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Slope Design and Implementation in Open Pit Mines: Geological and Geomechanical Approach

Jean-Alain Fleurisson^a *

MINES ParisTech - Centre de Géosciences, 35 Rue Saint Honoré, 77305 FONTAINEBLEAU Cedex, France

Abstract

Slopes in open pit mines must be considered as geotechnical structures. Therefore their design and implementation must be conducted with all consideration including technical, economical, environmental and safety issues. But these structures are above all natural geological and geomechanical features and the geological structures as well as the petrographical nature of the rock material control the deformation and failure mechanisms. It is therefore important to implement a well-defined methodology which should be conducted according to the following phases: 1) rock mass characterization derived from the acquisition and analysis of geological and geomechanical data; 2) determination of the potential mechanisms of deformation and failure, and their numerical modelling; 3) slope design and definition of reinforcement and monitoring methods. This paper presents various available techniques and tools to achieve these successive phases and illustrate their implementation and also limitations through case studies of slope design in open pit mines.

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1. Introduction

Slopes of mines and quarries, some of which may reach several hundred meters deep, must be regarded as "geotechnical works" in the sense that we speak of mine works or civil engineering works. Their design and their implementation must be conducted according to rules of art with the general objective to define the geometry that will ensure the safety of the structure while minimizing the volume of material to be excavated, and therefore the final cost of the project. In addition to these economic issues, specific concerns about the environment must be considered, particularly in the context of procedures for abandonment of mine sites where the problems of long-term slope stability may arise.

But these works are, above all, geomechanical objects for which the geological structure, the nature of the constituent materials and their mechanical behaviour control the process of deformation and failure considered in the slope design. This close connection with the geological structures therefore requires first to identify these structures in order to implement the appropriate means of investigation, modelling and calculation.

This article reminds the principles of slope design in open pit mines, and presents techniques and tools available to address the successive stages of slope design. Their practical implementation is then illustrated by two case studies of open pit mines.

* Corresponding author. Tel.: +33 1-6469-4813; fax: +33 1-6469-4711.
E-mail address: jean-alain.fleurisson@mines-paristech.fr

2. Principles of slope design in open pit mines

Considering the importance of stakes, the slope design in open pit mines must be based on a well-controlled methodology, especially since experience shows that each rock mass characterized by its geological structure is unique, and therefore there are no standard recipes that achieve the right solution with certitude. This methodology can be broken down into several phases: 1) characterization of the rock mass through the acquisition and analysis of geological and geomechanical data, 2) identification of potential mechanisms of deformation and failure, and their modelling; 3) the slope design and the definition of methods of reinforcement and monitoring. These phases largely developed by Cojean and Fleurisson [1] are briefly recalled here.

2.1. Phase 1: rock mass characterisation

This phase involves the acquisition of geological, geomechanical and hydrogeological knowledge by observation and measurement. It employs all the disciplines of earth sciences and mechanical sciences, and particularly the disciplines of the engineering geology, geotechnics, soil and rock mechanics, hydrogeology and groundwater hydraulics.

First, the geological approach is essential in order to analyse material behaviour. The geologist identifies the petrographic nature of the materials (rocks or soils) and their states of weathering and fracturing. These data are essential for the characterization of mechanical properties of materials. It also provides the spatial variability of these parameters throughout the mass.

Similarly, the geologist identifies geological structures of the deposit. This will be used to determine precise relationships between the different units of the deposit and potential mechanisms of deformation and failure.

The data obtained from this initial geological approach are significant because they will then guide and optimize the geological and geotechnical field investigations using subsurface geophysical methods, drilling operations or shallow excavations carried out with hydraulic excavators which can, cost effectively, provide valuable information. A detailed example of such investigations is given in paragraph 3.2. It is of course recommended to consider a "geotechnical enhancement" of all the drillholes performed for deposit prospecting or resource evaluation. It is also important to schedule field investigations for geotechnical purposes only, in order to characterize especially waste materials where final pit slopes are usually located.

Particular attention must be given to the discontinuity network that cuts the rock mass at different scales. Natural variability of the geometric but also mechanical parameters of the discontinuities requires statistical study and therefore the implementation of rigorous sampling methods. They include the following stages (Fleurisson [2]): field measurements of discontinuities through systematic survey on outcrops, excavation face or oriented core drilling; classification of discontinuities in directional sets using stereographic projection techniques or automatic classifications; statistical analysis of the geometrical parameters of each set using histograms of the principal geometric characteristics of the discontinuities: dip direction, dip angle, persistence or trace length and spacing.

Some drillholes must be used to install piezometers in order to detect level of the groundwater.

The acquisition of petrophysical and mechanical parameters required for subsequent calculations are then made from intact samples, on which standard laboratory tests can be performed in order to determine petrophysical parameters and characteristics of deformability and strength: density, different deformability moduli, cohesion and internal friction angle of soil, shear strength parameters of discontinuities.

In some cases it may be useful to perform in-situ mechanical tests in boreholes (pressuremeter or dilatometer, etc...) or on surface (shear tests of materials or rock mass discontinuities analysis, etc...).

2.2. Phase 2: Determination of potential mechanisms of deformation and failure

The analysis of geological structures and geotechnical parameters of the considered material, as well as, analysis of mechanical stresses generated by the mining excavation lead to identify the most critical mechanisms of deformation and failure.

In general, the simplification of these critical mechanisms using homogenization and generalization techniques is required in order to set up physical and then numerical models that allow the quantification of the risk of failure. Such

simplification processes inherent to any numerical modelling should not be underestimated and should be used with caution. In each situation, we must be able to estimate the difference between results produced by the model and reality.

Few mechanisms presented in Figure 1 are highly dependent on the geological mass structure, where engineering geologists have to identify the surface and volumes with greatest deformability and lowest shear strength.

In the plane failure mechanism (Figure 1a): the failure surface may correspond to bedding joints in sedimentary formations, foliation or schistosity planes in metamorphic formations or a crack or a lithological contact between clayey weathered rocks and bedrock.

Slides and failures along two or more discontinuities or discontinuity sets occur in rock mass and involve classical mechanisms of shearing along discontinuities such as **wedge failure** (Figure 1b), various types of **toppling failure** (Figure 1c), step or bilinear failure mechanisms, or more complex mechanisms such as arching, bending, toppling or buckling of rock slabs. More or less rigid rock material, and more or less weathered discontinuities walls play a critical role in the occurrence of these mechanisms.

In slopes excavated in soil or highly jointed and weathered rock mass where there are no geological structures to control the failure, the most unstable failure surface is approximately a circular arc. This **circular failure surface** (Figure 1d) results from a process of localization of deformations. It is the archetype of landslides; however the specific shape of this failure surface and the associated failure mechanism cannot be generalized.

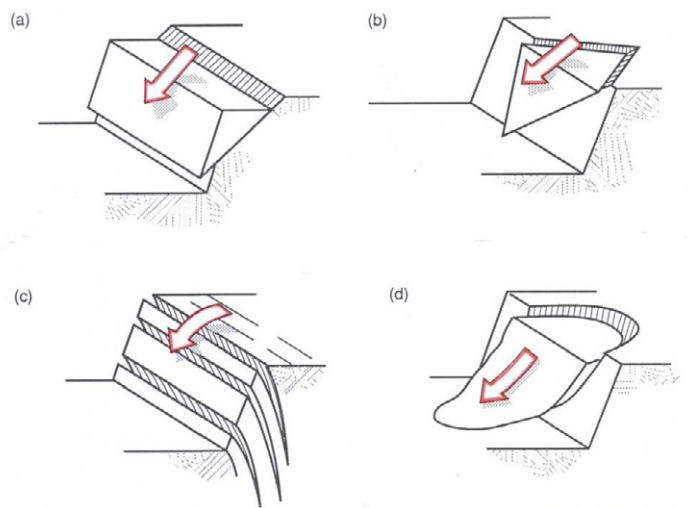


Figure 1: Some elementary processes of slope failure: (a) plane failure, (b) wedge failure, (c) toppling failure, (d) circular failure (modified after Hoek and Bray [3])

Very often, a sliding surface (generally in convex shape) follows different sources of weakness within the mass, for instance: pre-existing discontinuities, stratigraphical joints or in depth weathered zones. Such polygonal surface is therefore a mixed mode failure in which part of the failure surface is structurally controlled and part is failure through the soil or rock material.

In many cases, the discontinuous nature of the rock mass as well as the mechanical behaviour of the rock material itself plays an important role in the process of deformation and failure. In this case, especially when large volumes are involved, very complex mechanisms may occur and are difficult to characterize. In such cases, numerical modelling emphasizing the discontinuous or continuous aspects of the rock mass allows describing the most likely theoretical process of deformation. The implementation of these models, however, requires a comprehensive knowledge of many mechanical parameters. From the earliest stages of the project, monitoring systems and instrumentation must be installed to monitor the behaviour of solid in order to make the best use of modelling.

2.3. Phase 3: Modelling – Deformation and factor of safety calculations

All the geological, hydrogeological and mechanical data collected for the study allow building a geomechanical model of the rock mass which will be used for numerical modelling using computational tools tailored to the mechanisms of deformation and failure identified in the previous stage.

However, it is first necessary to clarify the context of modelling, in particular: the **geometric scales of the problem** (stability of a single bench, a set of three, four, five benches, or the entire pit side, 100 m, 300 m, 600 m or more in height); **the type of mechanical loading** (short and medium term stability of slope during the mining operations phase, long-term stability of final pit slopes at the end of the mining operation and after rehabilitation processes, stability in extreme conditions (e.g. hazard studies) corresponding to especial hydraulic loading (e.g. unusually high underground water levels) or specific dynamic loadings (earthquake); **the accuracy of the geological, hydrogeological and geotechnical data** collected for the study which will always give a partial knowledge of the real natural environment. In order to overcome the problem of accuracy in some datasets, it is necessary to perform a **parametric analysis** considering a realistic variation range for the poorly known parameters, and also by comparing responses from the expected deformation and failure in the soil or rock masses.

After the definition of the problem, calculation of stability parameters or deformations can be undertaken.

Factor of safety calculations are based on the theory of limit equilibrium. The mechanical problem is simplified and the stability of the slope is defined using the concept of factor of safety (FoS) which is defined by the ratio between the maximum resisting forces or moments and the acting forces or moments along a potential failure surface. From a theoretical point of view, the slope is stable if the FoS is greater than one; but in practice the theoretical level of safety must be adapted to the accuracy of the input data. For short-term stability analyses, safety factors of 1.2 to 1.3 would be acceptable, while for long-term stability, factors of safety usually range between 1.4 and 1.5. It is wise to perform these calculations using both average values of mechanical parameters and also lower realistic values. These latter values are always the basis of the design process.

In some cases, the simplicity of the concept of safety factor and the simplification of the process of deformation and failure are excessive, and it is necessary to carry out **deformation calculations** which give the deformation of a soil or rock mass in response to a mechanical or hydraulic loading. The corresponding numerical methods such as finite elements (FEM) or finite differences methods (FDM) valid for **continuous media** (soils in general), or other models and numerical methods suitable for **discontinuous media** such as distinct element method (DEM) require a high level of knowledge of the existing geomechanical objects (mass geometry, heterogeneity and anisotropy, mechanical behaviour), around the initial conditions (state of stresses in the mass, etc..) and the boundary conditions (mechanical and hydraulic conditions)

Figure 2 gives results obtained using the DEGRES software developed by MINES ParisTech and the National French Coal Company in order to analyze the stability of the Carmaux open pit mine and design the bench and overall slope angles (Tanays [4], Fleurisson et al. [5], Fleurisson [6]).

At the scale of a bench or a set of benches, the geological object under consideration is typically discontinuous due to the presence of two or three discontinuity sets. Elementary failure mechanisms such as plane, wedge, and toppling or bilinear failure mechanism) directly controlled by the discontinuity network give a realistic approach of the real failure mechanism.

In these cases, stability of rigid element separated by discontinuities (such as joints, bedding planes, schistosity, faults) is considered. Stereographical projection techniques are suitable to identify the kinematic occurrence of such failure mechanisms by comparing the orientation of the slope with the orientation of the devolved discontinuities (Hoek and Bray [3]). This kind of analyses is suitable to be computerized and was automatically performed in the DEGRES software.

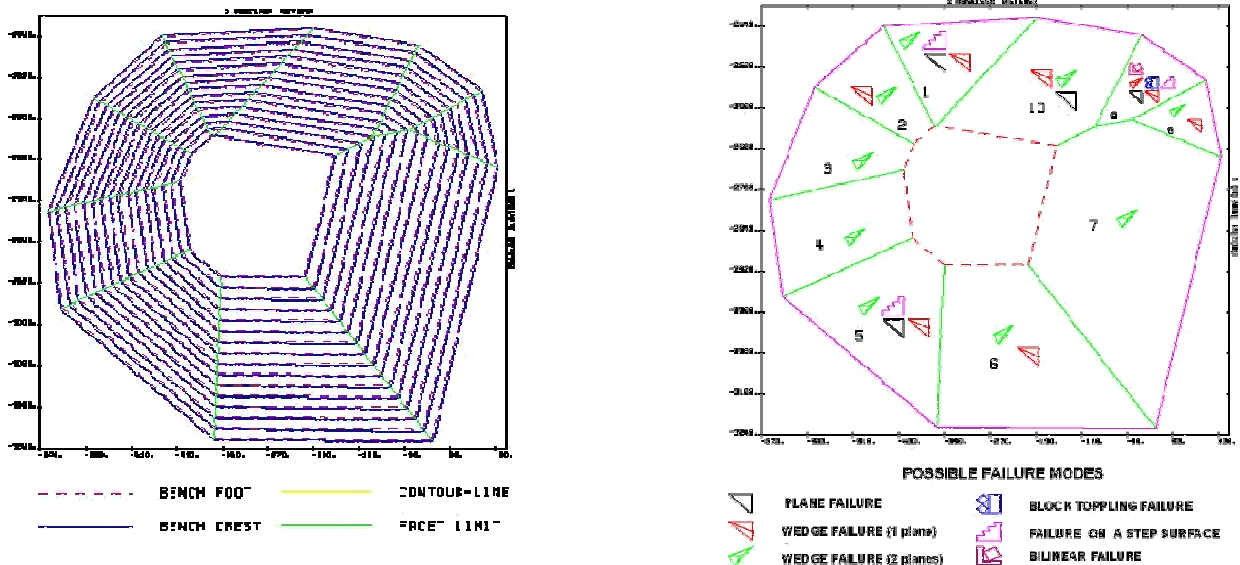


Figure 2: Geometrical pit model (left) and detection of the failure risks (right) using the DEGRES software.

In a first stage, it automatically provided a geometrical model of the pit starting from a basic contour line which can be the crest or the bottom line of the pit and according to geometrical parameters of the bench and pit side. The pit is then modelled as a set of faces with constant parameters (same strike, average slope, bench height and slope angle) as illustrated in the left part of Figure 2.

In a second stage, the model of discontinuity sets is set up. Each discontinuity set is represented by an average individual described by its orientation (dip direction and dip angle), its persistence, its spacing and its mechanical parameters, cohesion and angle of friction.

Slope instability can then be detected depending on the two following phases.

The purpose of the first phase is to identify the kinematic occurrence of various elementary failure mechanisms: plane failure, wedge failure, failure on a step surface, toppling failure and bilinear failure. This is carried out based on the automatic analysis of the geometrical relationships between the discontinuity sets and the different geometrical objects considered, bench or pit side. The software displays for each facet of the geometric model, at the scale of a bench or the whole pit side, the risks of failure (Figure 2 right). The second phase involves, for each failure mechanism identified at the previous stage, computation of volumes of potentially unstable rock mass and corresponding factor of safety using limit equilibrium methods and based on the mechanical and hydraulic parameters of the discontinuities involved in the failure mechanism.

From these results it is possible to give an assessment of the condition of stability of the rock mass, to advocate changes to the project (slope angles, concavity or convexity of the slope in vertical or horizontal plan in order to reduce the appearance of excessive stresses in some areas of the massif) or to propose appropriate methods of stabilization such as mechanical reinforcements or drainage.

If the mechanical properties of the rock mass, and in particular those of the discontinuities systems, play an essential role in the onset or not of instabilities according to the failure mechanisms controlled by the geological structures, other parameters, such as changes in hydraulic conditions and dynamic loading, are triggering factors that can lead to particularly catastrophic scenarios.

2.4. Phase 4: Methods of reinforcement and monitoring

Based on the above calculations, the slope stability expert will design the slope angles in order to ensure the desired level of stability. Different scenarios incorporating or not reinforcement systems (surface water drainage, rock mass dewatering, mechanical reinforcement using rock bolts and grouted cables in rock mass or soil nailing) could be studied. For each

scenario, gains or losses related to stability and also the relevant costs of these systems and their implementation will be quantified in order to facilitate decision-making that always returns to the mine operator.

Finally, in many cases, a slope monitoring using a wide range of auscultation devices can be recommended: topographic monitoring, control of groundwater levels, measurements of displacement and deformation in drillholes, etc... For all the great mining or civil engineering works, monitoring has become an ally of the modelling and calculations. If, on this, a large initial investment must be made early in the life of the work, then an ongoing dialogue must be established between measurements and calculations. It always results in a benefit to the mine operator, economically and in terms of security.

3. Case studies

These two case studies of slope design in open pit mines are illustrations of methods and techniques used to develop the most realistic geomechanical model and the implementation of appropriate numerical modelling. The author thanks SOMAÏR and Office Chérifien des Phosphates (OCP) companies for giving permission to publish the results of studies he has done for them.

3.1. The Ben Guerir phosphate open pit mine (OCP, Morocco)

The Ben Guerir open pit mine is located 70 km north of Marrakech. It is part of the Ganntour phosphate deposit dated Cretaceous-Eocene which is a vast plateau of about 125 km long and 25 km wide. The Ben Guerir deposit consists of several phosphate layers separated by siliceous marly and clayey interbeds in a sub-horizontal tabular geological structure.

At the time of the study in the early 80s, only two phosphate layers were mined leading to bench faces with a maximum height of 20 m, but it was expected that they can reach almost 100 m with the development of the mining operations. The mining method, conventional for this type of deposit, was to mine the deposit trench by trench, and in each of them, to blast the waste overburden, to remove it with draglines and therefore to daylight the exploitable phosphate layers. A particular blasting pattern, named longitudinal-double trench, was used and consisted in the blasting of the waste overburden in the trench numbered n before having removed the already blasted overburden in the trench numbered $(n-1)$.

Field observations on the working face of the trench $(n-1)$ when blasting the overburden of the trench n , showed: 1) the opening of a millimetre to centimetre thick clayey joint over the entire length of the blasting zone (length higher than 400 m), and 2) in the central part of the blasting zone, decimetric displacements of the whole blasted mass of trench $(n-1)$ on the clayey joint over a length of more than 100 m. These clayey joints, which had not been identified during the preliminary reconnaissance works because of their thinness, were actually present at the bottom and top of each phosphate layer and continuous throughout all the deposit. Moreover, it appeared that the blasting pattern resulted in the formation of vertical cracks parallel to the bench face and with a great extension.

As the reality of such movements was proved experimentally, a failure model aimed at simulating at best the observed phenomena was developed (**Erreur ! Source du renvoi introuvable.**). This is a bilinear failure mechanism involving the clayey joints (plane 1) and vertical cracks induced by blasting (plane 2). The plane 2 is a potential failure plane through the blasted mass. This 2D analysis is justified because of the lateral extension of structures involved in the failure mechanism (stratigraphic joints and longitudinal cracks).

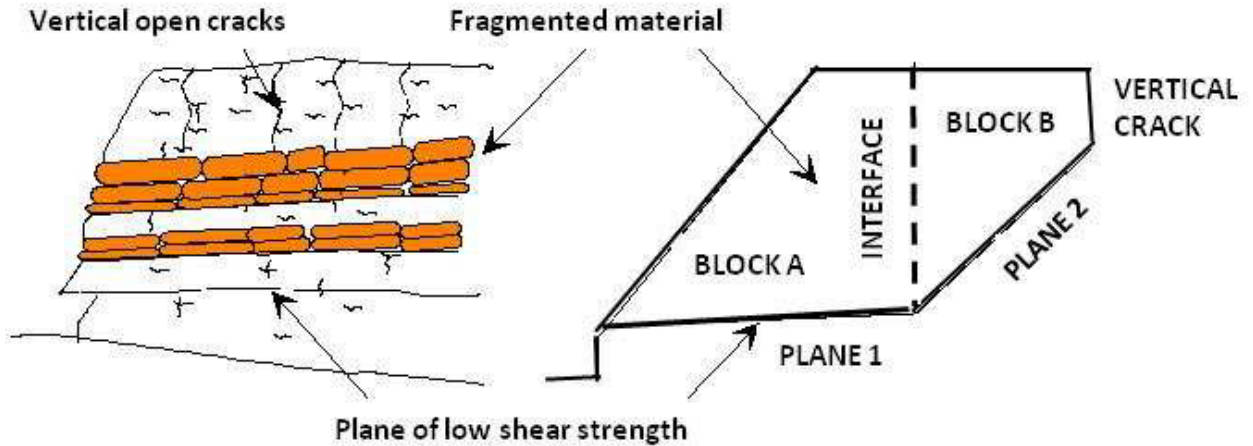


Figure 3: Schematic geometry of a working face after blasting of the overburden, and corresponding failure mechanism (modified from Fleurisson [7]).

In order to analyze the influence of the explosive, a numerical model was implemented in two phases (Fleurisson [7]):

- Firstly, a dynamic analysis, called in pseudo-static conditions, is performed: It amounts to considering the action of the explosive as a horizontal acceleration which adds to the acceleration of gravity. This leads to a new force diagram and a factor of safety called dynamic F_{dyn} is calculated in the same way as the static factor of safety F_{stat} . This method requires setting a value of horizontal acceleration. If F_{dyn} is less than 1, a phenomenon of progressive failure begins.
- As the action of the explosive is limited in time, the analysis is continued by the calculation of the total displacement of the potentially unstable mass. The method is to compare, step by step of displacement, the potential energy released by the moving mass with the energy absorbed along the system boundaries and within the mass that is breaking. At each step, the overall energy balance of the system is evaluated taking into account possible changes in the geometry and damping of the action of the explosive. This procedure is repeated until the total energy balance becomes negative. The displacement induced by the dynamic loading is then obtained.

This method is similar to the method used in earthquake engineering to analyze the stability of certain structures such as earth dams (Newmark method in particular). This numerical model has allowed finding the magnitudes of the observed movements of the working faces (Figure 4). He especially highlighted, from a semi-quantitative point of view, the influence of the bench height on its stability under dynamic loading, and the need to decrease the blast impact represented by the initial horizontal acceleration used in the calculation model.

This led to propose a new blasting pattern, called transversal because the lines are fired perpendicularly to the bench face, with two main objectives: 1) to prevent the development of longitudinal structures parallel to the bench face and unfavourable to the stability, and 2) to reduce the unit charge (explosive charge per delay) so that the rock mass is loaded as low as possible.

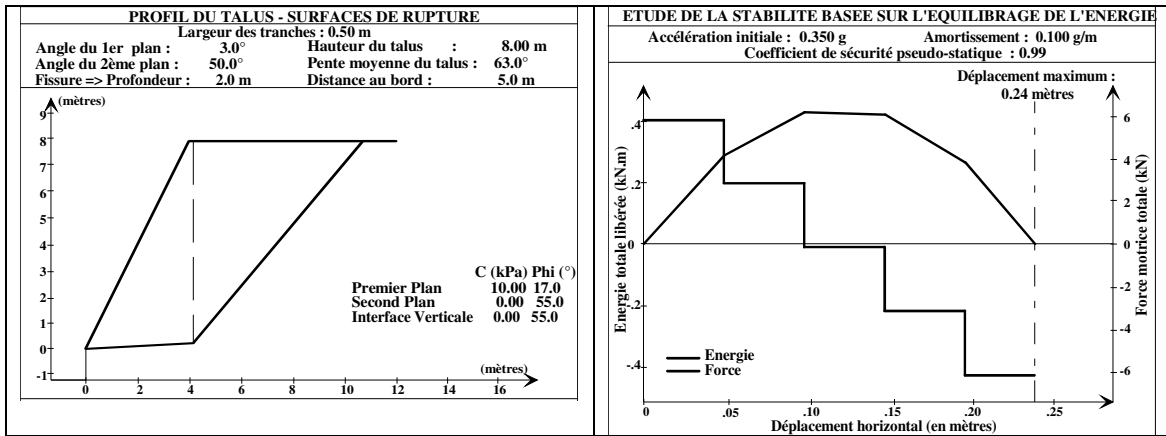


Figure 4 : Failure mechanism and calculation of the displacement induced by a dynamic loading due to rock mass blasting (from Fleurisson [7])

3.2. The Tamgak uranium mine (SOMAÏR, Niger)

The Tamgak mine, operated by the company SOMAÏR, subsidiary of AREVA NC Niger, is located near the town of Arlit. It is part of all the uranium deposits located in the detritic formations of the Tim Mersoï's Palaeozoic basin just west of the Air massif (Figure 5). In the Arlit region, all the economic uranium deposits are located in the sandstone sedimentary formations dated Upper Carboniferous and Lower Permian. They fall into a NS lineament at a distance of less than 5 km east the Arlit-In Azaoua fault which is the major tectonic feature in the region over a length of several hundred kilometres (Figure 6).

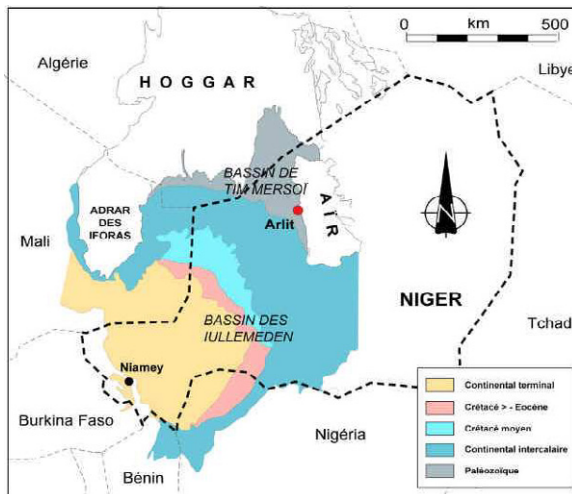


Figure 5 :Geological map of the Iuellemeden and Tim Mersoï sedimentary basins (from Gerbeaud [8])

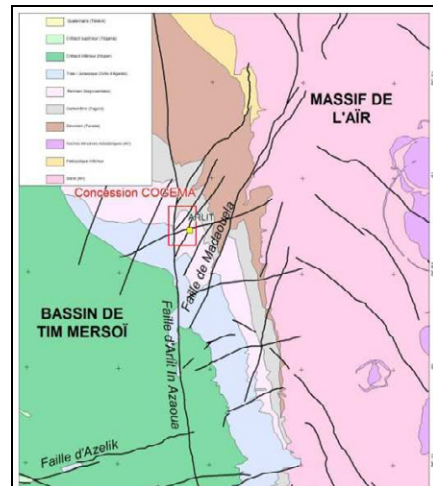


Figure 6: Geological map of the Arlit fault (from Gerbeaud [8])

The Tamgak deposit can be divided into two main parts (Figure 7):

- The "plateau" zone, located east of the North-South Arlit fault: it is a sub-horizontal tabular zone with a slight dip angle southwards. In this zone the classical rock sequence of SOMAÏR mines is found.
- The "deeper" zone located west of the Arlit fault: it is the lower compartment of the Arlit fault and corresponds to the Arlit flexure zone where layers are progressively dipping to 30°, the flexure being accompanied by a series of N0 or N140 faults with moderate throw.

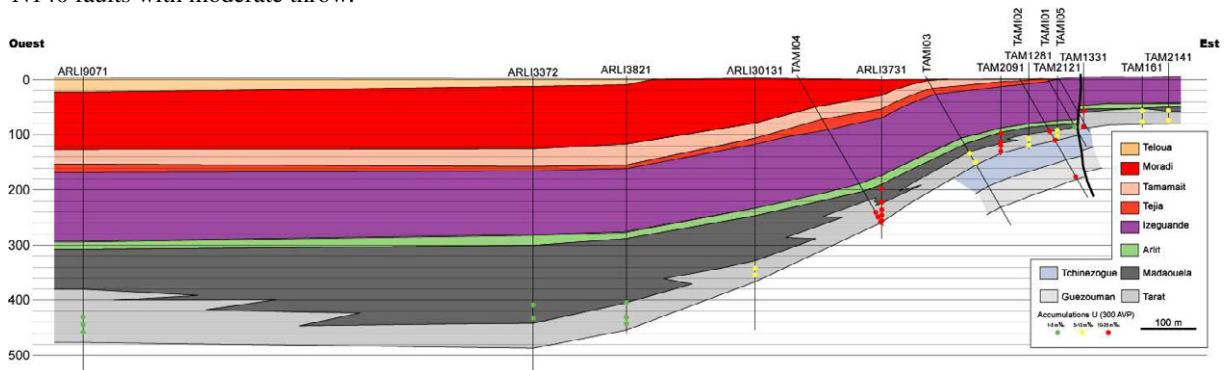


Figure 7 : West-East geological cross section including the TAMI1 to TAMI5 core drillholes.

The main objective of the geotechnical study was to define the slope profiles which will provide the stability of the final pit slopes at small and large scale, especially the stability of the western pit side, which is located just west of the Arlit fault. In order to build the geomechanical model required to calculations of stability, a geological and structural study of the Arlit fault zone was conducted. The objectives were to better understand the geometry of the fault zone, and to characterize the fractured zones associated with the fault in term of their lateral extension perpendicularly to the fault strike and the intensity of discontinuities in each zone.

To do this we relied on the analysis of existing data (oriented core drillings TAMI1 to TAMI5 made in 2007) and new data acquired during reconnaissance work carried out specifically in this study: two 250 m long geotechnical trenches intersecting the Arlit fault zone, two vertical core drillings performed in the suspected area of the Arlit fault in the North and South part of the study area, and measurements of discontinuities using wall optical and acoustic imaging techniques in two rows of old destructive boreholes drilled for the deposit reconnaissance (Figure 8).

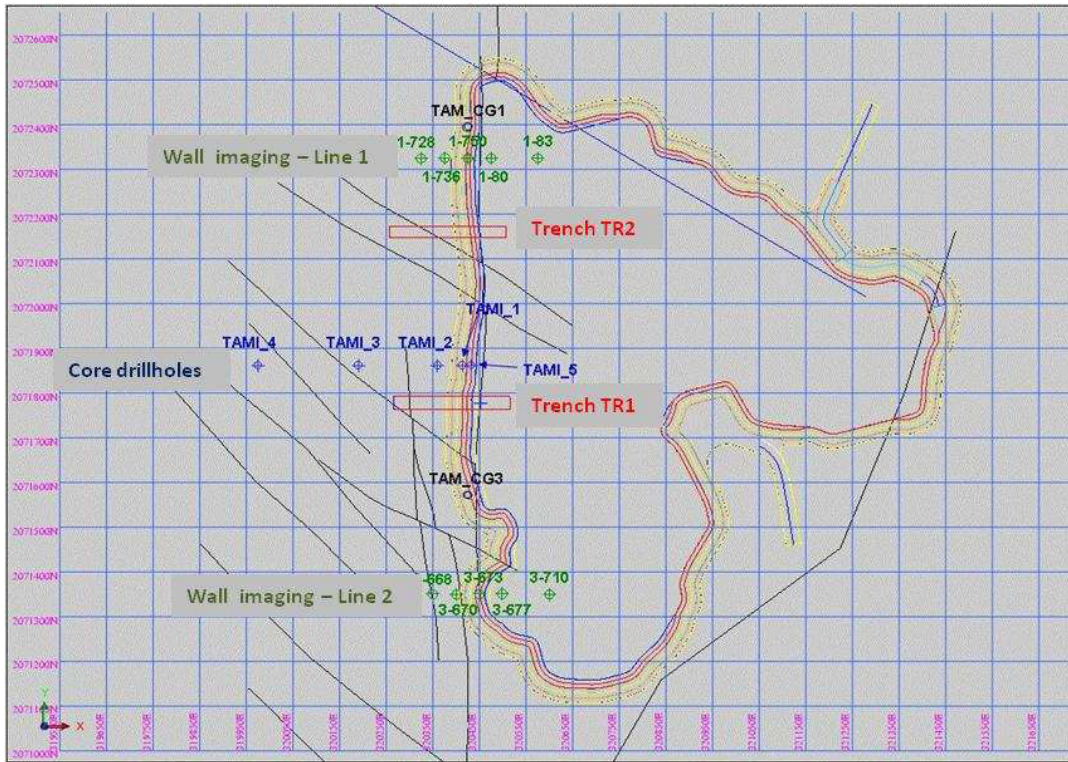


Figure 8 : Location of the geotechnical investigation works, Tamgak final pit contour and major faults.

According to AFTES guidelines [9], systematic surveys of discontinuities along the walls of each reconnaissance trench were used to build a "structural cross-section" of the rock mass close to the Arlit fault as shown in Figure 9.

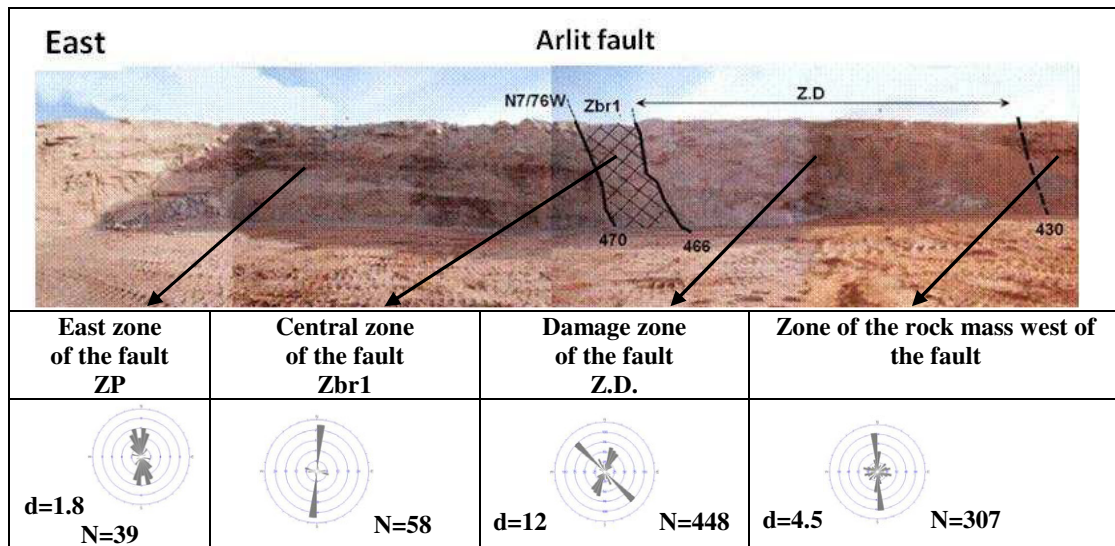


Figure 9: Trench TR1 – South wall : structural zones and for each zone: rose diagram of discontinuity strikes, d=number of discontinuity per metre, N= number of measured discontinuities.

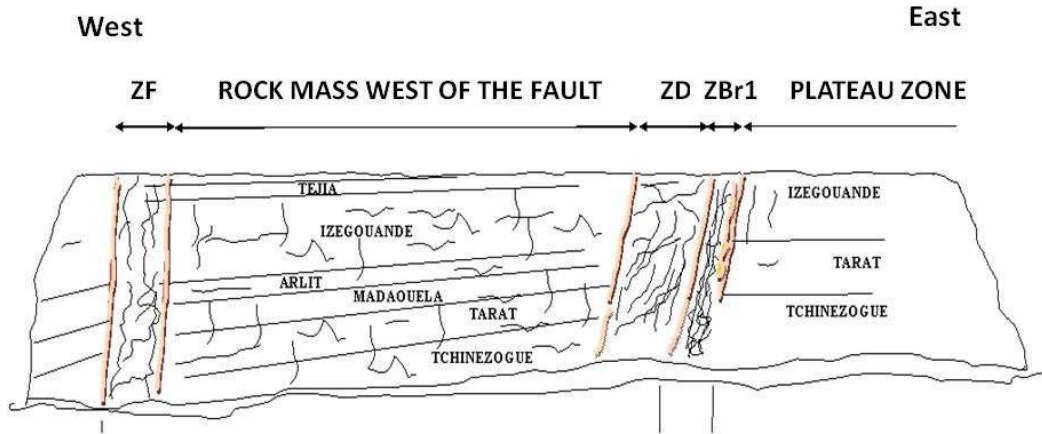


Figure 10 : Geological model of the Arlit fault zone

Correlations between discontinuity measurements performed on the different investigation works were used to build the geological and structural model of the rock mass near the Arlit fault (Figure 10). The following units can be distinguished: the **plateau zone (ZP)** located east to the Arlit fault with subhorizontal and slightly jointed layers; the **central zone (Zbr1)** orientated North-South with a dip angle of 80° westwards and approximately 15 m wide, where the initial geological structures are disintegrated and the rock mass is intensively jointed; the **damage zone of the fault (ZD)**, approximately 35 m wide also oriented North-South with a dip angle of 80° westward, where the geological structures are still visible but the rock mass is still highly jointed; the zone of the "rock mass west of the fault" consisting of eight geological formations with layers dipping at about 20° to the west and which have a medium degree of fracturing, but higher than the plateau zone located east of the fault. More westwards, this zone can also be intersected by other major tectonic structures oriented to N140 (ZF).

Mechanical rock mass parameters were then allocated to each geological unit of this model, based on the dominant lithology and geotechnical quality of the rock mass defined by the Geological Strength Index, parameter introduced by Hoek and Brown [10] to define the failure criterion of jointed rock mass. On this basis, a stability analysis at large scale allowed defining the slopes of the western pit side that provide a safety factor of 1.3 (Figure 11 for illustration).

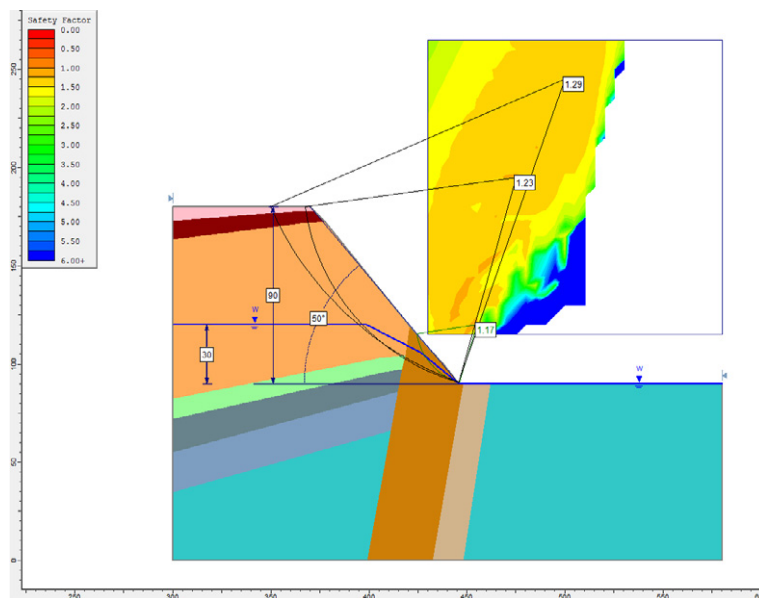


Figure 11: Example of stability calculations using the SLIDE software (profile 1, H=90m, Slope angle=50°, water table with normal drawdown at 2H/3)

4. Conclusions

This paper emphasizes the importance of a geological and therefore structural approach in order to address the slope design in open pit mines whose stability is largely controlled by geological structures. The identification of these structures, early during the field work, allows defining the geological reconnaissance but also the specific geotechnical investigations required to set up the as realistic and reliable as possible geomechanical model. The choice of appropriate modelling methods and calculation will result. This type of integrated and well controlled procedure is the only way to optimize the slope design that respects both the safety and also economic constraints.

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