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Slope Stability Analysis: Case of the West Wall of the EMZ Pit at the Essakane Gold Mine in Burkina Faso (West Africa)

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Abstract

Knowledge of the state of stability of mining pits is both a basic condition, an essential axis and a safety benchmark for mining operations. This stability is largely based on the knowledge of the rock mass sheltering the mining works and this requires a perfect characterization of all of its structural formations through mapping (manual or digital). The families of discontinuities, namely family 1 (bedding), family 2 (Joint 2) and family 3 (Joint 1) obtained through structural mapping in the Essakane open pit mine, made it possible to analyze the failure modes at the origin of rock instabilities. The respective dips of these different directional families are: 77˚ - 85˚/N 058˚ - 068˚, 66˚ - 74˚/N 133˚ - 143˚, 25˚ - 35˚/N115˚ - 130˚. An average safety factor of 4.3 was estimated for the area with a quality of the rock mass (RMR) estimated at 47. The results obtained reflect on the one hand the risks of instability associated with the quality of the rock mass studied and on the other hand highlights the state of stability of the study area.

Keywords

Stability, Cartography, Discontinuities, Safety Factor, Essakane

1. Introduction

Rock excavations have many uses. Whether it is to build roads, tunnels, buildings, hydroelectric dams, quarries, surface or underground mines, these excavation works must be given special attention. Indeed, the rock is intersected by geological structures, or discontinuities [1]. It is imperative to predict rock instabilities and stabilize the excavations in order to make them safe.

The study of the stability of mining slopes is a discipline of geotechnics which aims to assess the stability of slopes in open pit or underground mines [2]. It is essential to guarantee the safety of people and equipment and to minimize the risk of environmental disasters. Geotechnical problems are complex, and the equations that link soil parameters are generally irreversible and nonlinear [3].

In open-pit mines, rock instability is a major concern, and its failure has negative consequences on the economy and safety of personnel and equipment [4]. The term rock instability refers to the movement of a rock mass, in which the blocks do not only move by sliding, but can also fall in free fall, slide, bounce, or roll [5]. The behavior of rock masses has been the subject of many studies for decades and slope stability analysis methods are becoming more and more common practice. According to Khemissa and Rahmouni [6], slope stability problems are one of the phenomena often considered to be natural risks triggered by the force of nature alone (soil properties, slope angle, presence of water, etc.). However, human action is often preponderant in this type of hazard and constitutes one of the most widespread factors of instabilities. Many methods of stability calculation have been proposed by different authors. These differ in the assumptions accepted by their authors (equilibrium calculation methods), limit, fracture calculation methods, strain (calculation methods) and by the ease of their implementation (calculations using charts, automatic calculations using software), but they all agree to define an overall safety factor according to which stability of the slope studied is considered insured or compromised [7].

In Essakane, several geotechnical events have been recorded with more or less severe consequences for the health and safety of employees and mining operations. These events are somewhat distributed in the pit and most of them are located on the west wall of the Essakane Mining Zone (EMZ) pit, which presents structures that are quite complex to understand for better planning of activities in the sector. The effects of the blasting on the wall come at the same time to accelerate the process of instability which can lead to falling blocks. The main objective of this study is to analyze the stability of the west wall of the EMZ pit, which involves geological and geotechnical characterization, numerical modeling and an evaluation of the stability of the zone. Achieving the objective will specifically involve to determine the families of discontinuities in the study area and the failure modes associated with them and the safety factor of the area.

2. Location and Geology of Study Area

The Essakane gold mine is located in the northeastern part of Burkina Faso (**Figure 1**). It straddles the border between the provinces of Oudalan and Séno, in the Sahel region, and is about 330 km from the capital Ouagadougou. Essakane lies within the Paleo-Proterozoic Gorouol greenstone belt [8]. It is an orogenic gold deposit characterized by quartz-carbonate stockworks and is hosted

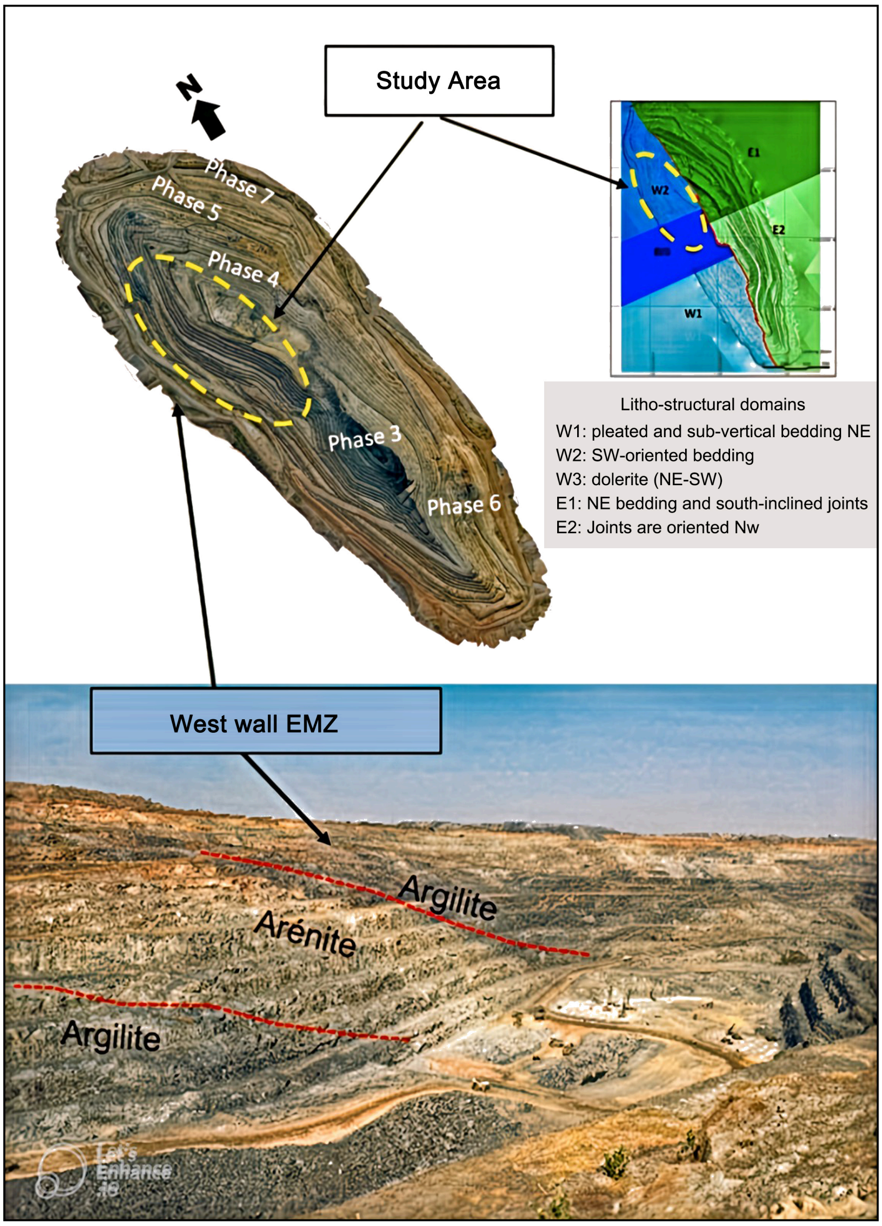

Figure 1. Location of the study area.

in a sequence of arenite and argillite of Birimian age (2.0 to 2.3 billion years). The local stratigraphy can be subdivided into a Birimian succession metasediments with lower green shale facies (meta-argilites, arenites and volcano-sediments), conglomerates and subordinate felsic volcanites, and a succession underlying Tarkwaïenne comprising siliceous detrital metasediments, and volcanitesmafic to andesitic.

The Essakane Mining Zone (EMZ) pit is subdivided into several mining zones called "Phases" (**Figure 1**). Operation is carried out simultaneously according to the schedule in these different phases. The study area concerned the west wall of phase 4 delimited by two structural domains. The lithological units encountered in the sector are arenite and argillite in which there are intrusions. At first glance, the wall presents a large number of intersecting structures. This zone is in full development and therefore faces various geotechnical risks such as instabilities, falling blocks which are linked to the nature of the rock, the types of structures or discontinuities encountered on the face of the wall and the blast drilling activities that take place in the pit.

3. Methods and Materials

Before starting a stability analysis, it is important to collect the relevant information for this analysis, and that of sufficient quantity and quality (accuracy) to use the chosen technique correctly. Depending on the type of structure, the parameters most controlling the stability of the excavation vary. In the case of an open pit, these parameters are the orientation, dip, spacing and continuity of the discontinuities present in the rock mass [9]. For the study area, a mapping of the discontinuities present on the studied wall will be carried out then will follow the determination of the types of instabilities associated with the mapped discontinuities and finally a field check accompanied by a simulation of rock falls showing the risk probable that this would cause.

3.1. Mapping of the Various Discontinuities and Associated Failure Modes

To map the different discontinuities, two types of mapping, namely manual mapping and digital mapping, also called photogrammetry, were used. Manual mapping has been done on the basis of a mapping sheet designed for this purpose and which lists all the parameters to be measured in the field. A camera has been used for the shots. The Dips6.0 software developed by Rocsciencehas allowed to produce cyclospherical projections and density stereograms of fracture poles. For digital mapping or photogrammetry a camera professional brand NIKON D7000, for the shots was used. It is equipped with three lenses of different ranges and a laser pointer used to determine the distance from the wall to be photographed. The range of the objectives is defined as follows: 500 m, 150 m and 50 m depending on the size of the objective. The processing is done goes from the transfer of the photos taken from the camera to the Sirovision software then the geo-referencing through the 2D and 3D editing stages of the photos.

The failure modes associated with the different discontinuities are obtained through a kinematic analysis with the Dips software. The percentage of discontinuities causing a rupture that is greater than 30% will be considered as potential instability [10], it is the only criticality.

3.2. Limit Balance Safety Factor Analysis

The analysis of the factor of safety of the zone was carried out by limit equilibrium with the software Slide V6.020. It is a 2D slope stability analysis program for evaluating the factor of safety of failure surfaces in soil or rock slopes. The Design (map) and the drone data (topography) of the pit were necessary for a quality work. The Slide program uses the slice method procedure (**Figure 2**) based on dividing the slope into a number of segments and then calculating the inter-slice forces and the balance of moments on a given failure surface. In this study, the Janbu Simplified method was used for the estimation of the safety factor (F).

$$F = \frac{\text{soil shear strength}}{\text{mobilized shear stress}} = \frac{c' + \sigma_n' \tan \Phi'}{c_m' + \sigma_n' \tan \Phi_m'} \tag{1}$$

where the mobilized shear stress is the shear stress required to ensure equilibrium.

c' = effective soil cohesion

c_m' = cohesion mobilized

Φ' = effective internal friction angle

Φ_m' = angle of internal friction mobilized

σ_n' = effective normal stress

(If $F > 1$, there is no failure; if $F < 1$, there is failure; if $F = 1$, there is limit equilibrium)

It should be emphasized that using the factor safety as a measure of stability has its limitation such as the simplification of complex problem, complex geometries, dynamics effects (FS doesn't account for dynamics effects like earthquakes, which can play a significant role in some situations), environmental factors (FS may not consider long term environmental effects that could affect stability over time).

3.3. Principle of the Slice Method

This method consists of considering the forces which tend to retain a certain volume of ground, delimited by the free forces of the slope and a potential failure surface, and those which tend to set it in motion.

For any circle with center O and radius R for which safety with respect to the risk of slipping is verified. The slice method consists of cutting the ground volume (included in the FE arc) into a certain number of slices bounded by vertical planes. A tranche (n) is subject to:

- Its weight W.
- The inter-section forces broken down into horizontal forces H_n and H_{n+1} and vertical forces V_n and V_{n+1}.

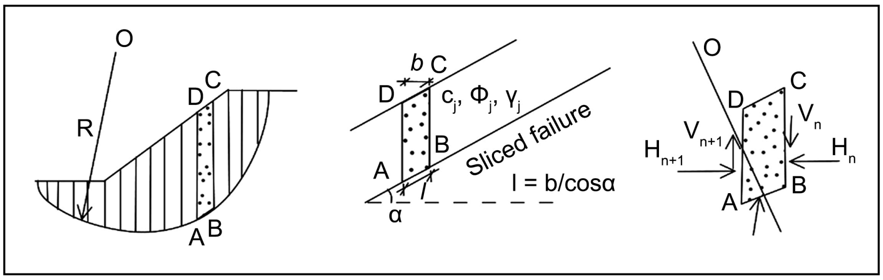

Figure 2. Forces acting on a sliced failure surface.

- The reaction Rn of the underlying medium on the arc AB (shear resistance). It breaks up into a normal and tangential component.

3.4. Janbu's method

Janbu's method satisfies the balance of forces as opposed to other methods such as Bishop's method which satisfies the balance of moments. Additionally, Janbu's method can be used for circular and non-circular failure surfaces. Non-circular failure surfaces are more common in nature at Essakane (due to the existence of soil layers with different properties, the hard nature of the rock (arenite, argillite) or due to geometric restrictions). Examples of such surfaces are shown in Figure 3.

In Janbu's method, the sliding mass is divided into vertical slices and the following static equilibrium conditions for each slice are considered:

- Sum of vertical force $\sum F_y = 0$
- Sum of forces parallel to sliding surface $\sum F_{\parallel} = 0$

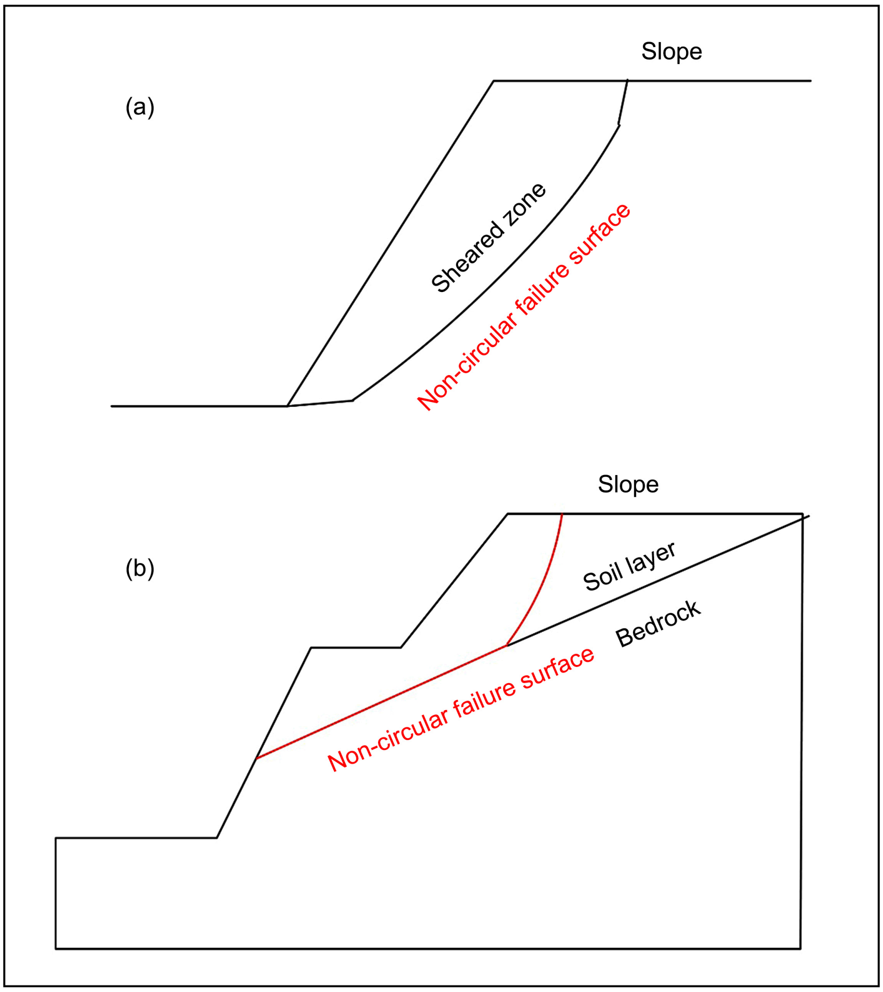

Figure 3. Examples of typical non-circular failure surfaces, including: (a) a failure surface that cuts through a sheared zone, and (b) a failure surface that begins as circular but is then interrupted by a stronger geologic formation (bedrock).

For the entire soil mass, the equations used are:

- Sum of vertical forces $\sum F_y = 0$
- Sum of horizontal forces $\sum F_x = 0$

By combining these equations with Equation (1), the safety factor of Janbu's method is expressed as follows:

$$F = \frac{\sum_{i=1}^{n}\left(c_i' b_i + \left(W_i - u_i b_i + \Delta V_i\right)\tan\Phi_i'\right)/\left(m_\alpha \cos\alpha_i\right)}{\sum_{i=1}^{n} W_i \tan\alpha_i} \tag{2}$$

where

$$m_\alpha = \left(1 + \frac{\tan\alpha_i \tan\Phi_i'}{F}\right)\cos\alpha_i \tag{3}$$

and

α_i : angle of slice i of surface failure

W_i : weight of slice i

Φ_i' : effective internal friction angle of slice i

c_i' : effective cohesion of slice i

u_i : pore pressure at base of slice i

n : number of vertical slices

ΔV_i : inter-slice shear forces

Janbu's method initially neglects inter-slice shear forces. Their effect is then taken into account by applying an empirical correction coefficient f_0.

Equation (2) then becomes:

$$F = f_0 \frac{\sum_{i=1}^{n}\left(c_i' b_i + \left(W_i - u_i b_i\right)\tan\Phi_i'\right)/\left(m_\alpha \cos\alpha_i\right)}{\sum_{i=1}^{n} W_i \tan\alpha_i} \tag{4}$$

The correction factor f_0 depends on the soil resistance parameters and the geometry of the slope. In particular, the segment that connects the toe and the top of a potential failure surface is derived and its length is measured (L). Subsequently, the maximum vertical distance between this segment and the failure surface is also determined (d). Finally, the ratio d/L is calculated and the correction factor f_0 is derived via **Figure 4**.

Janbu's method equation using in our study has certain limitation about capturing complex soil behaviors, non-homogeneous soil profiles or situations involving water infiltration.

To conduct the safety factor analysis with the Slide V6.020 software, cross-sections (AA, BB) of the west wall of the EMZ pit with the different formations and structures composing it were considered (**Figure 5**). The choice of the location of the sections was made taking into account the frequency of discontinuities and places with a high potential risk of instability [10]. The software was configured according to the lithological parameters (see legend in **Table 1**) of the pit, that is to say the type of material, the resistance of the rock, the cohesion, etc. The strength type use for all analysis in this study is Mohr Coulomb.

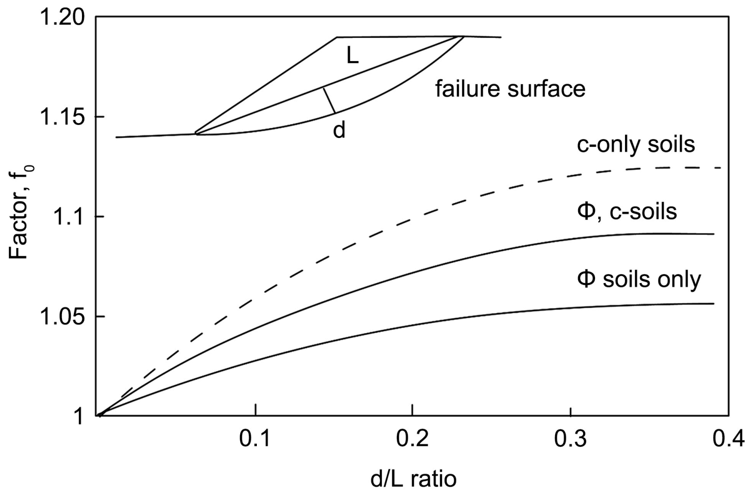

Figure 4. Janbu correction factor f_0 [11].

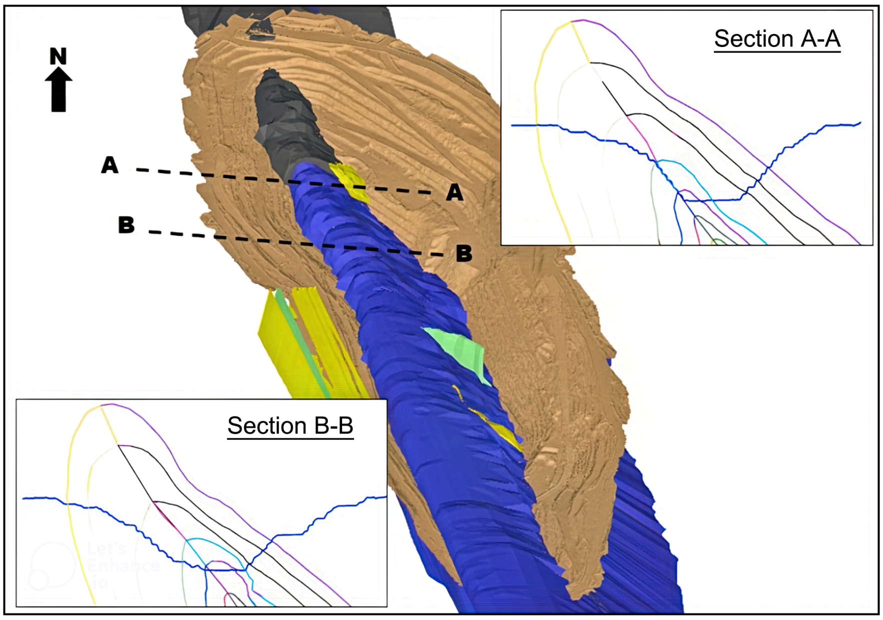

Figure 5. Cross section of the EMZ pit in different sections (March 2021).

Table 1. Lithological parameters (Swiss standards SN 670, 2007).

Material name	Color	Unit weight (kN/m³)	Cohesion (kPa)	Phi (deg)	UCS (MPa)	GSI	Mid	D
Saprolite		24	20	60				
Transition		24	28	55	45	51	7	1
Turbidity		27	34	58	110	63	15	1
Argilite		31	49	69	121	74	15	1
Arenite		34	56	75	221	74	17	1

4. Results

4.1. Families of Discontinuities and Failure Modes in the Study Area

4.1.1. Families of Discontinuities

The two manual and digital mappings by photogrammetry (Sirovision) carried out in the same area reveal three (03) families of discontinuities which are family 1 (bedding), family 2 (Joint 2) and family 3 (Joint 1). For both types of mapping, family 1 (bedding) and family 2 (Joint 2) have approximately the same dip and dip direction characteristics, respectively 77˚ - 85˚/N 058˚ - 068˚ family 1 (bedding) and 66˚ - 74˚/N 133˚ - 143˚ family 2 (Joint 2). For family 3 (Joint 1) we have a directional mean of 25˚ - 35˚/N 115˚ - 130˚ for ordinary cartography and 5˚ - 15˚/N 073˚ - 085˚ for digital cartography. Also, we have more structures mapped at the digital level than at the ordinary level, which results in a high density of concentration and is explained by the fact that with digital mapping, it is possible to map the different structures, even those tending from sub-horizontal to horizontal and areas inaccessible by ordinary mapping. These subparallel to parallel structures are difficult to map due to their low dip. Ordinary cartography made it possible to assess in the field the degree of roughness of the various structures. Structures with high roughness are more stable than others. Similarly, the type of filling (quartz, clay, etc.) of the various joints has an impact on the stability of the structures. The geometric characterization of the structures of the two types of mapping (digital and manual) gives the following stereographic results (**Figure 6** and **Figure 7**):

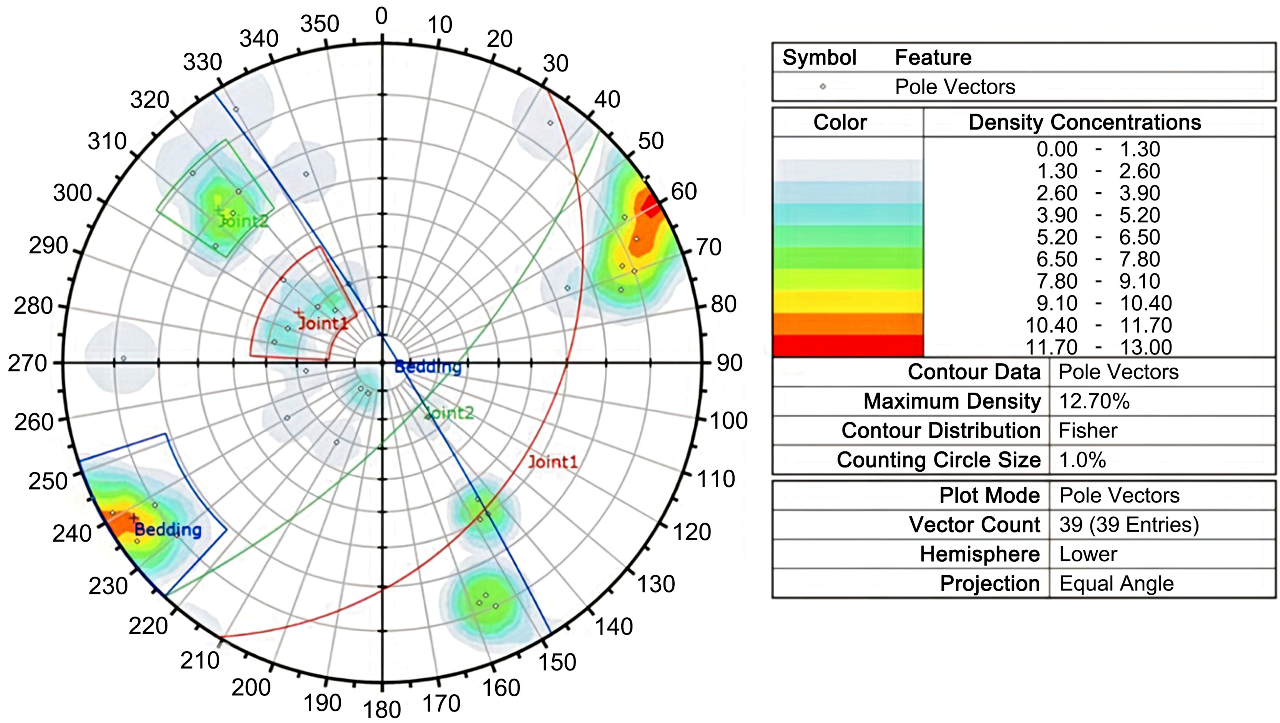

Figure 6. Families of discontinuities resulting from ordinary mapping.

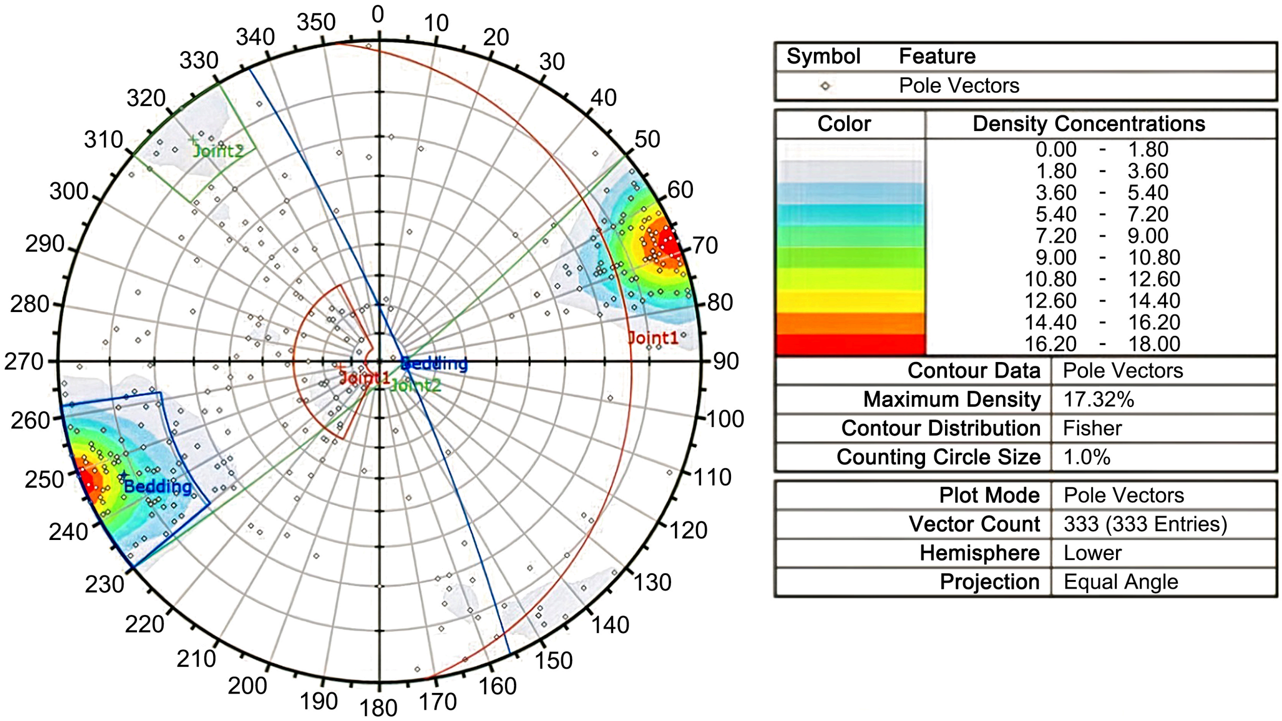

Figure 7. Families of discontinuities resulting from mapping by photogrammetry.

4.1.2. Failure Modes in the Study Area

The failure modes defined by the Dips software are planar failures, wedge failures and tilt failures. The software delimits the zone of structures likely to cause these different failures and at the same time evaluates the percentage associated with each type of failure. The statistical results of the failure modes are presented in **Table 2**. We note a difference in the percentage of failure according to the mapping method (manual or digital). None of the results obtained for the 3 types of rupture is higher than the criticality threshold (30%). This demonstrates that the different failure modes do not represent potential failure instability for the study area.

4.1.3. Study Area Safety Factor

The stability analysis of the different AA and BB sections carried out on the west wall of the EMZ pit with the slice method gives the following results with regard to the safety factor (**Figure 8** and **Figure 9**). Section AA gives a safety factor of 4.06 and section BB a safety factor of 4.54. Local safety factors analysis carried out at different benches in the study area has showed local safety factors of less than 1 at times, but overall an average safety factor of 4.3 is obtained which is well above the target required.

5. Discussion

With the manual mapping for a failure and slip surface of a given rock block, it is possible through the characterization of the mechanical parameters to evaluate both the forces that resist slip and those that favor it. For example, the roughness

Table 2. Failure mode statistics according to the mapping process.

Failure mode	Ordinary or manual mapping			Cartography digital by photogrammetry		
	Family 1 (Bedding)	Family 2 (Joint 2)	Family 3 (Joint 1)	Family 1 (Bedding)	Family 2 (Joint 2)	Family 3 (Joint 1)
Planar failure		2.56%			6.01%	
Corner failure		18.08%			17%	
Failure by tipping		17.95%			17.42%	

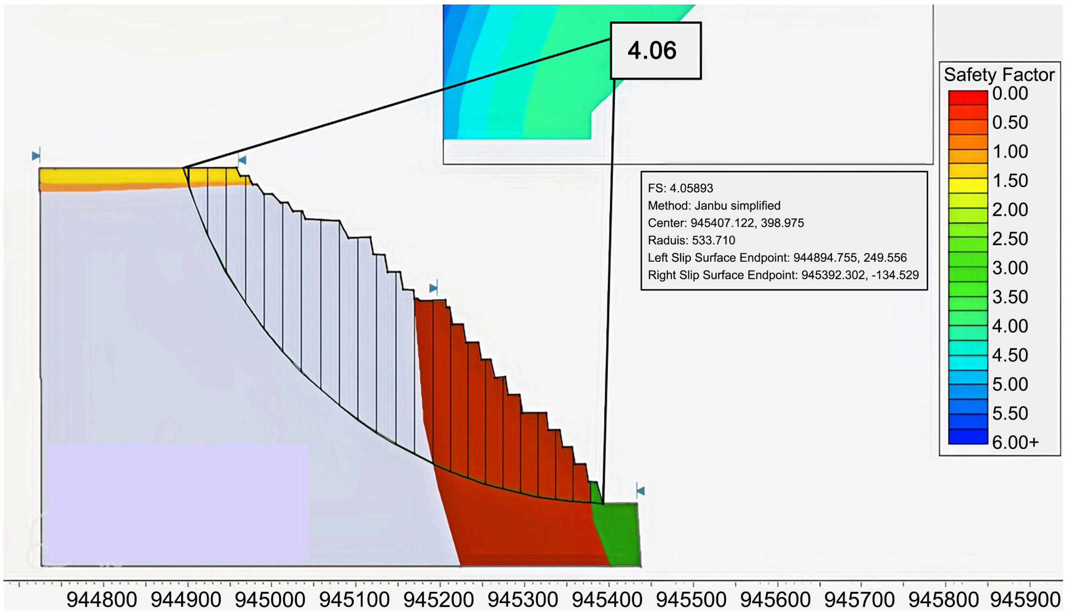

Figure 8. Section AA safety factor.

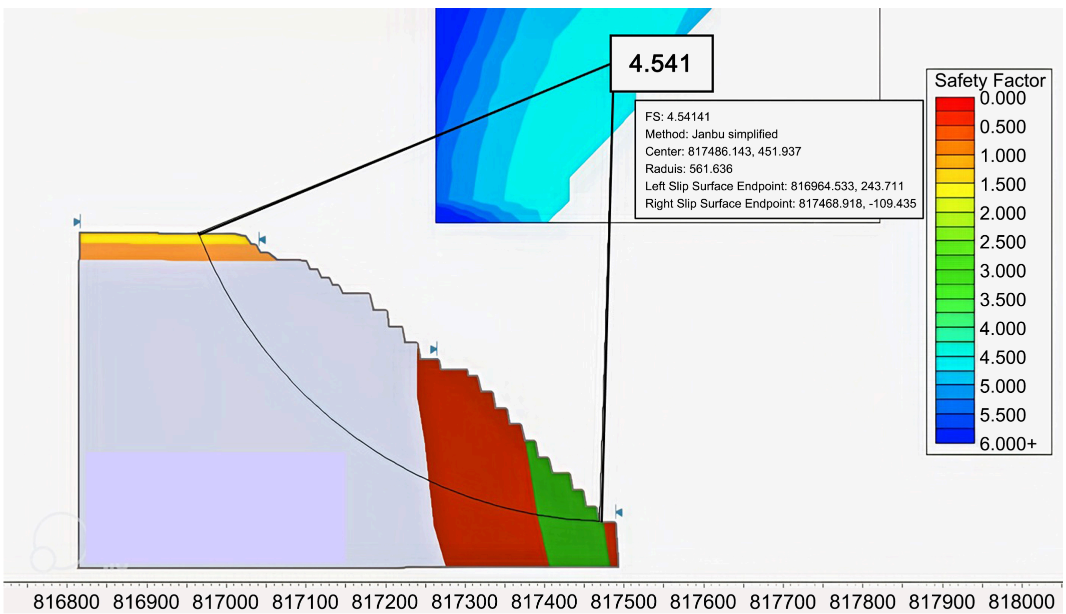

Figure 9. Section BB Safety factor.

allows to assess the resistance to shearing and therefore to sliding. For two planes of discontinuity in the same rock mass, the one with the highest roughness will be the most stable. Similarly, for two different filling joints (quartz and clay) under the same geomechanical and geometric conditions, the one filled with clay will be more exposed to instabilities, which can directly affect the stability of the discontinuity. Through manual and digital mapping (photogrammetry), a lot of information on the discontinuities of the study area was collected. This information allowed the evaluation of the quality index of the rock mass (RMR) of the mining operation which is of good quality therefore a better appreciation of the degree of instabilities.

Typically, structural mapping of rock walls is carried out manually, either by following a path or by directly examining the wall through windows. Both of these methods have been tested, as documented by [12] [13] [14] [15]. However, it often happens that a significant portion of the exposed surfaces is inaccessible, preventing direct access to the walls. Moreover, fieldwork is time-consuming and limited by mining operations, which can make sampling locations hard to reach.

Recently, remote structural characterization techniques that don't require direct contact with the rock wall have been developed. These include close-range digital photogrammetry mapping and terrestrial laser scanning (Lidar). Numerous studies have focused on these approaches, particularly over the past decade. [16] [17] [18] [19], and [20] have shown particular interest in photogrammetry. Several other authors have conducted comparative studies of both methods, including [21] [22] [23] and [24].

These two techniques offer several advantages, such as: collecting a greater amount of data from hard-to-reach walls, reducing errors associated with the sampler, improving the quality of recorded work, allowing faster execution while minimizing the impact on mining operations, enhancing the safety of workers conducting characterization work, examining the rock wall from a wide variety of angles and scales, adequately addressing most rock mechanics and field control problems.

At the Kikialik mine, an underground mine, in Raglan in Canada of the Xstrata Nickel mining company, a study similar to the present study has been conducted [25]. The photogrammetric approach conducted in this study aimed to characterize the orientation, spacing, and length of discontinuity traces. The digital approach identified three families of discontinuities, whereas the manual approach identified only two families. Family 1, which is subhorizontal, wasn't observed along the manual line. Regarding the orientations of families 2 and 3, it was observed that the average orientations and dispersion around these mean values were the same regardless of the approach used. It has been concluded that the photogrammetric approach enabled adequate structural characterization of the rock mass, despite the challenges encountered in the field.

The results obtained on the families of discontinuities, namely that the discontinuities subparallel to parallel to the slope are difficult to map are in agreement with those of Dubois and Grenon [25].

The analysis of the safety factor of the study area carried out with the Slide software gives an average safety factor of 4.3, which attests to the stability of the slopes of the different benches. Closset and Wojtkowiak [26] explain that obtaining a point safety factor of less than 1 in a place in a rock mass does not necessarily lead to instability or ruin of the structure. Instability becomes obvious when the overall safety factor is lower than the limit stability factor which is 1. The state of stability of the West wall does not prevent instabilities such as falling blocks due to vibrations of blasts or the effect of water on the rock walls occur.

6. Conclusion

In the mining industry, pit stability is of great importance in maintaining a safe working environment for workers, equipment and infrastructure. The geological and geotechnical reconnaissance is the first step before any analysis. This study aimed to analyze the stability of the West wall and this through the collection of all the information on the instabilities detected on the wall. The information obtained made it possible to determine the families of discontinuities as well as the potential rupture modes of the zone and at the same time to estimate the safety factor of the zone. The study of the stability of the West wall reveals that the structures and their orientation have a direct impact on the stability and that the bedding is the set of the most devastating structures at the level of the EMZ pit. At the end of this study, it must be recognized that the stability of the embankments and the pit as a whole in open pit or underground mines is a major challenge for the geotechnical team in view of the increasing depth of the pit and the accelerated rate of resource exploitation. Thus, staying at the forefront of new technologies in geotechnics is of capital importance for better monitoring of the walls of the pit.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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