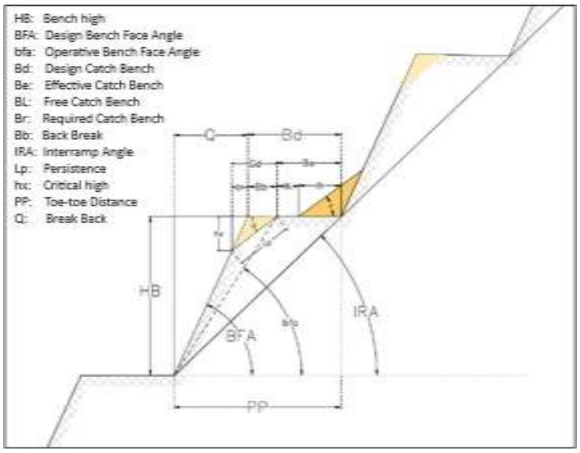

Figure 1. Geometric parameters considered for the evaluation of the Banco – Berma Design

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Read and Stacy (2010) mention that the main function of the bank-berm is to provide a safe environment for personnel and equipment that must work near the slopes; these must satisfy the needs of reliability, which requires slope faces and ridges. stable, safety, this translates into berm widths sufficient to retain and mitigate the risk of rockfall and contain spill material from upper banks; and finally, guarantee long-term access to the banks for activities such as slope monitoring and cleaning up fallen rocks or spill material.

1.2. Slope stability analysis by deterministic methods

According to Gonzales de Vallejo (2004), the analysis of slope stability with a deterministic methodology consists of selecting the appropriate values of the physical and resistant parameters that control the behavior of the rock mass, based on them and the appropriate laws of behavior, defining the state of stability or the Safety Factor of the Slope. The forces acting on a potential failure or slip plane are analyzed, assuming that there are no external forces on the slope, they are due to the weight of the material (W), Cohesion (c) and friction (ϕ) along of the plan See Figure 2.

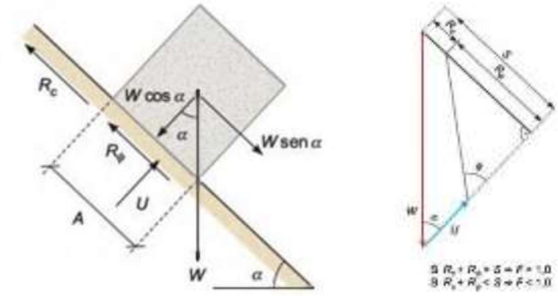

Figure 2. Forces acting on a failure surface
Source: Gonzales de Vallejo (2004)

The Safety Factor is given by:

$$\mathrm{F.S} = \frac{(\mathrm{R_c} + \mathrm{R_\phi})}{\mathrm{S}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (\text{Equation } 02)$$

Where:
Rc = Cohesive forces = cA
Rϕ = Frictional forces = W cosα tgϕ
S = Forces tending to slide = W sinα
A = Area of failure plane

Total Failure Probability

According to Duncan and Christopher (2004), to determine the probability of failure, the F.S is recognized as a random variable and the Probability that this factor is less than or equal to 1 is sought:

$$\mathrm{P.F} \;=\; \mathrm{P}[\mathrm{F.S} \leq 1] \ldots\ldots\ldots\ldots. (\text{Equation } 03)$$

Table 3 shows the acceptance criteria for the F.S and the P.F, according to Read and Stacy (2010).

Table 3. Values of the Acceptance Criteria for the F.S and the PF

		Acceptance requirements		
Slope scale	Consequence of failure	F.S (min) (static)	F.S (min) (static)	P.F (max) P [F. S<=1]
Bank	Low – High	1,10	N/A	25-50%
Inter-ramp	Low	1,15-1,2	1,00	25%
	Moderate	1,20	1,00	20%
	High	1,2-1,3	1,10	10%
Overall	Low	1,2-1,3	1,00	15-20%
	Moderate	1,30	1,05	10%
	High	1,3-1,5	1,10	5%

Source: Read and Stacy (2010)

The probability of total failure is established according to the conjunction of the probability of the condition of occurrence of failure modes, the probability that the Safety Factor is less than 1 and the probability of the condition of structural persistence. According to Ojeda (2017), the Total probability is established according to the following relationship:

$$\text{Total Design Failure Probability (PT)} = P_c * P_f * P_{Lp} \ldots\ldots \text{(Equation 03)}$$

Where:
Pc: Probability of the Condition occurrence of the Failure mode. Determined from the orientation relationship of the families of discontinuities that affect the slope through a planar or wedge-type mechanism. It was determined by using @Risk software.

Pf: Probability of Failure. This probability was estimated from the resistant properties of the discontinuities, using the @Risk software.

PLp: Probability of persistence length. Defined as the probability of a given instability mechanism affecting less than 1/3 of the bank height. It was determined using @Risk software.

2. Materials and Methods

2.1. Design and type of research

The design of the present study is of the non-experimental quantitative type, observation and correlational study techniques were applied, that is, correlations were described between independent variable indicators: Safety factor and Probability of failure with the dependent variable slope design on a scale of bank. Figure 3 shows the relational scheme of the study variables.

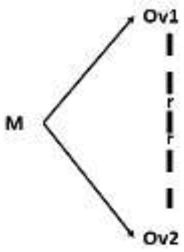

Figure 3. Scheme of the Non-Experimental Design

M = Sample
Ov1= Observation of variable 1: Methodology with probabilistic approach Total
Ov1= Observation of variable 2: Optimal Slope Design
r = Correlation

According to (Hernández, et al., 2014) the purpose of the Transsectional or Cross-sectional design is to delimit variables and examine their appearance and interaction at a given time. It is possible to compare it to "taking a photograph" of an event. The present study is based on the observation of the discontinuities of the rock mass in its natural environment to determine its properties and how they are related to the geometry of the bank and its level of stability.

2.2. Slope design procedure.

The methodology for the Design of Slopes in rock masses, with a Total Probability approach, takes into account the following steps.

- Geotechnical Mapping. Data collection from the rock mass in windows was carried out systematically.
- Analysis of geotechnical information. The analysis of the geological, structural and rock mass information was carried out to define the geotechnical domains. Each domain was subdivided into geotechnical design sectors according to the direction of the slope.
- Statistical analysis of discontinuities. In each sector, the main families of structures were determined through stereographic analysis of the poles. Likewise, the measures of central tendency and the statistical distribution functions of dip, dip direction, persistence, cohesion and friction were calculated.
- Kinematic Analysis. The kinematic analysis of the structures for planar and wedge type failure mechanisms was carried out, the maximum number of instabilities in each case was determined and the normalized cumulative frequency curve was constructed for apparent dip of the slope with a range of angles from 90° to 30°. °. With the acceptance restriction of a cumulative frequency of 50% and 35%, the operational and design slope face angles were defined respectively, with which the expected backbreak or slope was measured.
- Berm Width Design. Using the Ryan and Prior formula (Eq.04), the minimum berm width was calculated assuming 80% reliability of retention capacity. Next, the slope is added to the minimum berm width to obtain the design berm width. Thus, the geometric Interramp Angle was also obtained, which was verified to correspond to a normalized frequency less than 20%.
- Kinetic analysis. The kinetic evaluation of the potential planar and wedge type failure mechanisms was carried out, obtaining the deterministic Safety Factor in each case.
- Total probabilistic analysis. The probabilistic analysis consisted of three stages, firstly, the probability of occurrence of a planar and wedge type failure mechanism was determined, secondly, the probability of failure in which the mechanism generates a lower safety factor was determined. to 1, thirdly, the probability that the persistence has a length less than a critical length that meets the restriction of 1/3 of the bank height compromised in the instability was determined. Finally, by combining the 03 results, the Total System Probability for each sector was determined, thereby validating the berm design.

The procedure of the methodology applied in the present study is shown graphically in the diagram of Figure 4

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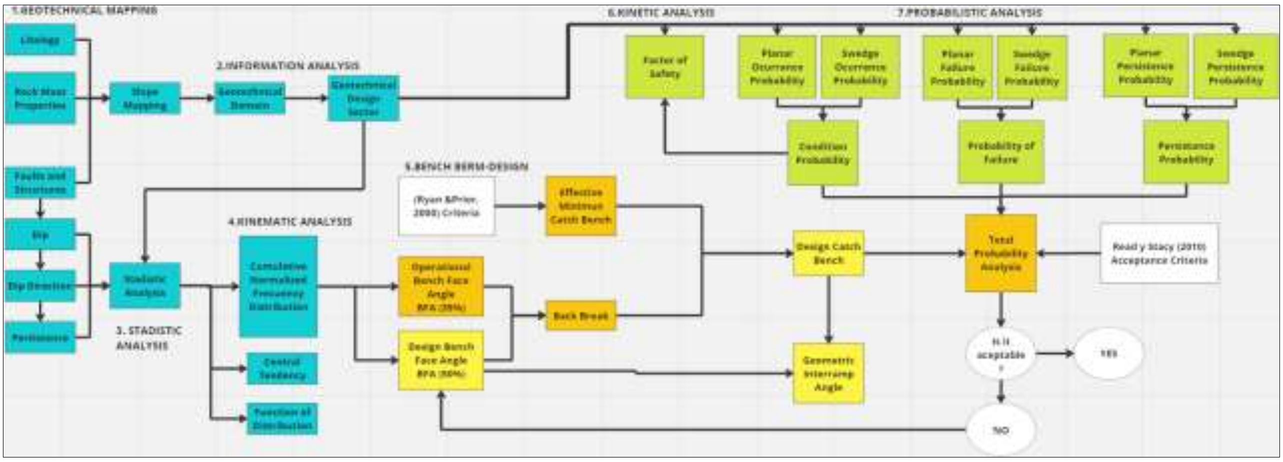

Figure 4. Outline of the Slope Design Methodology through Total Probability analysis.

3. Results

3.1. Analysis of geotechnical information

The regional lithology of the study area includes sequences of sedimentary rocks belonging to the Goyllarisquizga group from the Lower Cretaceous, followed by shales and limestones from the Inca, Chulec and Pariatambo formations, from the Upper Middle Cretaceous. Overlying there are colluvial, alluvial and proluvial deposits and residual soils. The described sequences have been affected by Tertiary dacitic and andesitic-dioritic intrusives, probably related to the mineralization of the INGEMMET repository (1980).

For the purpose of the geomechanical characterization of the Intact Rock and the discontinuities, the information from 28 tests for determination of Physical Properties, 66 Uniaxial Compression tests according to lithology to determine the Simple Compression Strength and 16 Direct Cut to determine the cohesion and friction of discontinuities.

The present study is based on information from 103 geotechnical mapping windows. 02 Geotechnical Domains were defined based on the lithology and structural conditions of the site. The Eastern Domain constituted by Sedimentary type Lithology (sandstone) and the Western Domain formed by Intrusive type lithology (andesite). The present study has focused on applying the methodology for the Eastern Domain, see Figure 5.

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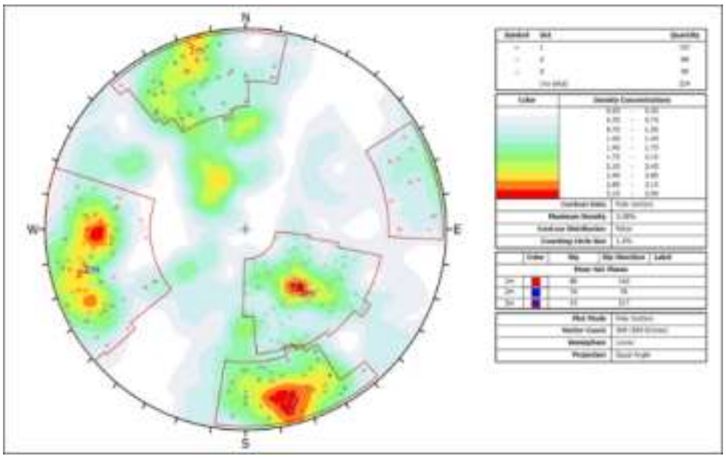

Figure 5. Families of discontinuities Eastern Domain – Mapping

In the geotechnical domain of study, the subdivision was carried out into design sectors according to the orientation of the slopes, as can be seen in Figure 6.

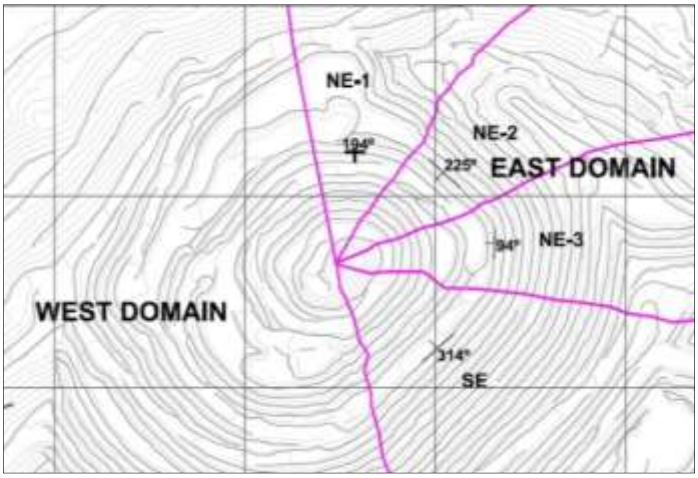

Figure 6. Location of Design Sectors in the Eastern Domain

In the Eastern Domain that corresponds to the study area, 04 geotechnical design sectors were defined based on the orientation of the slopes, and in each of them the main families of discontinuities were determined, and for each of these sets, Central tendency analysis was performed and the statistical distribution function was determined.

3.2. Statistical analysis of the properties of discontinuities.

For each family of discontinuities, the statistical analysis of Dip, Dip Direction and Persistence was carried out, the results are shown in Table 2

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Table 2: Statistical parameters of Dip, Dip Direction and Persistence according to design sector

Domain	Sector	Slope orientation		Set #	Dip (°)	Mean Dip	DE Dip (°)	Dip Direction (°)	Mean Dip Direction	DE Dip Direction	Function of Distribution	Persistence	Mean	N	Function of Distribution
		βs (°)	αs(°)		βj(°)	Mean Dip		αj(°)							
EAST	NE-01		194	J1	50	50.0	16.9	167	167.1	19.1	Normal	J1	6.0	25.0	Exponential Negative
				J2	70	70.8	10.5	295	295.3	16.2	Normal	J2			
				J3	70	71.2	5.8	53	54.3	12.0	Normal	J3			
	NE-02		225	J1	40	40.5	10.5	174	173.4	13.6	Normal	J1	5.1	44.0	Exponential Negative
				J2	62	62.7	14.7	61	60.6	8.6	Normal	J2			
				J3	46	47.5	5.2	342	339.4	16.4	Normal	J3			
	NE-03		94	J1	83	80.1	7.3	70	70.5	11.3	Normal	J1	4.1	157.0	Exponential Negative
				J2	52	52.6	14.1	159	159.0	16.3	Normal	J2			
				J3	39	40.2	12.0	327	327.1	17.5	Normal	J3			
	SE		314	J1	73	72.9	9.0	95	104.4	32.4	Normal	J1	3.8	283.0	Exponential Negative
				J2	62	62.9	13.5	343	341.4	15.7	Normal	J2			
				J3	71	71.5	10.0	164	169.1	34.4	Normal	J3			

Note:
αs (°): Dip Direction of the design slope
βj: Dip of the discontinuity
αj: Dip Direction of the discontinuity

DE: Standard Deviation
N: Number of data

Likewise, the statistical analysis of the cohesion and friction of the discontinuities in sandstone lithotype was carried out, which corresponds to the Eastern Geotechnical Domain. See Table 3. For practical purposes and based on the theory that at bench scale stability is controlled mostly by the friction of discontinuities, a cohesion of 0 was considered.

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Table 3. Statistical parameters of Friction and Cohesion

Rock type	Ítem	Mean	Standard deviation	Coefficient of Variation	Function of Distribution
Sandstone	Friction	29.92	2.11	0.07	Normal
Sandstone	Cohesion	0.12	0.01	0.12	Normal

3.3. Kinematic analysis

The percentage of occurrence of planar mechanisms and wedges was determined according to the number of poles of the families of discontinuities identified in each geotechnical design sector, considering a Bank face angle of 90° and according to the dip direction of the geotechnical design sector, the results are shown in Table 4.

Table 4. Analysis of the Statistical Occurrence of Instabilities

Domain	Sector	Slope orientation		Set #	Dip (°)	Dip Direction (°)	Estatistical Potential ocurrence of the instability mechanism		
		βs (°)	αs (°)				Planar	Wedge	
EAST	NE-01	58	194	J1	50	167	13%	J1&J2	48%
				J2	70	295	0%	J2&J3	0%
				J3	70	53	0%	J3&J1	37.5%
	NE-02		225	J1	40	174	83%	J1&J2	15%
		71		J2	62	61	0%	J2&J3	0%
				J3	46	342	0%	J3&J1	0%
	NE-03		94	J1	83	70	0%	J1&J2	9%
		53		J2	52	159	9%	J2&J3	0%
				J3	39	327	0%	J3&J1	0%
	SE		314	J1	73	95	0%	J1&J2	27%
		65		J2	62	343	46%	J2&J3	24%
				J3	71	164	0%	J3&J1	0%

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The average curve of the planar and wedge type failure mechanisms was determined. To define the operational and design BFA, it was decided to accept 50% and 35% instabilities respectively. As an example in Sector NE-01, see Figure 6, it is observed that the definition of the operational BFA (50%) is equal to 58° and the design BFA (35%) is equal to 51°. Table 5 shows the summary of the operational and design BFA of each sector.

Table 5. Operational and Design BFA

Sector	BFA Operational β (50%)	BFA Design β (35%)	Slope dip direction αs (°)
NE-01	58	51	194
NE-02	71	63	225
NE-03	53	46	94
SE	65	57	314

3.4. Berm Width Design

Firstly, to determine the minimum berm width, the Ryan & Prior (2000) criterion was used, which determined the minimum required berm width with 80% reliability of the retention capacity. Considering a bench height of 15m, there is a minimum berm width of:

$$BW(m) = 0.17(15m) + 3.5m$$

$$BW(m) = 6.05m$$

Secondly, the BFA (50%) and BFA (35%) were plotted with a bank height of 15m, and the expected back break (BB) was determined. The design berm width is equal to the sum of the back break and the minimum berm width. Finally, the geometric IRA was determined.

As an example, Figure 7 shows the definition of BB, BFA (50%), BFA (35%) and Design CB.

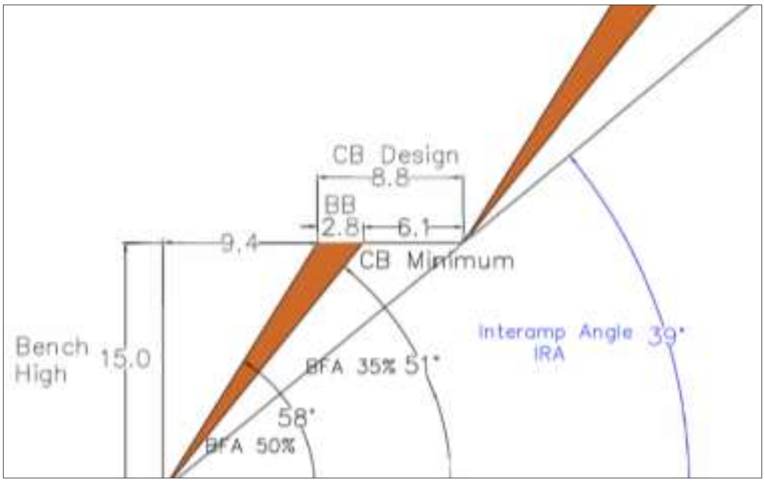

Figure 7. Geometric calculation of the Interramp angle (IRA).

Thirdly, the comparison was carried out in the cumulative frequency graph, where it is verified that the IRA must correspond to less than 20% of instabilities. In the case of sector NE-01, with an IRA of 39° it corresponds to 9%, which is less than 20% acceptability. See Figure 8. Which meets the requirement.

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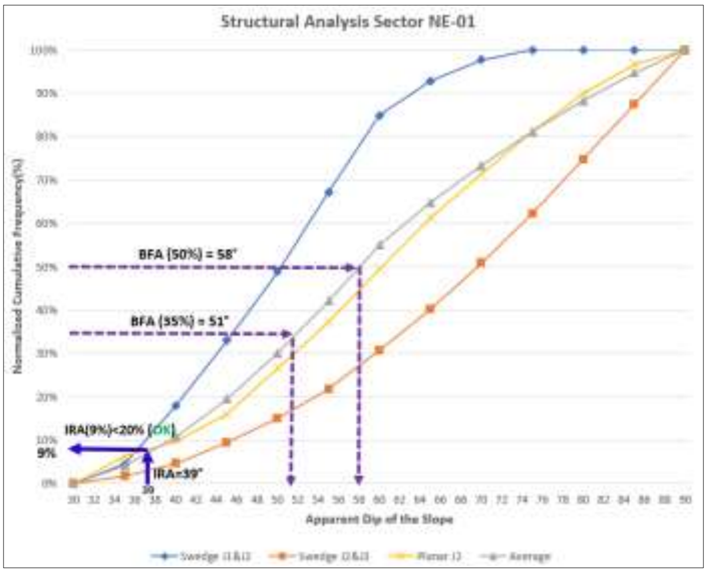

Figure 8. Validation of the Interramp Angle.

Table 6 shows the summary of the design parameters obtained in terms of Bank Face Angle, Berm Width and IRA of the other design sectors.

Table 6. Design parameters, according to geotechnical sector

Sector	BFA β (50%)	BFA β (35%)	Back Break (BB)	CB Min. Ryan & Prior (2000)	CB Design	Ɵ IRA (Ryan&Prior)
NE-01	58	51	2.8	6.05	8.85	39
NE-02	71	63	2.5	6.05	8.55	48
NE-03	53	46	3.2	6.05	9.25	36
SE	65	57	2.8	6.05	8.85	44

3.5. kinetic analysis

The safety factor was determined for the largest structures, considering the planar and wedge-type failure mechanisms. Table 7 shows the results of the deterministic analysis of each geotechnical design sector.

Table 7: Deterministic analysis of each geotechnical design sector

Domain	Sector	Slope direction								
		βs (°)	αs (°)	Set #	F.S. Planar	Wedge	Plunge αi(°)	Trend βi(°)	Wedge	F.S. Wedge
EAST	NE-01	58	194	J1	0.48	J1&J2	34.9	205.8	J1&J2	0.83
				J2		J2&J3			J2&J3	
				J3		J3&J1	29.0	166.7	J3&J1	1.04
	NE-02	71	225	J1	0.69	J1&J2	32.0	168.9	J1&J2	0.92
				J2		J2&J3			J2&J3	
				J3		J3&J1			J3&J1	
	NE-03	53	94	J1	0.07	J1&J2	37.2	125.2	J1&J2	0.76
				J2		J2&J3			J2&J3	
				J3		J3&J1			J3&J1	
	SE	65	314	J1		J1&J2	46.2	103.2	J1&J2	0.55
				J2	0.31	J2&J3	36.2	257.5	J2&J3	0.79
				J3		J3&J1			J3&J1	

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Note: To determine the Safety Factor, it has been considered that cohesion does not influence stability, since it is an evaluation at the bank level.

For practical purposes, in the F.S type Wedge it was considered as a conversion constant from planar to wedge type analysis (K=1).

3.6. Total Probabilistic Analysis

3.6.1. Probability of failure mode occurrence

The probability of formation or occurrence of planar and wedge-type failure mechanisms was determined taking into account the corresponding structural conditions (C1, C2 and C3). The results of the analysis for the planar type failure mode are shown in Table 8, the @Risk software was used applying the Monte Carlo method, as indicated in Figure 9.

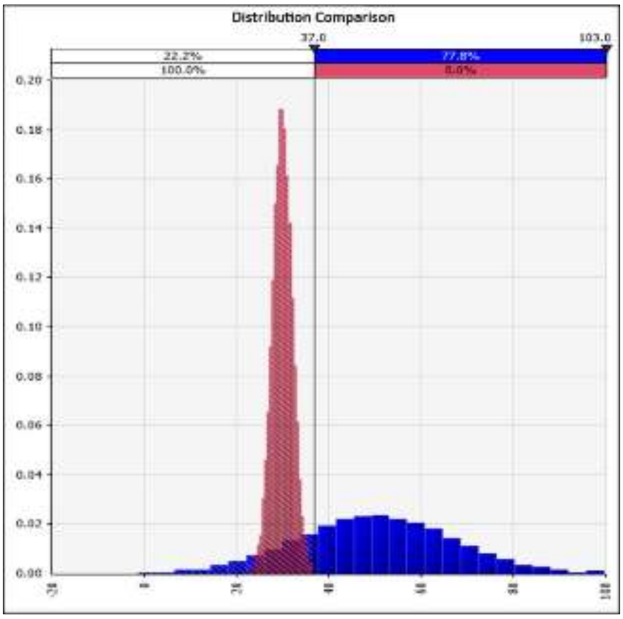

Figure 9: Determination of the Probability for Condition C1 (βj>ø). @Risk Software.

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Table 8. Probability of occurrence of planar and wedge mode failure

Domain	Sector	Slope direction		Set #	Dip (°)	Dip Direction (°)	C1: βj>ø	C2: ø<βs	C3: αj>αs-20 y αj>αs+20	Pr.C1 ∩ Pr.C2 ∩ Pr.C3		C1: αi > ø	C2: αi< βs (°)	C3: βi>=αs-80 y βs<=αs+80	Pr.C1 ∩ Pr.C2 ∩ Pr.C3
		βs (°)	αs(°)		βj(°)	αj(°)	P1	P2	P3	Probability of occurrence Planar	Wedge	P1	P2	P3	Probability of occurrence Wedge
ESTE	NE-01	58	194	J1	50	167	78%	100%	35%	27.2%	J1&J2	41%	99%	93%	38.3%
				J2	70	295	100%	100%	0%	0.0%	J2&J3				
				J3	70	53	100%	100%	0%	0.0%	J3&J1				
	NE-02	71	225	J1	40	174	63%	100%	1%	0.6%	J1&J2	24%	100%	89%	21.0%
				J2	62	61	96%	100%	0%	0.0%	J2&J3				
				J3	46	342	98%	100%	0%	0.0%	J3&J1				
	NE-03	53	94	J1	83	70	100%	100%	38%	37.8%	J1&J2	53%	99%	99%	52.0%
				J2	52	159	88%	100%	0%	0.4%	J2&J3				
				J3	39	327	62%	100%	0%	0.0%	J3&J1				
	SE	65	314	J1	73	95	100%	100%	0%	0.0%	J1&J2				
				J2	62	343	97%	100%	32%	31.0%	J2&J3	48%	98%	67%	31.5%
				J3	71	164	1.00	1.00	0.00	0.000	J3&J1				

Note:
βs (°): Dip of the design slope
αs (°): Dip Direction of the design slope
βj: Dip of the discontinuity
αi: Plunge of the Wedge.
βi: Trend of the Wedge
αj: Dip Direction of the discontinuity

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3.6.2. Failure Probability Analysis (F.S < 1)

Kinetic analysis was performed for each family of discontinuities, according to failure mode. With this, the probability of Failure of each Design sector was determined with the condition that the Safety Factor is less than 1. Table 9 and Table 10 show the results for the case of planar and wedge failure respectively. Likewise, in both cases, the Monte Carlo methodology was applied in the @Risk software.

Table 9. Probability of Planar Failure (F.S.<1)

Domain	Sector	Slope direction		Set #	Dip (°)	Dip Direction (°)	PF. Planar (F. S<1)
		βs (°)	αs (°)		βj (°)	αj (°)	
EAST	NE-01	58	194	J1	50	167	88%
				J2	70	295	97%
				J3	70	53	100%
	NE-02	71	225	J1	40	174	84%
				J2	62	61	95%
				J3	46	342	100%
	NE-03	53	94	J1	83	70	91%
				J2	52	159	94%
				J3	39	327	79%
	SE	65	314	J1	73	95	97%
				J2	62	343	97%
				J3	71	164	100%

Table 10. Probability of Wedge Failure (F.S.<1)

Domain	Sector	Slope direction		Wedge	Plunge αi(°)	Trend βi(°)	PF. Wedge (F. S<1)
		βs (°)	αs (°)				
EAST	NE-01	58	194	J1&J2	34.9	205.8	69.4%
				J2&J3			
				J3&J1	29.0	166.7	41.2%
	NE-02	71	225	J1&J2	32.0	168.9	59.4%
				J2&J3			
				J3&J1			
	NE-03	53	94	J1&J2	37.2	125.2	87.6%
				J2&J3			
				J3&J1			
	SE	65	314	J1&J2	46.2	103.2	90.4%
				J2&J3	36.2	257.5	67.0%
				J3&J1			

3.6.3. Persistence Length Probability.

The next step was to determine the probability of Failure considering the condition of the critical length of the Persistence of the families of discontinuities under study. The results are shown in Table 11 and Table 12.

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Table 11. Probability of the length of Planar type structure Persistence

Domain	Sector	Slope direction βs (°)	Slope direction αs (°)	Set #	Dip (°) βj (°)	Dip Direction (°) αj (°)	Persistence L (m)	Lc (m)	P.F. Persistence Planar
EAST	NE-01	58	194	J1	50	167	6.00	6.53	57%
				J2	70	295			
				J3	70	53			
	NE-02	71	225	J1	40	174	5.10	7.78	100%
				J2	62	61			
				J3	46	342			
	NE-03	53	94	J1	83	70	4.10	5.04	89%
				J2	52	159			
				J3	39	327			
	SE	65	314	J1	73	95			
				J2	62	343	3.80	5.66	99%
				J3	71	164			

Table 12. Probability of the length of wedge-type structure persistence

Domain	Sector	Slope direction βs (°)	Slope direction αs (°)	Wedge	Plunge αi (°)	Trend βi (°)	Persistence L (m)	Lc (m)	P.F. Persistence Wedge
EAST	NE-01	58	194	J1&J2	34.9	205.8	6.00	8.74	56.6%
				J2&J3					
				J3&J1					
	NE-02	71	225	J1&J2	32.0	168.9	5.10	9.44	99.6%
				J2&J3					
				J3&J1					
	NE-03	53	94	J1&J2	37.2	125.2	4.10	8.27	89.0%
				J2&J3					
				J3&J1					
	SE	65	314	J1&J2					
				J2&J3	36.2	257.5	3.80	8.47	99.4%
				J3&J1					

With the results obtained, the Probability of Total Failure was determined, through the conjunction of the Kinematic Probability, Kinetic Probability and Persistence Probability; for each failure mode. Table 13 summarizes the results of the Total Failure Probability.

Table 13. Probability of Total Failure

Domain	Sector	Slope direction		Set #	Dip (°)	Dip Direction (°)	P. F. Planar Total	Wedge	Plunge αi (°)	Trend βi (°)	P. F. Wedge Total
		βs (°)	αs (°)		βj (°)	αj (°)					
EAST	NE-01	58	194	J1	50	167	13.5%	J1&J2	34.9	205.8	15.0%
				J2	70	295		J2&J3			
				J3	70	53		J3&J1			
	NE-02	71	225	J1	40	174	0.5%	J1&J2	32.0	168.9	12.5%
				J2	62	61		J2&J3			
				J3	46	342		J3&J1			
	NE-03	53	94	J1	83	70	30.7%	J1&J2	37.2	125.2	40.6%
				J2	52	159		J2&J3			
				J3	39	327		J3&J1			
	SE	65	314	J1	73	95		J1&J2			
				J2	62	343	29.8%	J2&J3	36.2	257.5	21.0%
				J3	71	164		J3&J1			

Table 14 summarizes the results of the design parameters defined for each design sector (Bank Face Angle, Design Berm Width and Interramp Angle), the Safety Factor of the maximum dimension structure and the Probability of Total Failure.

Table 14. Summary table of the Bank-Berm design parameters

Sector	Bench face angle (°)	Berm width (m)	Interramp angle (°)	F.S. Planar (max.)	F.S. wedge (max.)	P. F. Planar Total	P. F. wedge Total
NE-01	58	8.9	39	0.48	0.83	13.5%	15.0%
NE-02	71	8.6	48	0.69	0.92	0.5%	12.5%
NE-03	53	9.3	36	0.07	0.76	30.7%	40.6%
SE	65	8.9	44	0.31	0.55	29.8%	21.0%

4. Conclusions

- The study only focused on the application of the methodology for the Eastern domain of the study area, which is made up of 04 sectors of geotechnical design, these are: sector NE-01 with Dip Direction of 194°, NE-02 with Dip Direction of 225°, NE-03 with Dip Direction of 94° and SE with Dip Direction of 314°.
- In Sector NE-01, a design bench face angle of 58°, design berm width of 8.9m, interbank angle of 39°, Safety Factor for the maximum planar and wedge structure of 0.48 and 0.83 were obtained. respectively, Probability of Total Planar Failure of 13.5% and Probability of Total Wedge Type Carving of 15.0%. The results of the probability of failure are less than 50% which is the acceptable failure level, therefore, the design is validated.
- In Sector NE-02, a design bench face angle of 71°, design berm width of 8.6m, interbank angle of 48°, Safety Factor for the maximum planar and wedge structure of 0.69 and 0.92 were obtained. respectively, Probability of Total Planar Failure of 0.5% and Probability of Total Wedge Type Carving of 12.5%. The results of the probability of failure are less than 50% which is the acceptable failure level, therefore, the design is validated. This sector presents the lowest probability of failure within the geotechnical domain studied.

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- In Sector NE-03, a design bench face angle of 53°, design berm width of 9.3m, interbank angle of 36°, Safety Factor for the maximum planar and wedge structure of 0.69 and 0.92 were obtained. respectively, Probability of Total Planar Failure of 30.7% and Probability of Total Wedge Type Carving of 40.6%. The results of the probability of failure are less than 50% which is the acceptable failure level, therefore, the design is valid. This sector is the one with the highest probability of failure within the geotechnical domain studied.
- In the SE Sector, a design bench face angle of 65°, design berm width of 8.9m, interbank angle of 44°, Safety Factor for the maximum planar and wedge structure of 0.31 and 0.55 respectively were obtained. Probability of Total Planar Failure of 29.8% and Probability of Total Wedge Carving of 21%. The results of the probability of failure are less than 50% which is the acceptable failure level, therefore, the design is validated.
- It was proven that, in the sectors with a greater probability of failure, a lower bank face angle and a greater width of the design berm are considered acceptable designs, due to a greater probability of crest loss. Finally, in the sectors with a lower probability of failure, a greater inter-impact angle is considered an acceptable design.
- Through the applied methodology, it has been demonstrated that the results of the berm bench design process meet the acceptability criteria of the Probability of Failure. Therefore, the developed method, which considers the variability of the parameters of the rock mass discontinuities, allows designing safe and reliable slopes validated through an acceptable level of probability.

References

Duncan C. W., & Christopher W. M. (2004). ROCK SLOPE ENGINEERING Civil and Mining. London and New York: Spon Press.

Gonzales de Vallejo L. I. (2004). Ingeniería Geológica. Madrid: PEARSON EDUCACIÓN, S.A.

Hernández Sampieri R., Fernandez Collado C., & Baptista Lucio P. (2014). Metodología de la Investigación. México D.F: McGRAW-HILL / INTERAMERICANA EDITORES, S.A. DE C.V.

Hustrulid W., MacCarter M. et al. (2001). Slope stability in surface mining. Society for mining, metallurgy, and explorations, Inc.(SME). Colorado 2001.
https://www.cnitucson.com/publications/2000_ch3__Catch%20Bench_sme_tr_pp.pdf

INGEMMET. Repositorio Institucional. (1980). Geología de los cuadrángulos de Cajamarca, San Marcos y Cajambamba. Hojas: 15-f, 15-g, 16-g - [Boletín A 31]. https://hdl.handle.net/20.500.12544/150.

Obregon C., & Mitri H. (2019). Probabilistic Aproach for open pit bench slope stability analysis - A mine case study. International Journal of Mine Science and Technology, 629-640. https://doi.org/10.1016/j.ijmst.2019.06.017

Ojeda M. A. (2017). Metodología de Análisis a escala de banco berma para la determinación de parámetros de diseño aplicado a mina la Alumbrera provincia de Tacamarca Argentina. Tacamarca, Tacamarca, Argentina. http://repositorio.udec.cl/handle/11594/3148.

OSINERMING (2019). Boletín Estadístico de la Gerencia de Supervisión Minera ACCIDENTES MORTALES. Lima, Lima, Perú. 30 de Setiembre de 2019

Read J., & Stacy P. (2010). Guidelines for Open Pit Slope design. Collingwood: CSIRO PUBLISHING.

Ryan T. M. and Pryor P.R. (2000) Designing Catch Benches and Interramp Slopes, Chapter 3, Slope Stability in Surface Mining, Society for Mining, Metallurgy, and Exploration, Inc., pp.27.