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Geomechanical Study of Inata Gold Mine Pits Rock Slopes, Burkina Faso (West Africa)

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Abstract: ***The Inata gold Mine, active since 2009, is an open pit mine operated by Avocet Mining. The mine is located 280 km northeast of Ouagadougou, the capital, in the western section of the Arbinda-Djibo volcano-sedimentary paleo-proterozoic belt. One of the main difficulties facing the mine is the high frequency of the footwall rock failures, affecting directly workers' safety and the economic viability of the project. This paper presents the stability analysis of rock slopes of the northern pit of the Inata gold Mine. The results indicate that the high degree in footwall failures is the main cause of the mine instability. The Rock Quality Designation values ranged from 6 to 10, and the Rock Mass Rating values from 35 to 45, suggesting that rock masses were initially composed of highly fractured and low grade materials. Furthermore, the Mining Rock Mass Rating values (18-30), clearly showed that mining greatly contributes to the footwall instability in the Inata gold Mine. The kinematic modeling of footwall failures also suggested a possible occurrence of planar and corner failure of the pit walls.***

Keywords: Pit, stability, slope failure, kinematic analysis.

1. Introduction

Since 2010, Burkina Faso, with seven active gold mines, has become the fourth gold producing country in Africa. The Inata gold Mine, active since 2009, is currently experiencing stability problems in its open pit footwalls. These problems are considered as one of the major sources of economic and security constraints experienced by the mine. The importance of a good embankment slope design is, without a doubt, a primary requirement of open pit mining. A good slope design will ensure the stability of pit footwalls, which will have a significant economic impact on mining. That is, steeper slopes allow greater extraction of the ore, but represent a higher risk in terms of the pit footwall stability. The embankment slope design of open pits requires a set of geological, economical, financial and operational variables basis on which a potential pit is built. The design should also maximize profits while respecting certain geometric constraints, and thus ensuring the footwall stability. The design of the Inata gold Mine pits, currently in use for ore extraction in four pits, was carried out through an iterative process. Since their construction, the pits have evolved differently, and instability and slope failures are inherent in most of them. Thus, when a mass of rock is heavily fractured, it can pose numerous instability risks. The potential of a footwall failure could be greatly reduced if ore extraction was done according to the basic rules of mining methods. A rock slope exposed to hydraulic pressures, drilling and blasting or an embankment not meeting the initial conceptual standards will be modified, and thus posing a high instability risk.

The main objective of this paper is to conduct a snapshot assessment of the rock slopes during the life cycle of active pits. To do this, i) a structural zoning of the pit was carried out, that is to say, the structural zones that control the stability of the tiers and final walls of the pit were observed, identified and measured using a combination of existing structural data and geotechnical mapping; ii) physical properties and rock mass quality were characterized; iii) various models of footwall failures were assessed.

2 Environmental Setting and Mining

The Inata gold Mine, owned by Avocet Mining Company, is located in northeastern Burkina Faso about 280 km away from the capital Ouagadougou (Figure 1). The mine was open in December 2009, and is expected to produce a total of 944,000 ounces, or 30 tons of gold throughout its lifetime (~ 7 year). The study area belongs to the arid bioclimatic zone with an average annual rainfall of 460 mm and a precipitation index that varies greatly from one year to another. Daytime temperatures in the area remain relatively high and range between 15 °C and 43 °C. Some temperature variations ranging between 10 °C and 19 °C can also be observed. These high temperatures are due to the strong sunshine occurring in the region with an average duration of 8.84 h/d. Evaporation and evapotranspiration are also very high as those specific to the Sahel climate parameters. Year-to-date evaporation in the area is around 3057 mm, whereas the relative humidity varies seasonally with maximum values of about 80% to 90% measured in the rainy season and minimum values (10% to 25%) in the dry season.

The mining of the gold deposit is achieved through an open pit method and ore blasting is done using explosives based on the following geometric settings (Photo a): i) in the fresh rock, the steps' height is 20 m, the width is 5 m and the angle of inclination is 65 °; ii) in the altered rock, the steps' height is 10 m, width is 5 m and the tilt angle is 60 °; iii) the average safety factor is 1.2 depending on the preliminary geotechnical studies. This safety factor corresponds to that of a rock mass in equilibrium which is generally modified by exploitation conditions. Besed on accessibility, representativity and work progress, the site of the study pit was selected. The pit selected is the eastern footwall of the northern pit (Figure 2a).

3 Geological Setting

Geologically, Inata is located in the western section of the Djibo-Arbinda (Birrimian) greenstone belt. The general metamorphism is that of green schist facies metamorphic prograde punctuated by areas related to the functioning of the shear zones and the establishment of plutonic body [1]. The geological formations of the area are essentially made of basic to intermediate volcanic and volcano-sedimentary rocks intruded by syn post-tectonic granitoids [1]-[2]. Gold mineralization in Inata is a meso-thermal vein-type [3]. This type of mineralization is generally associated with terrains affected by regional metamorphism and large deformations, so that the deposits invariably show rather a structural control than a lithological control. An intense supergene alteration affects the mineralization and enclosing rocks. The depth of oxidation sporadically exceeds 60 m, but locally may go lower in the fractured and brecciated zones.

Lithologically, the deposit is hosted by volcanic and sedimentary units affected by a zone shear plurikilometric of submeridian orientation (N10° E). These are formations of tuffaceous shale units, sheared and silicified with argillite interbedded chert and locally accommodated by plutonic body (Figure 2b). The western third of the North pit in our study, is occupied by argillites. The strongly altered facies are kaolinitised and found in the northeastern edge of the pit. Areas with high gold grades are almost exclusively made of stockwork of quartz (Figure 2c), whereas those with average grade are found close to felsic intrusions.

Structural analysis is obtained by processing airborne geophysical images in combination with in situ field data and interpreted in light of previous work [2]-[3]-[4]-[5]-[6]. The geophysical data used is derived from the following large scale exploration analyses (high resolution): the total magnetic field down to the poles conditions, combined with its first vertical derivative (with shades) for magnetometry, and the ternary uranium-thorium-potassium composition for spectral radiometry. These geophysical images were processed by Geosoft 6.4.2 and then exported to ArcMap 10 to be combined with field data and the available cartographic backgrounds. From this analysis, a new lithostructural map could be produced and an evolutionary structural pattern was proposed. The evolutionary structural pattern at a detailed scale locates the mineralized shear zone to the roof of the western flank of a faulted anticline. The system can be summarized in the following order: i) initiation of a sedimentary basin (the Souma) in a premature Birimian crust, ii) a compression phase of E-W with foliation axial plane to N350° and N10° E which produced folding P1 with iii) overlaps from west to east that have reactivated the previous compression in ductile brittle regime (Figure 3). Theses lithological and structural configurations make footwalls susceptible to breaking.

4 Analytical Procedure of Rock Slope Stability Study

Rock slope analysis of an open pit mine requires identification of various parameters such as: the importance of rock fracture (or discontinuities), the instability models, and the influence of the hydraulic pressure and that of the surincombant terrains. The importance of rock fractures in the slope stability analysis and the pit design requirements is assessed through rock fracture study that is used to: i) understand the geo-mechanical context so that infrastructure building can be planned under required security conditions, ii) provide indications on the tectonic setting, including the state of stress and the different phases of alterations. In fact, all accepted methods for designing basement, slopes and underground excavations of rock masses require reliable data on discontinuities [7]-[8]-[9]-[10]. That is, an unfavorably oriented discontinuity, or a group of adjacent discontinuities in a rock surface prone to low stress levels can break a block or lead to a complete collapse of the rock surface. Such a study can be conducted in three stages, namely: i) geotechnical mapping at pit level; ii) geomechanical characterization of the pit's bedrock and iii) kinematic modeling of footwall failure that may occur in the pit.

The geotechnical mapping consisted of gathering structural and lithological databases of the footwall under study. The eastern wall of the North pit was cut into eight windows over a total length of 420 m according to the method used by [11]. The sizes of windows vary from 10 to 30 m long depending on the density of the fracture and the type of lithology. Within these windows, measurements are made and certain parameters and description of structures are estimated (Photo b). This mapping technique allowed the measurement of all discontinuities of the defined zone within the footwall [9]-[12]. The following elements are measured during the geotechnical mapping:

- Numbering windows;
- Wall orientation (strike and dip);
- Orientation of discontinuities;
- Predominant lithologies of the window;
- Estimate of RQD (Rock Quality Designation);
- Degree of wall degradation;
- Wall moisture;
- Compression strength of the intact rock;
- Spacing and condition of rock joint wall.

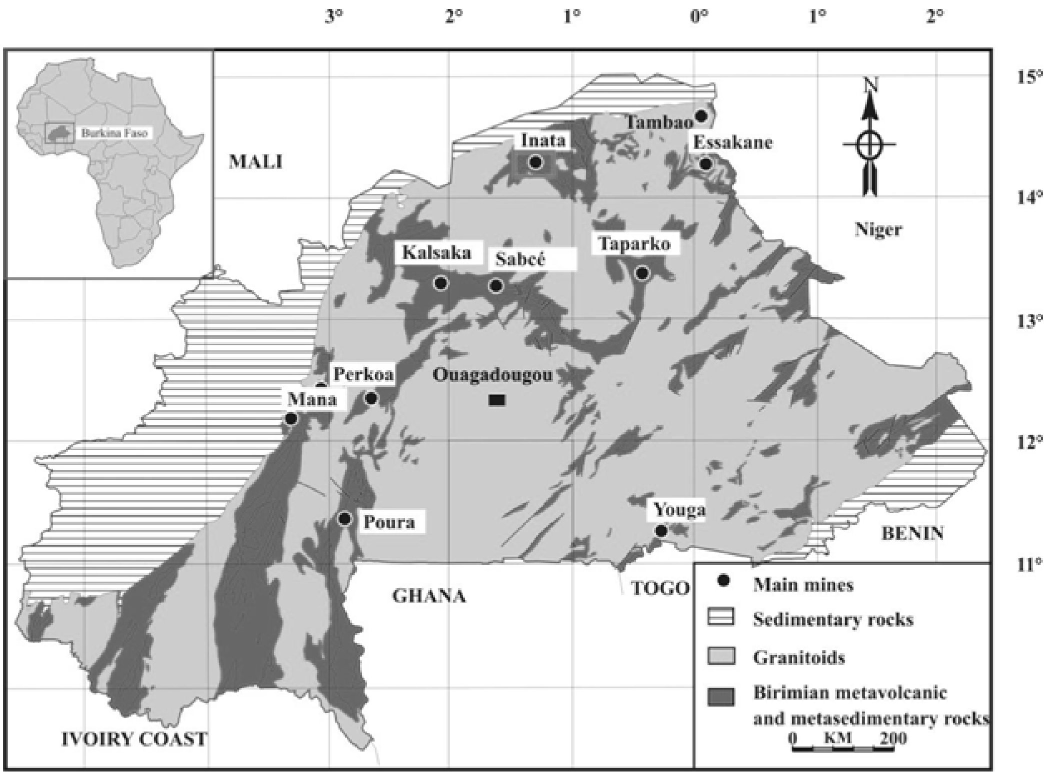

Figure 1: Geological map of Burkina Faso showing the study site.

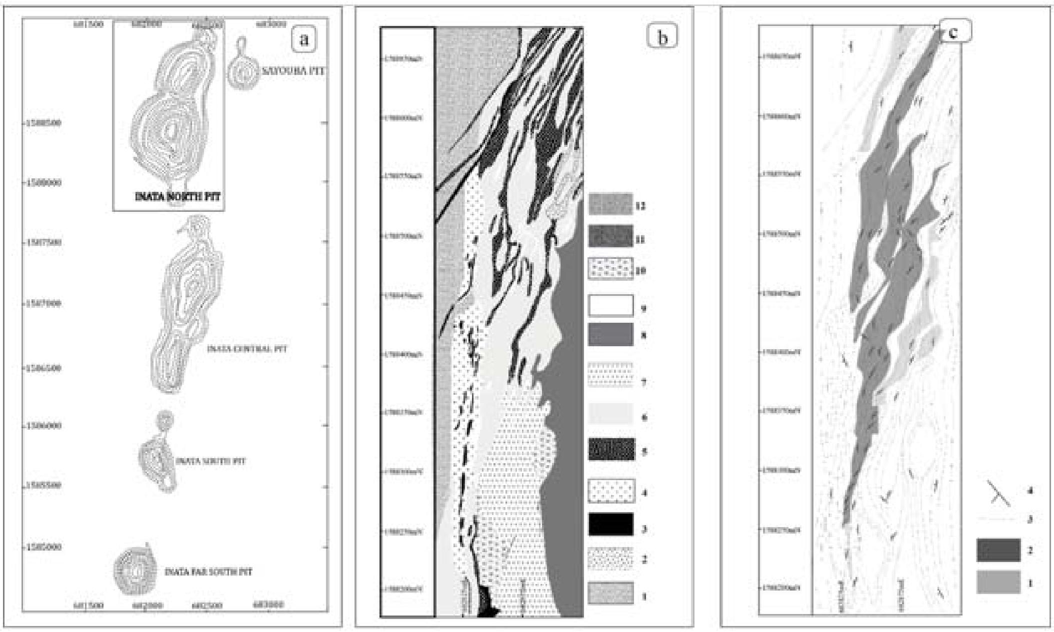

Figure 2 : Detailed structural and lithological map of Inata North pit (compiled from Donzeau et al., 2003; McCuaig et al., 2007) (a) Inata North pit location, (b) lithological sketch: 1- argillite, 2- high alteration area (kaolinite), 3- graphitic schist and black shale, 4- felsic intrusive, 5- mixed intrusive and tuff sandstone, 6- sheared silicified tuff and argillite with intrusive intercalation, 7- laminated chloritic schist, 8- porphyry intermediate volcanite, 9- quartz veins, 10- tuffaceous schist, 11- quartz veinlets, 12- chert. (c) structural sketch: 1- low to medium grade ore, 2- high grade ore, 3- regional foliation trajectories, 4- structures directions..

The characterization of the rock mass of the wall was achieved through RQD classification systems. Rock Quality Designation (RQD) defines the magnitude of solid fracturation and allows classification of the solid (good or bad) in terms of its stability [13]. The RQD value was calculated for each window wall mapped according to the formula:

$$RQD = 100e^{-0,1\lambda}(0,1\lambda + 1) \qquad (1)$$

where λ is the spacing of the joints in a window [14]

The Rock Mass Rating (RMR) derived by [15] is an improved version of RQD because it takes into account the parameters of the rock mass that can influence the stability of the wall, namely joint conditions in terms of alteration, filling, roughness, openness and persistence (JC for Joint Conditions), the compressive strength of the intact rock (IRS for intact Rock strength), joint spacing (JS for Joint spacing). The relationship is as follows:

$$RMR = RQD + IRS + JC + JS \qquad (2)$$

The Mining Rock Mass Rating (MRMR) developed by [16] was used in open pit in which some environmental parameters are likely to undergo modifications. The RMR system is therefore adjusted for better qualification of rock masses. The adjustment parameters are: the regional stress (I), the orientation of joints following excavation (O), the power factor of slaughter shots (B) and the alterability of the wall (W). The relationship is as follows:

$$MRMR = RMR*I*B*W*O \qquad (3)$$

The kinematic modeling of footwall failure allowed identification, from the mapping data, of the areas likely to break on the wall. Interpretation of stereograms generated by kinematic modeling software Dips 5.0 highlighted the possible failure models of footwalls. The modeling required the following input data collected during mapping:

- Structure orientation (dip direction);
- Spacing between the structures (m);
- Length of the structure (m);
- Type of structure;
- Surface shape of the structure (flat, corrugated, etc.);
- Appearance of the surface (smooth, rough, etc.).

The current study will only report the results of i) geotechnical mapping, and ii) the outputs of kinematic modeling of the footwall failures.

5 Results

5.1 Geotechnical Cartography

Slope stability in quarries and open pits is primarily related to the quality of the rock mass. The quality of the rock mass is analyzed qualitatively by a direct assessment of the walls and through characteristic indices. As far as the Inata Mine is concerned, the results of the rock mass fracturing indices (RQD), the Bieniawski classification codes (RMR), and the Laubscher classification index (MRMR), are summarized in Table 1.

Table 1: RQD, RMR and MRMR values of windows studied

Window N°	*Window length*	*Dominant lithology*	*RQD*		*RMR*		*MRMR*	
F1	30	Intrusive	8	Poor	38	Low	24	Low
F2	20	Intrusive /argilite	10	Average	39	Low	25	Low
F3	30	argilite	8	Poor	45	Average	29	Low
F4	30	Intrusive /argilite	10	Average	45	Average	29	Low
F5	40	Argilite	8	Poor	37	Low	24	Low
F6	10	Intrusive	8	Poor	45	Average	29	Low
F7	10	Argilite	6	Very poor	35	Low	18	Very low
F8	30	Intrusive	8	Poor	38	Low	24	Low

Intrusive rocks and argillite are the predominant lithology of the windows of the eastern wall of the North pit of the Inata gold Mine with moderate to intensive weathering. The rock mass is of average to low quality with RQD index ranging between 6 and 10. The wall is therefore susceptible to failure as confirmed by RMR index, an improved version of RQD, suitable for excavation works. The RMR index takes into account the uniaxial compressive strength of the intact rock (IRS) and rock joint orientations. For the Inata gold Mine, these values range between 35 and 45 and reflect a poor quality of rock mass on the scale of [15]. The MRMR indices were used in this study to assess certain mining activities (blasting, excavation, ore extraction.). The MRMR indices that vary between 18 and 30 and indicate a wall of low to very low quality on the scale of [16].

Furthermore, the qualitative assessment of the eastern wall of the North pit, shows fractures, joints and lithological contacts of various orientations (Photo c) as well as the effects of meteoritic runoff observable on the surface. The effects induced by blasting and poor grading (Photo f and g) are also observed. Those findings are consistent with classification indices that reflect poor rock mass quality, and consequently rock mass is vulnerable to breaking.

5.2 Kinematic Analysis of Failure Modes

When a rock mass is foliated and jointed (Photo c), it can present many risks of instability due to possible development of various failure models including: planar failure, corner failure, tilting failure (rock toppling) ([9]-[17]. Planar and corner breakage models occur in areas where sub-parallel to parallel discontinuities produce geometric shapes by intersection with the slope surface. The fractures, by tilting, develop in areas where discontinuities have dipping opposite to that of the angle of the slope. These failures can occur concurrently in a single open pit. In most cases, the degree of stability is estimated using a coefficient called factor of safety (F) (Hantz, 2001). This coefficient is defined as the ratio of allowable stress to an acting stress. In the case of a sliding plane, the average shear stress on the fracture surface is considered (Figure 4). The safety factor F is then the ratio of the maximum resisting force that can oppose the slipping to the driving force tending to cause slipping. There is therefore slope failure if F is less than 1.

Investigations of possible breakage of windows through geotechnical mapping indicated two possible ways of window breaking of three windows out of eight (Table 2):

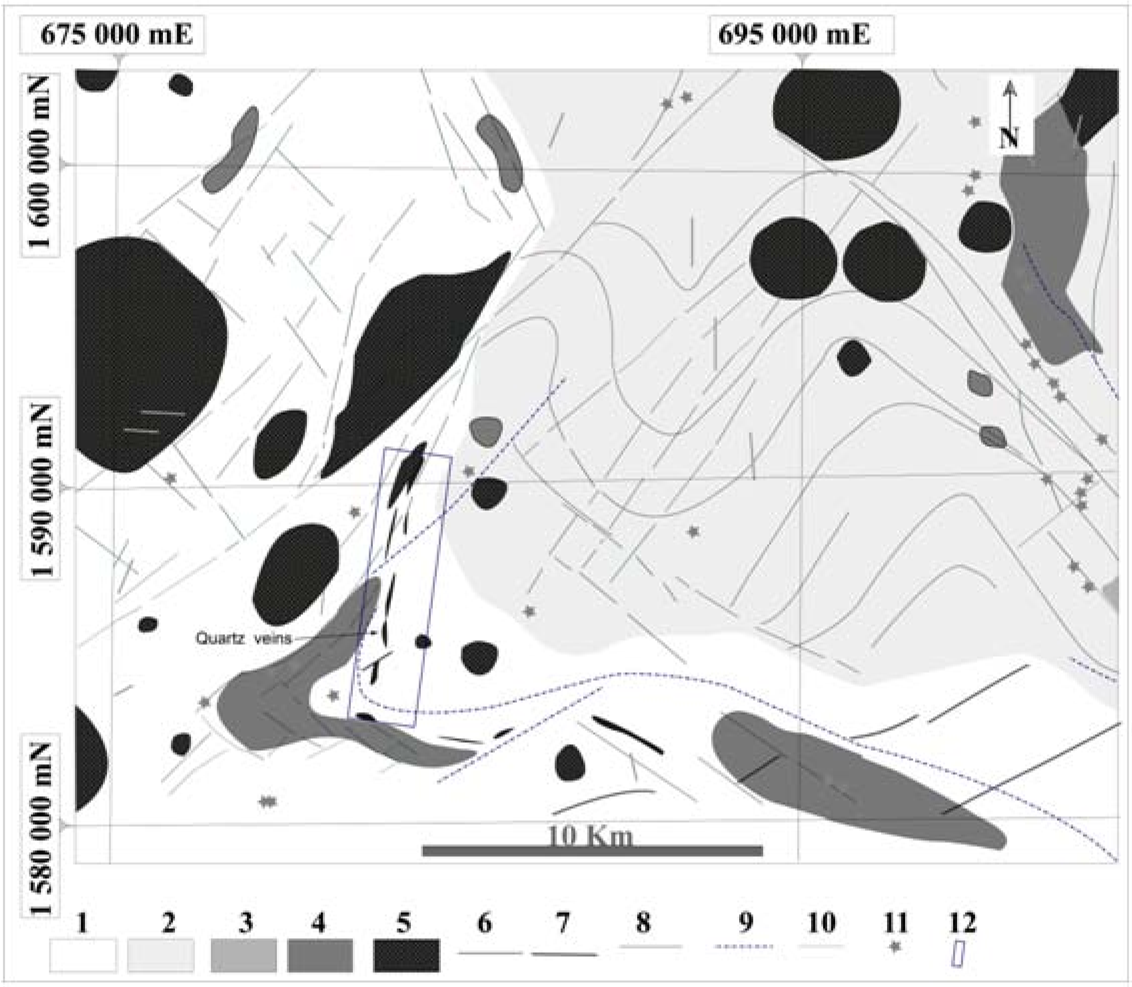

Figure 3: Synthetic lithologic and structural map of Inata gold mine context. (1) mixed epiclastic volcanoclastic (2) turbiditic sediments (3) intermediate to mafic volcanites (4) gabbro-diorite (5) granite (6) quartz veinlets (7) doleritic dykes (8) bedding (9) thrust contact (10) inferred fault/shear zone (11) artisanal work (12) study area

That is the corner failure mode is likely to occur in windows 4, 5 and 7 (Figure 5a and photo e) and planar failure mode may occur in window 7 (Figure 5b). The common feature of these windows is that they are all predominantly made of clay stone lithology. This strongly foliated formation is more susceptible to breakage than less distorted felsic intrusive rocks. The corner failure mode can be materialized in the stereogram Figure 5a with two families of intersecting planes in the rupture zone (gray area crescent moon). The areas concerned are those where the foliation is orthogonally intersected by joints thereby forming unstable blocks. As for a possible planar failure mode, it is shown in the stereogram in Figure 5b in which some discontinuities poles (marked by star) find themselves in the rupture zone. The planar failure is due to the foliation that seems to be the predominant geological structure in the area. In addition to this foliation, Inata is subparallel to parallel to the direction of the wall of the pit (280-310°) and steeply dipping angle of 70° on average. The tilting failure mode was not observed or considered in any of the windows studied. However, the studies carried out by [18] show a possible tilting failure on the west wall, but the probability of occurrence remains low.

As far as the Inata is concerned, various calculated indices, observations, including the nature of the fractured rock mass as well as mining conditions of the pit are responsible for the observed stability vulnerability of the footwall.

Table 2: Summary of failure modes encountered

Failure mode	**Window N°**							
	F1	**F2**	**F3**	**F4**	**F5**	**F6**	**F7**	**F8**
Tilting	No	No	No	No	No	No	No	No
Planar	No	No	No	**Yes**	**Yes**	No	**Yes**	No
Corner	No	No	No	No	No	No	**Yes**	No

6 Conclusions

Previous geotechnical studies have suggested that the orientations of the geological structures of the bedrock of the Inata gold Mine exacerbate slopes instability of the pit. These studies also suggested that a mapping of discontinuities should be performed regularly during the slope reduction. The findings of this article are as follows: i) the rock mass of the eastern wall of the North pit of the Inata gold mine is made of a low quality material leading to a degree fracturing indicated by RQD values ranging from 6 to 10 and RMR value of 35-45; ii) MRMR (18-30) values as well as qualitative observations based on kinematic analysis of stereographic background pointed to a possible occurrence of failure of the wall; iii) may occur either in the edge or in the plan. These mapping data can be used to revise parameters previously recommended for the design of new pits and propose necessary rectification of the initial parameters.

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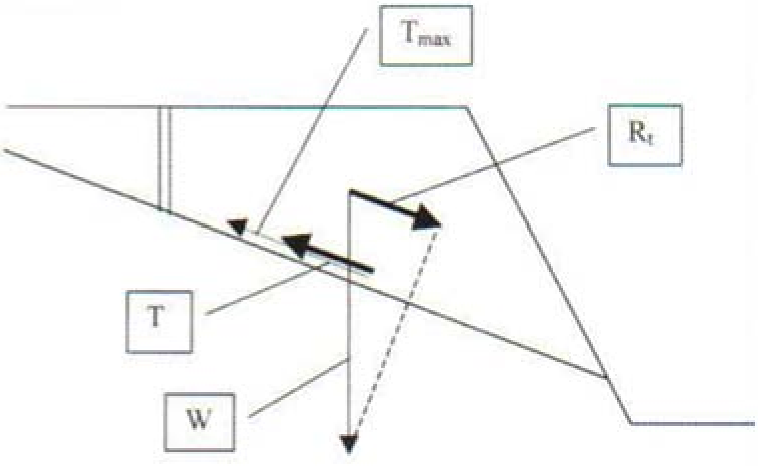

Figure 4 : Evolution of stability for a plane slip (Hantz, 2001): W: weight; R_t: Driving force; T: Resistant force; Tmax: maximum resistance force $F = T_{max}/R_t$ is the safety factor.

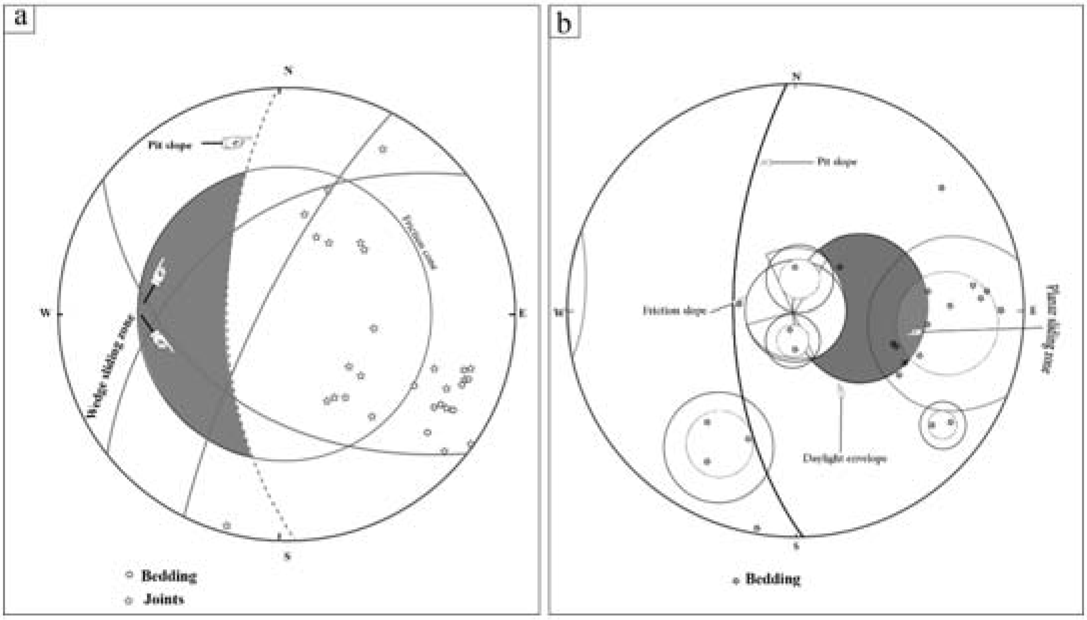

Figure 5: (a) stereogram indicating the possibility of a corner failure, (b) stereogram indicating the possibility of a planar failure.

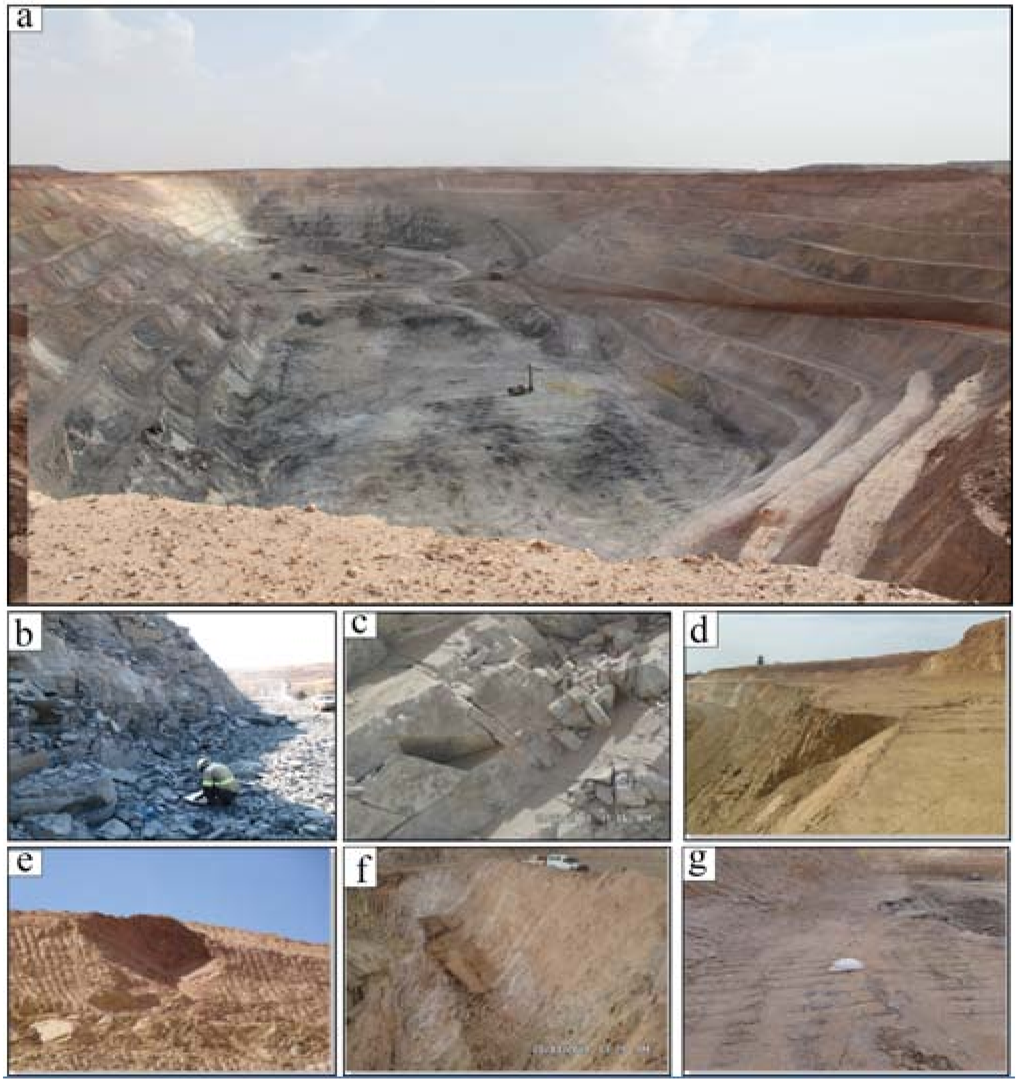

Photo: (a) Shooting of the northern pit of Inata gold mine, (b) Geotechnical mapping session, (c) Joints of varied orientations, (d) Planar failure on the wall; (e) Corner failure on the intersection of two joints of different orientations; (f) Area of the wall where the sizing of the bleachers and slope are not respected: the step width <5 m and slope angle is 70° instead of 65°; (g) Fracture caused by blasting