A Review on Rock Slope Stability: Failure Mechanisms, Stabilization Techniques and Implications for Mining Engineering

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ABSTRACT: Mines worldwide are now exploited at very large depths to recover minerals lying within the rock strata. The increase in the mining depth often leads to real risk of large-scale stability failure. This would further be aggravated by mining companies seeking to realize large profits by often operating at the steepest possible slope. As the slope angle increases, its stability decreases and in case of collapse, casualties are often immense. It is therefore crucial to conduct a thorough analysis when designing slopes. In this review paper, we have gathered the most relevant and updated information regarding rock slope stability and its practical application in the field of mining engineering. Specifically, after reviewing the principle underlying rock slope stability, we have presented a clear procedure for geological data collection and computational techniques used for slope analysis. Stabilization and protection techniques used in rock slope have also been presented and in the end, we have analyzed how these different technologies are applied in the field of mining engineering through bench design in open-pit mines and shaft design in underground mining.

KEYWORDS: Slope analysis, Discontinuities, Data collection, Computer analysis, Mine design.

1. INTRODUCTION

Rock mechanics is a field of earth science that has been recognized as an independent engineering disciple just a few decades ago, at a same level as soil engineering or water sciences. The subject of rock mechanics started in the 1950s from a rock physics base and gradually became an independent discipline around the 1960s (Hudson and Harrison 2007). It mainly focuses on the mechanical properties of rocks and their influence in engineering projects such as mine excavation or tunnel construction. It uses different techniques to analyze the rock mass response to continuous and discontinuous loadings and therefore helps to set principles characterizing rock mass response to stress as well as a reliable layout for using these notions and results for real-world problems. Various practical challenges have occurred in different engineering fields such as mining engineering, geothermal energy recovery, tunneling, or underground hazardous waste isolation and rock engineering concepts have been used to enhance operations efficiency and industrial value. Besides, some key developments in numerical and computational methods have been the real trigger to these advances in rock engineering practices.

The main difference between rock and other engineering materials lies in the fractures and discontinuities that characterize its structure. Therefore, rock structure has a predominant influence on how the rock mass would respond to internal or external stress solicitations. In the field of mining engineering, it can determine the choice of an excavation method and the mine design as long as it would control subsidence, excavation spans, support requirements and fragmentation characteristics. The rock mass is characterized by various discontinuities which at some point can cause rock slope failure.

In contrast with soils, where slope's failure varies from being circular in the case of homogeneous materials to non-circular when dealing with layered soils; for rocks, however, most slope's failures are the consequence of the effects of discontinuities within its structure. At the same time, the intensity or mode of failure will depend on the geomechanical properties of discontinuities present in the rock structure namely orientation, spacing, persistence and roughness.

This paper aims at collecting, analyzing and discussing the most updated information about rock slope engineering and in particular, its failure mechanisms, the techniques of site investigation and geological data collection and also, the conventional and numerical methods used for rock slope data analysis. We will also study the stabilization and protection techniques for rock stability, as well as the application of these technologies in the field of mining engineering.

2. PRINCIPLE OF ROCK SLOPE STABILITY

2.1 Slope features and definitions

Slopes stability can have a huge economic impact on companies operating in the field of mining or civil engineering and is therefore a relevant engineering topic to address. Slope failure can bring costly damages that could be hard to remediate. But we often note that there is a trade-off that companies have to deal with; therefore, on one hand, slopes need to be steeper for a better economic outcome and on the other hand, low slopes would be a better choice for ensuring structural stability (Basahel and Mitri 2017). However, a bad judgment or appreciation when taking into consideration these factors can increase the risk of slope failure in the mining or construction field. In civil projects like highway construction, slope failures can be catastrophic with life losses and should therefore be given a consequent consideration.

There are many different ways of classifying slopes and one of them is to distinguish rock slopes and soil slopes which, even though have some similarities are relatively different regarding the methods of analysis (Che et al. 2016). Nevertheless, in some cases, those differences fade away especially when the rock reaches the weathered stage where its texture and behavior is similar to that of a soil. Another approach for classifying slopes is based on the expected mode of failure (translational or rotational). For rock slope failure, translational sliding (along joints) will be the most encountered type of failure whereas for soil slope the rotational mode would be more frequent (Bieniawski and Station 1990). However it is important to note that in densely jointed rock masses, rotational failure would occur very often. In most cases, the slope height and angle are the major factors of rock stability. Discontinuities (faults, joints, bedding planes …) and water are also some properties of high importance for slope stability analysis. One basis objective when analyzing slope stability is the determination of a factor of safety for the concerned rock slope. In the case of translational sliding (most frequent in rock slope failure), a factor of safety is obtained by dividing the resisting forces by the driving forces acting in a parallel direction to the translation (e.g. Figure 1).

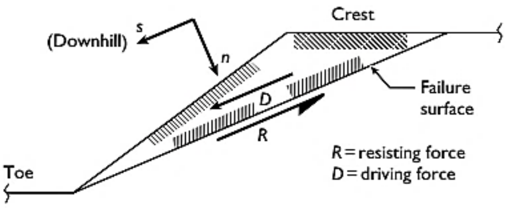

Figure 1 Resisting and driving forces during translational slope failure (Pariseau 2017)

2.2 Rock discontinuities and geomechanical properties

2.2.1 Major types of structural features

Rock mass is generally defined as the complete in situ medium, including all different kinds of structural features (Hoek 2017). From previous research on rock structural features, we can retain four major types of discontinuities frequently encountered within the rock mass. These are:

- Bedding planes: They are planes separating the rock mass into two or more blocks (beds, strata). They can also be acknowledged as an abrupt interruption in the process of rock mass deposition. One common characteristic to bedding planes is their high persistence even though in some cases sediments can form between the beds (Havaej and Stead 2016).
- Joints: They are often considered as the most common and significant structural features encountered in rocks. They can be defined as geological breaks displaying no apparent displacement. Besides, many grouped parallel joints will form a joint set and the intersection of these joint sets is called a joint system. It is important to note that joints can be open (with or without infillings) or healed.
- Folds: They are structures where the effects of tectonic forces in general, will change the structural behavior of the strata due to flexure. Both the formation method and the geometry are taken into consideration when classifying folds.
- Faults: Contrary to joints, faults are fractures which would display recognizable shear displacement. The orientation of those displacements would often be used for faults classification. They generally appear either in echelons or in groups (Hills 1983).

2.2.1 Geomechanical properties of rock discontinuities

An accurate description of discontinuities in the rock mass would always be a fundamental basis for identifying, monitoring and mitigating potential failure which may occur (Kumar et al. 2017). Therefore, the level of likelihood for a discontinuity to lead to rock failure will be determined by its geomechanical properties. The most important parameters for characterizing discontinuities are (e.g. Figure 2):

- Orientation: It is also known as the spatial disposition of the discontinuity and is defined using the dip which indicates the maximum declination between the discontinuity and the horizontal, and the dip direction (or azimuth) which is measured clockwise from the North. By convention, the notation dip direction/ dip would preferably be used (Blair et al. 1955).
- Spacing: It is the distance measured perpendicularly between two discontinuities. For a set of joints we will generally adopt the mean spacing (Riquelme et al. 2016). Data obtained from the spacing calculation are used to evaluate the level of structural anisotropy of the rock mass and to define the size / the shape of blocks forming the rock mass.
- Persistence: It generally refers to the length of a discontinuity along the surface of the rock mass. We can therefore distinguish discontinuities with a very low persistence (Modal trace length≤1m) and those with a very high persistence (Modal trace length≈20m) (International Society for Rock and Committee on Field 1974). Some of the features which are influenced by the persistence of discontinuities include the shear strength within the plane of discontinuity, the mode of fragmentation and the rock mass permeability.
- Roughness: This parameter is used to evaluate the smoothness of a discontinuity relatively to its mean plane. The roughness has a major influence on a discontinuity shear strength especially when the space between the discontinuity walls (aperture) is negligible. Therefore parameters like large aperture or thick infilling will reduce the influence of the roughness (Kundu et al. 2017).
- Infilling: This refers to the material contained in the apertures found on the rock mass. Infillings can be made up of soft materials (like clay) or hard materials (quartz for instance). The nature of the infilling will have a great influence on the discontinuity shear strength.

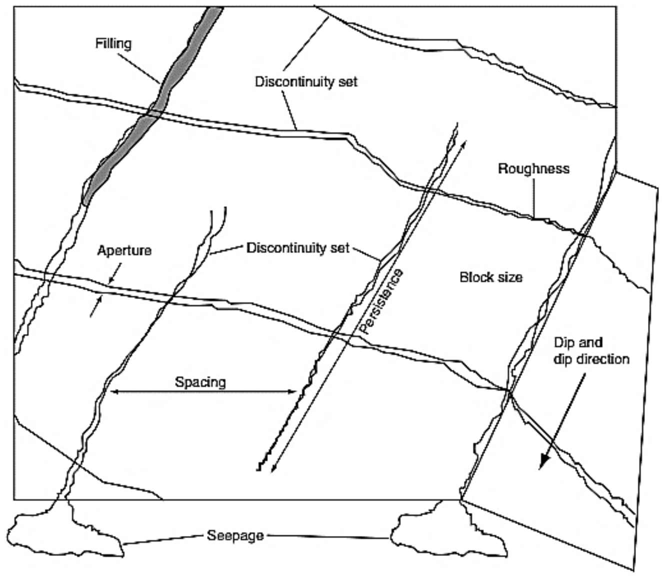

Figure 2 Representation of discontinuities on a rock mass (Simons et al. 2013)

2.3 Influence of weathering on rock stability

Rock weathering is commanded by two basic principles which are: the duration of the weathering should be long enough to cause noticeable damage to the rock and also, the weathered product (decomposed rock) should remain on site and not be cleared away by erosion or any other process (Liu et al. 2014b). Weathering is the resulting effects of physical and chemical transformations progressively affecting the rock structure with time. Physical weathering includes mechanical processes such as thermal expansion and contraction, mechanical exfoliation and wetting/drying which will break down the rock mass and create a larger number of surfaces exposed to weathering. On the other hand, chemical weathering will generally lead either to the dissolution of rock minerals or the creation of new chemical bonds and molecules due to various reactions between water and minerals inside the rock mass (Pinheiro et al. 2015). Chemical weathering will mostly be influenced by factors like temperature, the size of the grain subject to weathering and the type of the host rock. In tropical regions, because of the high temperature and intense rainfalls, weathered rock covered with low-strength soil or residual soil will undergo an erosion process which ultimately will lead to slope failure (Moore et al. 2009). In those regions, a mitigation approach would be to plant some vegetation on and around the concerned area in order to reduce the effects of erosion.

The design of rock slope would generally take into consideration the characteristics of the weathering process in relation to the depth but also how the host rock properties could affect that process. Besides, in the case of a possible continuous weathering process during the lifetime of the project, it is advised to consider a decreasing rock mass strength with time when designing the rock slope.

3. DIFFERENT TYPES OF ROCK SLOPE FAILURE

3.1 Slope failure causes and processes

Many causes can justify slope failure, being in a soil or a rock structure. However, a single factor would rarely be the only reason for failure (Christian et al. 1994). In most cases, many factors or causes would act simultaneously or complementarily in a way to trigger soil or rock slope failure. These factors can be classified into two main categories: Factors that act to increase shear stress and factors that act to reduce shear stress (Norris 2008).

3.1.1 Failure due to shear stress increase

Stress increase can be the result of either human actions or a natural change in the rock environment. Human actions such as mining, quarrying, road or tunnel construction can cause shear stress increase through the removal of lateral support, the augmentation of slope surcharge but also the removal of underlying support of the slope (Bostanci et al. 2018). On the other hand, natural events namely rain, hail, snow and water charges can also lead to additional surcharges on the slope; water contained in pores, cavities or cracks would undergo a freezing and swelling process, creating lateral pressure and therefore increasing the shear stress. Natural events like tectonic uplift stresses or stress relief are often associated with a moderate increase in the overall slope of the region (Geo et al.). Another phenomenon such as transitory earth stress can be triggered by both human actions (blasting, heavy traffic, machinery usage) and natural events (earthquakes).

3.1.2 Failure due to shear stress decrease

This mode of failure can be the consequence of physical and chemical reactions happening within the rock mass. Some of these physicochemical reactions include clay (or clay-like materials) transformation upon disturbance, resulting in structural change and shear stress decrease in the rock mass. Another phenomenon like weathering can create a change in the rock shear strength through clay softening, hydration/dehydration and rock disintegration (due to thermal effects); all of this would result in cracks creation on the bedding and shear plane. We also have cases where water content, pore pressure and fractures may trigger changes in intergranular forces leading to drastic changes on the level of water table and seepage, therefore affecting the shear stress in the rock mass (Wyllie 2014).

3.2 Plane failure

Plane failure is often considered one of the simplest modes of failure. In the plane failure, the unstable block which is detached from the rock mass slide along a basal slip plane (plan of failure) (e.g. Figure 3). Generally speaking, this kind of failure is likely to happen when the following conditions are met:

- The slope face and the plane supporting the sliding should be parallel or very close to (within approximately 20°).
- The sliding plane should outcrop (daylight) in the slope face, which corresponds to a sliding plane having a dip angle smaller than the one of the rock slope face.
- The angle of friction on the considered plane should also be less than the dip angle of the sliding plane.
- Some weak zones of low resistance should exist within the rock and around the unstable block so as to delimitate the boundaries of the failure.

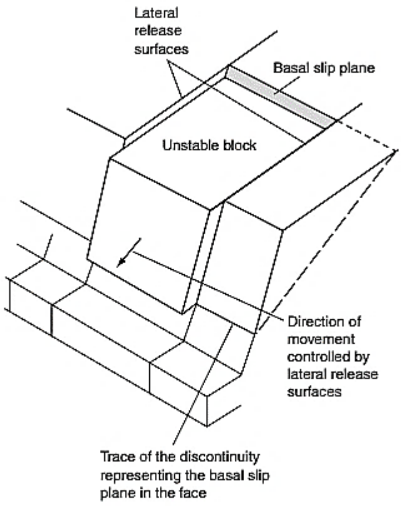

Figure 3 Planar failure mode (Blair et al. 1955)

3.3 Wedge failure

One characteristic of wedge failure is the fact that it does not require the existence of release surface before its occurrence. That property makes wedge failure to be one of the most dangerous if not the most dangerous rock slope failure mode (Konya et al. 2006). Wedge failure will likely occur when the intersection of two discontinuities strike in a direction almost similar to that of the slope face and moreover, the dip angle of this intersection line will be larger than the friction angle of both discontinuities (e.g. Figure 4). Comparatively to plane failures, a much considerable range of geomechanical conditions could be at the origin of wedge failures occurrence. In practice, the main conditions for wedge failures occurrence are:

- The necessity for two discontinuities planes to intersect and form what is called a line of intersection which commands the sliding mode.
- The dip angle for the intersection line, on one hand, should be greater than the mean friction angle of both slide planes, and on the other hand, smaller than the dip angle of the slope face.
- The direction of the line of intersection dip angle should be divergent to that of the slope face for the sliding to be possible.

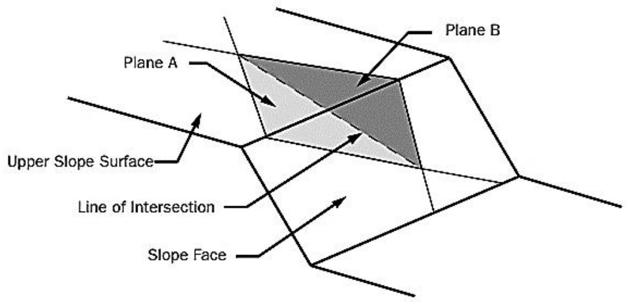

Figure 4 Wedge failure mode (Kliche 2019)

3.4 Circular failure

This mode of failure will likely occur in a context where discontinuities present a sort of random pattern or with no particular sets. There are certain situations where cuts or drillings need to be performed on weak rocks resulting from weathering or tight fracturing (Dong et al. 2018). In such situations then, failure may not occur following a particular set of discontinuities and would probably happen within a zone having a circular shape (e.g. Figure 5).

Generally speaking, circular failure (also known as rotational failure) will occur under the condition that the different constituents or particles found inside the rock have a much smaller size than that of the rock slope. Therefore, there would be many similarities between rock material and soil when it comes to their failure mechanism in a situation where the dimensions of the rock fragments are negligible compared to the dimensions of the slope (Stewart 1981).

For materials disclosing characteristics similar to those presented above, it is then extremely important to design the slop taking into consideration the high probability of circular failure.

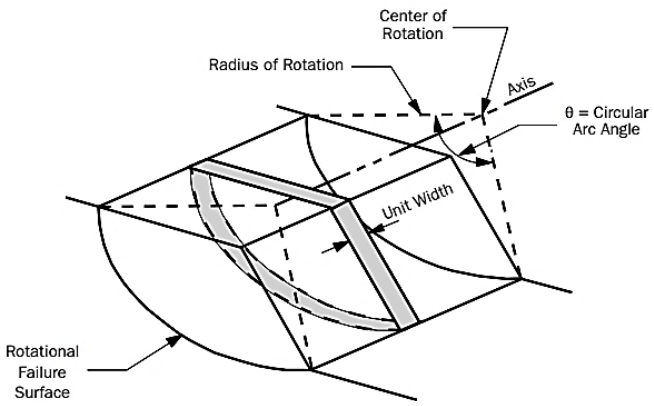

Figure 5 Circular failure mode (Kliche 2019)

3.5 Toppling failure

The main specificity of toppling failure is that it will induce a rotation of rock blocks around a fixed surface at the base (e.g. Figure 6). In this failure mode, the tension cracks are very intense at the top of the considered zone compared to the base (Gao et al. 2017).

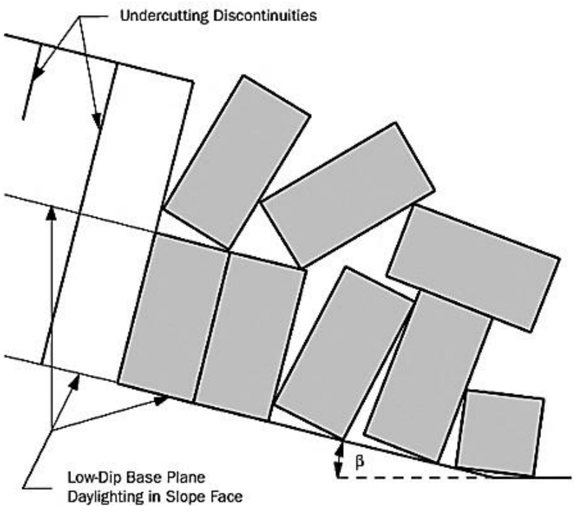

Figure 6 Toppling failure mode (Kliche 2019)

Based on field observations, we would distinguish two main types of toppling failure mode. This differentiation would be of a high importance as it will determine the most appropriate design method to use in each case.

- Block toppling: In general three sets of discontinuities (the intersection of two of them dipping into the slope face and the third one in a direction close to the angle) will be necessary for this type de toppling failure to occur (Gu and Huang 2016). Bedded sandstone and columnar basalt are generally inclined to experience this kind of failure as they often have well developed orthogonal joints.
- Flexural toppling: This failure mode is mostly encountered in a case of very tight discontinuities which dip in a direction forming a steep angle with the slope face (Johari and Lari 2017). This phenomenon is widely seen with thinly bedded shale where orthogonal joints are poorly developed.

4. SITE INVESTIGATION AND GEOLOGICAL DATA COLLECTION

4.1 Preliminary investigation

This is the first phase of investigating the slope stability. During this phase, the main objective would be to gather all the information and previous studies available in relation to slope characteristics (Kromer et al. 2015). We would need to look at the available reports and geological maps, check the available air photographs of the studied zone and also make some fields visit to check and compare field observations with the gathered information. When applicable, it is also advised to examine the behavior and performance of some slopes found in almost similar geological conditions to the one under investigation (Kliche 2019).

Some of the important information one should particularly look for are:

- The material type: we should figure out whether the material could be considered as a rock, a soil or both.
- The characteristics of the structural geology: This will enable us to have an overview on the existing discontinuities on the slope. It could therefore be possible to predict the presence of bedding planes, faults, joints, folds, etc.
- The hydrological data: This is used for identifying the presence or not of groundwater which is very important as any change in its properties will affect the slope behavior (Lv et al. 2017).

At the end of the preliminary phase, many information could be drawn, such as the possible slope failure modes, the various zones at risk, the forecasting of the overall slope angle, the possible issues related to groundwater and that would then help to establish a feasibility study plan (Hunt 1984).

4.2 Geologic data collection procedure

Regarding slope stability investigation, a specific pattern will generally be followed during the data collection process. This procedure will be implemented during field works where important information on the slope characteristics and behavior would be collected and then analyzed later in a laboratory (Vanmarcke 1977). Geological data collection will generally be conducted following the five major patterns listed below.

1. Exploring and determining the boundaries existing among different geologic materials: At this stage, the activities will mainly focus on determining the approximate features of the slope using simple or rudimentary techniques (Goodman 1976). For instance, evaluating the level of weathering (change in color, resistance to hammer's impact), observing the sedimentation variation (particle size distribution) and analyzing the spacing and persistence of joints.
2. Analyzing the rock slope structural features and determining the existing discontinuities: At this stage, the aim will be to identify different discontinuities such as joints, shear zones, bedding planes, folds or faults (Hu et al. 2018a).
3. Establish a map of existing discontinuities: This includes identifying the location (coordinates) of the discontinuity, its orientation (dip and dip direction/strike), its persistence materialized through a coefficient of continuity K_c (K_c=1 for major features and K_c<1 for minor ones) (Kliche 2019). This stage will also allow the

determination of the host rock type, the level of joint spacing, the degree of discontinuities roughness and openness. For this last case, if we have an opened fracture, we should check for the presence and the nature of the infilling (clay, granular or crystalline material) and then measure the infilling thickness (Asaoka and Agrivas 1982).

4. Executing a sampling program: This activity will consist of collecting intact rock samples namely the weathered and unjointed ones, collecting some sample presenting some discontinuities which will be used for shear testing, and finally in the case there are some infillings, collecting the infilling material which will undergo soil mechanics tests.
5. Analyzing the conditions of the groundwater: Check and localize the presence of springs and discharge point within the studied zone. In case of springs, its discharge should be monitored and measured on a frequent basis (Hu et al. 2018b). We should also try to evaluate the rock permeability as well as the permeability of joints on its surface.

4.3 Techniques for collecting discontinuity data

Due to the irregular shape of rocks, access to certain zones of the rock mass could be very challenging and then reducing the extent of the analysis to be conducted. Therefore, the method to use for discontinuity data collection will depend on the rock mass accessibility (Jiang et al. 2017). In many cases, it might be possible to access the rock surface and its related characteristics but the collected data could possibly not be representative of the rock behavior at the depth of interest due maybe to the weathering effects (Liu et al. 2017a). In the process of rock slope design, a certain amount of information could be available from surface exposure but there would often be the need to resort to drill hole information so as to get more detailed data. In some other cases, surface exposures might not be available or just unusable due to their lack of representativeness and in those cases, drill holes information would be the only source of data (Simons et al. 2013).

The process of discontinuity survey is based on the collection and interpretation of a large range of data characterizing the rock mass. In general the external, as well as the internal structure of the rock mass, could constitute a real challenge when trying to analyze the rock structure and its discontinuity network especially if the host rock has an irregular, highly fractured face. Thus the importance to ensure that measurements are made based on objectives but realistic sampling procedures which would lead to rigorous data analysis.

Based on the literature, an average of 1000 to 2000 discontinuities should be analyzed for obtaining reliable results able to characterize the site (Duncan et al. 2014). This objective can be reached by selecting samples containing approximatively 150 to 350 discontinuities but collected from different zones (between 5 and 15 different locations) nearby the host rock, which initially would have been proven to be representative of the geological structure of the formation. In the specific cases where the need for representativeness and accuracy of the data would impose to consider a very large number of discontinuities (because of the extent of the site for instance) then a minimum of 200 discontinuities should be considered (Phillips et al. 2017).

As mentioned earlier, the degree of accessibility of the rock mass would define the method of collecting discontinuity data that should be adopted. In general, there are two principal data collection techniques which will be used as sampling techniques; these are the logging of drill hole and the direct examination of the rock surface (in case it is exposed and accessible). When opting for drill holes, we would generally need the core detailed fracture log along with a report of the drill hole wall inspection procedure (Panek et al. 2018). On the opposite, when dealing with an exposed surface, the most popular sampling techniques are the scanline sampling and the window sampling.

Table1 Reliability of different data collection methods based on the data type (Simons et al. 2013)

Data type	Direct measurement	Surface photography	Drillhole core	Geophysics methods
Location	A	A	A	B
Discontinuity type	A	B	A	C
Dip	A	B	B	C
Dip direction	A	B	C	C
Spacing	A	A	B	C
Persistence	A	A	C	C
Roughness	A	B	B	C
Wall strength	A	D	B	D
Aperture	A	C	C	B
Infill nature	A	C	B	D
Seepage	A	B	D	C
Block size	A	A	C	C

A:Reliable results**; B:**Average reliability**; C:**Poor reliability**; D:** No results obtained

5. COMPUTATIONAL TECHNIQUES FOR ROCK SLOPE ANALYSIS

Rock slope analysis is generally performed in order to assess the level of safety and functionality of the excavated slope like road cuts or open pit mines, but also to evaluate the conditions of equilibrium for natural slopes (Feng 2017). The main parameters which would influence the selection of an analysis method are the site conditions and the potential mode of failure (Liu et al. 2017b). However, we should be aware of the limitations associated with the different analysis methodologies.

Nowadays, there is a wide range of rock slope stability analysis tools, each one having its strengths and weaknesses. In general, we will distinguish two main approaches for rock slope analysis namely the conventional methods and the numerical methods.

5.1 Conventional methods of rock slope analysis

When referring to conventional methods, we will generally highlight two major techniques which are the kinematic analysis and the limit equilibrium analysis. Except for these two methods, there is also a third one known as rock fall simulators analysis which is an analytical computer-based technique use to study discrete rock block falls (Tang et al. 2017).

5.2.1 Kinematic analysis

The kinematic analysis will predominantly focus on the possibility of translational failures caused by 'daylighting' wedges or planes formation (Feng 2017). Therefore, the use of this method will require a thorough analysis of the rock mass structure, along with the characteristics of the existing discontinuities that may influence the rock slope stability. For carrying out this task, engineers will generally rely on the use of stereonet plots or some other computer programs specialized in the analysis of planar and wedge formation (e.g. Figure 7). For instance, the program DIPS will rely on friction cones, wedge and toppling envelopes as well as discontinuity properties analysis to visualize and determine the application of kinematic analysis on rock slopes. Besides, the user should always keep in mind that this method only takes into consideration potential sliding failures resulting from single or intersected discontinuities (Liu and Xie 2014).

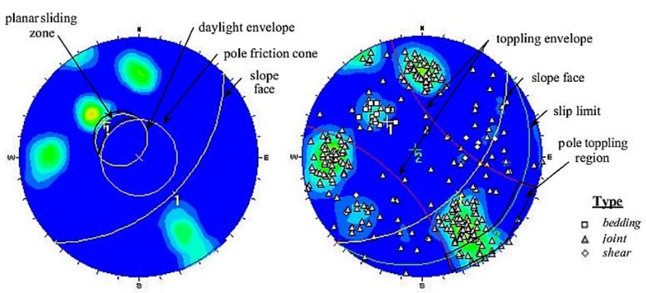

Figure 7 Planar (L)/ toppling (R) kinematic feasibility and stability analyses using stereographic constructions (Eberhardt 2003)

5.2.2 Limit equilibrium analysis

In the case of landslides where various failure surfaces can be subject to translational or rotational displacements, limit equilibrium analysis will generally be the most convenient method. The analysis based on this method would either focus on determining a parameter known as the safety factor or otherwise use a back-analysis to compute some shear strength elements characterizing the slope failure (e.g. Figure 8) (Mahmoud and Mansour 2017). These approaches are largely popular in the field of rock slope engineering even though most often, complex fracturing and deformation will be part of the rock slope failure process and therefore the hypothesis of a 2-D rigid block integrated into the limit equilibrium analysis would not be very pertinent (Reddy 2010). Nevertheless, in the case of highly weathered or fractured rock slopes (which will therefore tend to behave like a soil continuum), or discontinuities presenting simple block failure, limit equilibrium analysis has been proven to be highly efficient (Kim et al. 2002).

Limit equilibrium techniques will all follow the same analysis pattern which aims at assessing the differences between resisting forces (or moments) and driving forces (or moments). However there could be some differences among these methods and we would distinguish between the translational analysis case, the toppling analysis case or the rotational analysis case. These analyses would mainly be based on the type of failure and the different assumptions included in the computations (Harrison and Hudson 2000).

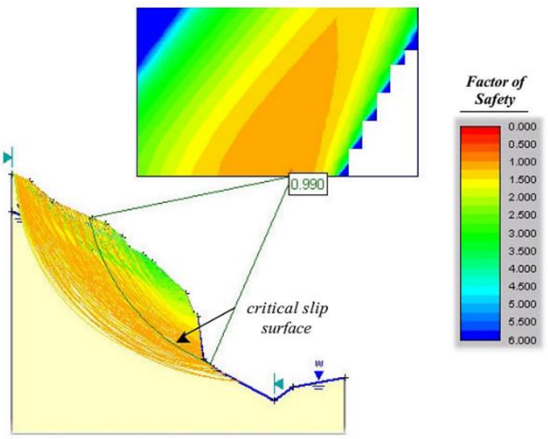

Figure 8 Limit equilibrium analysis of a rock slope performed using a critical surface search routine (Eberhardt 2003)

5.2.3 Rock fall simulators

Hungr and Evans in their work on rock slope, described analytical solutions as an approach that considers the rock block as a point characterized by its mass and velocity; that point has a ballistic trajectory when moving in the air but would rather bounce, slide or roll in a case where it is in contact with a slope surface (Glade et al. 2005). This can be true when using coefficients of normal and tangential restitution to adjust the two components of the velocity (normal and tangential) upon contact. The above two coefficients represent bulk measures of the various impact properties, including deformational process, contact sliding and the interchange process between rotational and translational momentum (Ulusay and Aydan 2016). Then, the main parameters which would guide the coefficients assessment are the shape of the block, the roughness of the slope surface and other properties such as the deformational and momentum properties.

When we incorporate all these computational techniques in an analysis, we obtain what is known as rock fall simulators. Some popular simulation programs like ROCFALL will use the velocity variation of the rock block when it moves on the slope material to analyze and predict the trajectory for which the block might fall (Inc. 2001). Rock fall simulators can also serve to improve the remedial measures by determining the kinetic energy and the exact location of the impact on the rock block.

5.2 Numerical methods for rock slope analysis

Conventional methods are most often used for simple case study which ranges from slopes with basic characteristics to simple loading conditions. And therefore they are unable to provide a thorough understanding of slope failure. In practice, most of slope failure cases will include complex geometries, non-linear behavior and some other uncommon mechanisms which will require the use of more sophisticated methods known as numerical modeling techniques (Vanmarcke 1977).

5.2.4 Continuum approach

Slope failure analysis based on continuum models all work with finite-element and finite-difference methods. With the continuum approach, the studied domain will be discretized into many different small domains before the analysis (e.g. Figure 9) (Melentijevic et al. 2017). Afterward, similarly to the finite-difference method, the computation result which actually will be a very close numerical approximation of the exact solution, will be drawn from the results given by the governing equations (differential equations of equilibrium, strain-displacement and strain-stress equations). When encountering cases of rock slopes characterized by voluminous intact rock, rock with low shear strength or highly fractured, then continuum methods are the most suitable techniques to use (Meng et al. 2018).

Practically, there are some 2-D continuum computer programs, based on plane strain assumptions which will provide unreliable results when analyzing heterogeneous rock slopes presenting a complex structure, lithology or geology. On the contrary, 3-D continuum codes just like FLAC3D or VISAGE (Salciarini and Tamagnini 2009) will give users the possibility to have a three-dimensional view of the mechanisms related to the slope stability analysis such as slope geometry, water pressures, field stresses or seismic events (Itasca Consulting 2002).

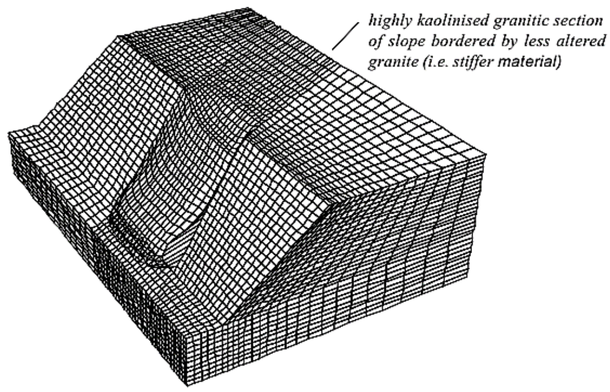

Figure 9 3-D finite-element model showing rock slope displacement along a china clay slope in the U.K. (Eberhardt 2003)

5.2.5 Discontinuum approach

Continuum methods, whether being 2-D or 3-D programs, even though are very useful for the analysis of rock slope failure may often face some limitations related to the accuracy of the representation they provide for the rock mass. In particular, when we are in a case of a rock mass filled with joint sets, it appears much more efficient and indicated to use a discontinuum modeling method (Lees and Institution of Civil 2016). With the discontinuum approach, the studied domain is managed similarly as putting together a series of distinct blocks interacting with each other under the influence of an external loading and characterized by a rapid motion (e.g. Figure 10). The appellation discrete-element method (DEM) is often used to describe this method. Another limitation associated with continuum codes is that they can be very fastidious and time-consuming when one would try to modify them so as to better represent the existing discontinuities. Besides, analytical principles used by those codes would only allow the existing orders of magnitude used for elastic displacements to be applied to inelastic displacement too, which will potentially degrade the results quality (O. Hungr Geotechnical Research 2010). However, discontinuum analysis will allow the simulation of actions such as sliding, opening or closure happening between blocks or components. The discrete-element methods lie on the basic principle that the analysis should resolve the equilibrium dynamic equation of each compound in an iterative way until the boundary conditions are met. Nevertheless, there are three main variations of the discrete-element method namely the distinct-element method, the discontinuous deformation analysis and the particle flow codes (Coggan et al. 1998).

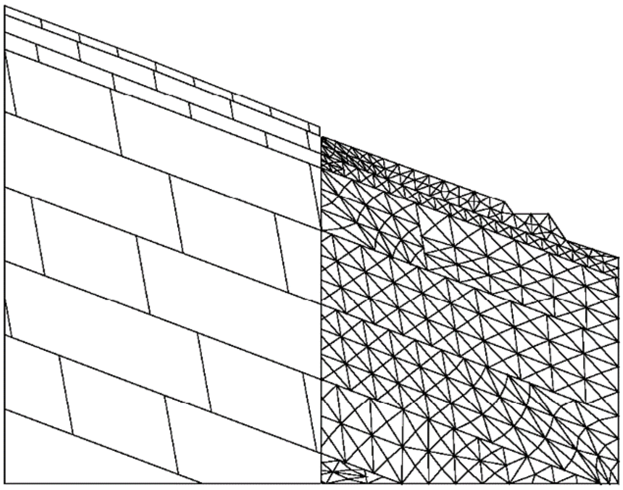

Figure 10 Rock slope distinct-element model showing discretization of geometry blocks into finite-difference elements (Eberhardt 2003)

5.2.6 Hybrid approach

Rock slope stability analysis using hybrid methods are essentially based on the usage of both limit equilibrium stability analysis and finite-element analysis, which is actually the principle underlining the functioning of a software like GEO-SLOPE (Park et al. 2016). Hybrid numerical methods have essentially been tested and used in underground rock mechanics involving solutions using both mixed finite/boundary-element and mixed distinct/boundary-element. Even though the separate use of continuum and discontinuum analysis methods can also provide, to a certain extent some results, there are some cases involving both discontinuities and brittle fracturing of the rock slope where both methods would be limited. However, when using coupled finite or distinct element codes, like with the software ELFEN, it is possible to model the intact rock behavior but also the evolution of fractures within it (Gharti et al. 2012). These methods rely mainly on the finite-element mesh approach to numerically reconstitute the rock slope or joint-filled blocks assembled through discrete elements which can perfectly simulate deformations related to joints. A general rule is that if the rock slope internal stresses are higher than the failure criteria characterizing the fine-element model, then a discrete fracture will originate (Goodman and Shi 1985).

6. STABILIZATION, MAINTENANCE AND PROTECTION OF ROCK SLOPES

In places close to public or strategic infrastructures such as highways, railways, power generation and transport facilities or residential areas, the matter of rock falls should be handled very cautiously. The principal factors which will influence the selection of a stabilization technique include the technical feasibility, the operational costs but also the simplicity of installation (Hoek et al. 1989). Slope stabilization techniques can be divided into three majors groups namely the methods which reduce the driving forces, the methods which increase the resisting forces and then those which focus on protecting the vulnerable installations or rely on a warning system (Codeglia et al. 2017).

6.1 Stabilization methods reducing the driving forces

6.1.1 Surface and sub-surface drainage

As mentioned earlier, water can have a significant influence on slope stability. At many occasions, rock slopes have collapsed just after heavy rains or due to a continuous period of freezing-thaw (Liu et al. 2014a). Therefore, reducing water pressure around the rock slope by installing drainage systems can be an effective measure to prevent its failure (Konya and Walter 1990). Drainage techniques can be conducted based on different sub-methods.

- Surface drainage: In the case of water flowing over the slope face and inside the tension cracks, it would be important to dig a ditch along the crest so as to adjust the water flowing direction and also avoid water stagnation. It is also recommended to use clay or plastic material to cover the tension cracks.
- Horizontal drains: The most efficient way to remove subsurface water using horizontal drains would be to drill the holes into the slope face, which will intercept the water table located under the vulnerable rock mass. Holes spacing and direction would be determined based on both the rock permeability and subsurface water location.
- Pumped wells: They are made up of vertical drill holes, operating along a perforated casing and an electric pump located at the bottom of the system.
- Drainage galleries: For this technique, drain holes would be drilled from the galleries to a fan aperture so as to increase the process efficiency.

To effectively prevent the phreatic level to be in contact with either the shoulder or the toe of the slope, it is strongly advised to provide a continuous layer of sub-surface drainage blanket (Sim 2016).

6.1.2 Scaling and trimming

This stabilization technique mainly consists of removing all the loose, overhanging and protruding parts of the rock slope which otherwise could easily fall off. In the case of scaling, the use of hand scaling bars, soft explosives or hydraulic splitters would be selected to cut off isolated blocks of loose rocks whereas in the trimming case, operations will rather focus on the removal of protruding rock in overhang areas using drilling, blasting and even scaling (Kliche 2019). Those operations are often conducted for lower slopes using equipment such as cranes or hydraulic booms and for high slopes using ropes or suspended cables. Scaling and trimming work can often be very fastidious due to the fact that operations might be slow, access to the study area very difficult and the obligation to rely only on light and hand-held equipment.

6.1.3 Resloping

When we are dealing with a case where it is not just some isolated blocks from the rock that are falling but rather the whole rock slope itself, then it is possible to reshape the rock slope by excavating its crest for instance in order to attenuate the driving forces. The reshaping and volume to take away are obtained from the computational techniques presented earlier. In general, slope stability will be influenced by its height and therefore resloping (which help to reduce the height) will act positively in keeping the slope stable (Rankilor 1981). After conducting resloping operations, the new slope should have features such that the slope inclination, as well as the rock strength and the groundwater influence would lead to a satisfactory safety factor. In addition, it is important to integrate the newly designed slope into the existing one so as to prevent the occurrence of steep slopes during or after the process of slope rectification (Sim 2016). If in the course of the excavation work, hazardous slope motion is observed, it would be important to install monitoring systems so as to give an alarm in case of critical stability conditions which could endanger workers life. Resloping includes techniques such as serrating, benching or bedding dip matching.

6.2 Stabilization methods increasing the resisting forces

6.2.1 Rock bolts, cables and dowels

If there is a possibility for a rock block to slide along a plane, therefore the normal force acting on that plane could be increased in order to enhance the resisting forces on the failure plane. In this case, rock bolts or cables with consistent tension could be used and encrusted in a more stable rock located nearby the failure surface. The reaction triggered by the created tension within the rock bloc would be normal and the intensity of shear forces operating across the considered plane would be controlled by the orientation of the rock bolts to the failure plane. Anchors can be used for mechanical stabilization of isolated blocks and slopes with a height ranging from 10ft to 100 of ft.(Bowles 2012). Rock bolts can be grouted inside the hole with or without pre-tensioning. In general, cables resistance or strength are higher than ordinary bolts and could therefore be used for stabilizing much larger blocks. Dowels are made up of steel reinforcing bars that are grouted into boreholes (e.g. Figure 11). In general, dowels would not undergo any post-tensioning and would have the effect of improving the shearing resistance of the surfaces subject to potential failure.

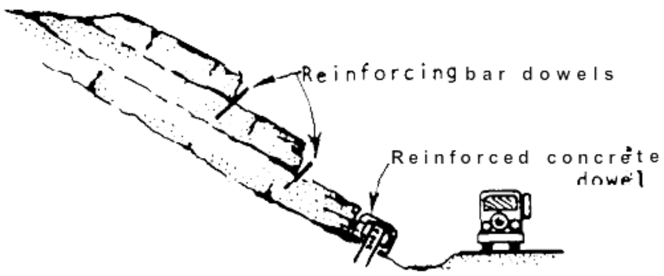

Figure 11 Dowels to support sliding blocks (Telford 1991)

6.2.2 Shotcrete

This technique mainly consists of spraying mortar and concrete mixture on the slope face so as to seal it and bind small or isolated fragments to the rest of the structure. This approach is proven to be efficient especially in preventing rock slope weathering and small blocks dislocations. In the specific case of rock slope stabilization, the thickness of the spray would vary between 50mm and 70mm (Wyllie 2015). Shotcrete can be used either wet or dry. In the case of a dry usage, the inputs (mortar and some additives) are mixed in-situ and compressed air is used to pump the mixture towards a nozzle where it would be combined with water. However, in the case of wet usage, a pre-mixing would be operated at the factory and then transported to the operation site. The tensile strength of the shotcrete can be further increased by using steel fibers, which create many tight bonding surfaces inside the rock.

6.2.3 Buttresses and retaining walls

Buttresses and retaining walls are stabilization methods, which consist of using reinforced concrete elements built at the base of the slope or under overhanging blocks of rock in order to prevent sliding by creating resisting forces. In the case of overhanging blocks that cannot be removed due to accessibility issues or the risk of generalized instability in the surrounding rock mass, concrete buttresses would be used to serve as a support to the structure. The strength of the concrete buttress should be high enough to support the block weight and well implanted in the face using tie-backs incrusted in the rock. Retaining walls are also an efficient means for failure block stabilization (Schlotfeldt et al. 2018). They are often made up of concrete or timber and operate in a way of opposing the sliding forces generated by the inclined slope thrust. Moreover, the foundations of the wall should be well encrusted in the rock mass using dowels and drain holes should be created along the wall so as to prevent internal pressure from the water.

6.3 Protection measures

6.3.1 Ditches

One efficient method for stopping the falling blocks at the base of the slope is by using ditches. During its design process, a particular attention should be given to the depth, width, and steepness of the concerned slope as well as the volume capacity of the ditch. When choosing the ditch geometry, elements such as the angle of the slope should be carefully analyzed as it influences the behavior of the falling blocks. In the case of lack of space to allocate to the ditch because of surrounding infrastructures, a catchment area can still be excavated at a very low cost or a low barrier made up of gabions can be installed at the borders of the roadway (e.g. Figure 12).

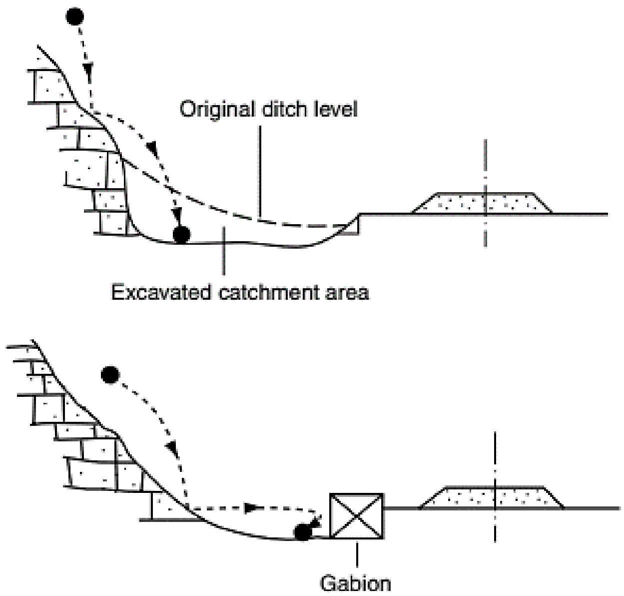

Figure 12 Shaped ditches with - excavated catchment area (Above) - gabions (Below) (Blair et al. 1955)

6.3.2 Fences

Fences will generally be used to intercept rock blocks falling to the slope base with an inclination of less than about 40°. In a case of a steeper slope, the falling blocks will be moving at a faster speed and could eventually cross over the fence. There is also the possibility to build fences where we have narrow gullies and only if the route of the falling block is clearly known (Darling 2011). Fences are often made up of wire mesh or solid interlaced rope attached to piles firmly incrusted in the ground. In general, the fence should be flexible enough so as to prevent the rock block to bounce after hitting it and an opening should also be allowed at the base of the fence to prevent accumulation of falling blocks at one face of the fence.

6.3.3 Wire Net or Mesh

Another common method for ensuring protection against rock falls is the use of mesh or wire net to cover the slope face presenting signs of rock falls. This will particularly prevent blocks of rock to completely detach from the slope face and bounce while falling. In general, two types of mesh would be used to fit those functions. The first type is the welded wire fabric, often used in concrete reinforcement and the second one is chain-link mesh, most common in fences installations (Huang and Yu 2018). Attaching the mesh directly to the slope face would not only keep the rock spallings in place but also lower rock removal at the base. In this case, pins (rock bolts, rock dowels and reinforcing bar) might be used under conditions of good strength and appropriate spacing in order to prevent them from damaging the mesh. Rock falls accumulating at the bottom of the slope should be frequently removed.

6.3.4 Rock sheds and tunnels

There might be some cases where the probability of rock fall (with subsequent damages) is very high and the above stabilization techniques can simply not be implemented (due to the site topography). Therefore, it would be necessary to build rock sheds or tunnels to mitigate the risk related to rock falls. Even though the construction costs of these infrastructures might be high, the maintenance would generally be more affordable (Kliche 2009). The construction of rock sheds should enable rock falls to rather slide on its roof instead of bouncing on it. Therefore, the roof should be inclined and covered with a layer of gravels. However if the area allows neither the construction of a rock shed nor the installation of any other stabilization equipment, a tunnel should be built to bypass the risky zone.

7. MINING ENGINEERING APPLICATIONS

The decision to start mining operations, the choice of the mining technique along with the design of the mine layout are all influenced by the nature of the geotechnical environment as well as the geomechanical behavior of the whole structure during excavations (Imaizumi et al. 2015). A predominant part in mine planning and design will incorporate notions related to geological data collection, rock properties and slope stabilization techniques.

7.1 Open-pit planning and design

For mining the ore from a surface mine, it might be necessary to excavate a large quantity of soil and rock and then move it to another location. The mine performance would depend on natural factors such as the ore body geometry and topography, the minerals distribution within the ore body or the failure angle (Kim et al. 2002). Some others factors such as the mining ratio, the type of equipment or the production rate would also have a large influence. Prior to exploitation, exploration activities would be necessary to define the amount of mineral to be exploited, but also to provide indispensable data such as pit size and layout, production rate, and also drilling and sampling information (Oppikofer et al. 2017). In particular, geotechnical investigations (including analysis of the rock type, degree of weathering, discontinuities) and geohydrologic investigations (underground water pressure, effects of erosion) should be conducted (Hustrulid et al. 2013).

A vital aspect of the design and operation of surface mining is the consideration of benches influence. In practice, the bench geometry will command the acceptable inter-ramp slope considering the need to ensure reasonable catch bench widths. In addition to the equipment, the bench slope would essentially be a function of the bench height, the bench face angle and the catch bench width. Bench height depends on the rock drilling and blasting equipment. Concerning the bench face angle, in the case of large open-pit mine slope, the design of the bench face is subject to the combination of all hard, jointed, weaker and altered rock conditions (Hustrulid et al. 2009). This variability would give the stable face angle, the shape of a probability density function. Finally catch bench widths are not uniform and vary from a point to another based on the slope geologic structure.

As a practical example, we will look at the case of the phosphate open pit mine of Kef-Essoun in Algeria. The research on this open pit has been carried out by Mohamed Fredj et al (Fredj 2018). This quarry, on September 2007 was subjected to a massive landslide on its North East side and later, premonitory signs were observed on the quarry North side signaling another potential slope failure. In this case, the limit equilibrium analysis method was chosen and using the Spencer calulation method, a safety factor of 1.302 (under static load) and 0.700 (under dynamic load) was obtained for the study zone. To stabilize the slope under the dynamic loading (so as to change the safety factor to a value above 1), the autors have resorted to the profiling method which consisted of:

- Reducing the crest to a level that makes it possible to cancel the effect of layers straightening
- Creating a bench of 15m height and widening the working platforms
- Scaling the bleachers

7.2 Underground mine planning and design

Underground mine planning and design aim at providing the best possible approach in terms of technical and economic requirements for extracting minerals from the ground. Four main steps would be engaged in that process namely a baseline assessment, a reserve evaluation, a preliminary planning and finally a subsystem design (Goel et al. 2012). The subsystem design would generally focus on the design of shafts which are the most important openings in deep mines. They are an indispensable way of providing fresh air, electricity and water to be used inside the mine as well as they ensure the transportation of ore products and the personnel in and out of the mine. In some case, 60% of the mine developing time can be dedicated to shaft sinking, depending on the mine depth (Nair and Chang 1973). Excavation design effectiveness would depend on the availability of a certain range of data related to the shaft, namely the geologic properties of the rock strata, the necessary shaft diameter, the shaft sinking method to be adopted and details about shaft lining, shaft foundations and shaft collar. The determination of the shaft diameter will be restricted by the size of hoisting conveyances and various installations used in the mine but more importantly the required quantity of air flow to be pumped inside the mine (Rafek et al. 2016). Regarding shaft sinking methods, they will depend on the rock strata properties and hydro-geologic conditions. In general, they would be classified into conventional methods which consist of a direct drilling followed by lining installation without prior ground stabilization, and then special methods. Conventional methods would be applied for rocks with good to high shear strength and limited water inflow while special methods would be used in the case of rocks with extensive fracture patterns or water-filled grounds. These special methods include the piling method, the caisson methods, the freezing method, the cementation process and the shafts drilling method.

A practical case of slope stabilization in underground mine is the Deep Geologic Repository (DGR) project for low and intermediate level waste undertaken by the organization OPG (Ontario Power Generation) in Canada (OPG 2012). In the past, the DGR project site has been used as the location for a heavy water plant which then created a significant land disturbance. One important phase of the DGR project is the design of the shaft sinking. For the shaft drilling stage, a drill jumbo suspended from the Galloway was used to advance the shaft in 5m lifts (or rounds). Afterward, the round was loaded with explosives. After blasting the round, the surrounding rock was weakened and a ground support was installed from the blasted rock pile (or muckpile). Based on the specific rock type and the properties of the various strata along the shaft depth, the type of ground support was defined. The results of the analysis showed that three different types of supports should be used for the shaft. These are:

- For rock formation with no overstressed zones: (i) 12mm diameter rock bolts 0.5 m long installed with mechanical anchors and (ii) 102mmx102mm welded wire mesh.
- For rock formations with only overstressed zones: (i) Fully resign grouted 25mm diameter thread bar type rock bolts 3.0m long and (ii) 102mm x 102mm welded wire mesh.
- For rock formations with overstressed zones and a potential occurrence of slaking: (i) Fully resign grouted 25mm diameter thread bar type rock bolts 3.0m long, (ii) 102mm x 102mm welded wire mesh and (iii) 75mm plain shotcrete with silica fume additive.

7.3 Slope management and monitoring in mines

The need for an economically optimized design would always imply a certain level of possible slope instability. Therefore, during the mining process, both mine planning and operational contingencies should serve to attenuate the risk associated to slope instability (Yu et al. 1998). The main principle which should be observed when it comes to slope mechanics are that: first, slope failures don't have a spontaneous occurrence, meaning that only a change in the forces acting on the rock mass would cause it to move. Second, in most cases, slope failure would lead to equilibrium because displacements due to sliding would reduce the driving forces while increasing the resisting forces until the rock mass movement ends (Abramson 2002). Third, warning signs would generally precede a slope failure as it has been observed that before major slope movement, measurable deformation or tension cracks development would occur. Slope management would generally follow two steps namely the identification of possible failure zones characterized by faults, joints or dikes and the monitoring of areas either subject to instability or presenting some displacement or tension cracks (Vehling et al. 2017). Finally, an effective slope monitoring program would systematically proceed through detection, measurement, analysis and reporting of any element corroborating slope instability. In order to ensure a reliable slope stability assessment, the measurement should be performed both on the surface and the subsurface.

8. CONCLUSION

Two of the most important factors that have a large influence on the stability of rock slope are the discontinuities shear strength and the localization and direction of these discontinuities. Other elements that should be equally considered when it comes to slope stability analysis are the type of the rock material, the groundwater conditions and other discontinuities properties including the nature of the discontinuity, the infillings, the surface roughness or the spacing.

Shear stress variation within the rock mass would lead to four major modes of slope failure namely the planar failure, the rotational failure, the toppling failure, and the wedge failure; with the last mode generally being considered as the most dangerous one since it does not require any release surface before occurring. For a better understanding of the slope stability phenomenon, operators would need to collect some data from the rock mass and analyze them using computer-based techniques. The collected data would include information related to the material type, the structural geology and the hydrology. Meanwhile, based on the calculation process, the computational techniques would be classified as either conventional methods or numerical methods.

Finally, rock slope can enter a state of instability and even fail through the means of rock blocks sliding out, rock blocks flexing or toppling and rock blocks detaching from the slope surface and falling. This would cause a serious risk for the people and installations within the rock vicinity. Thus, stabilization techniques such as re-sloping along with other protection measures would be implemented to minimize that risk. In the context of mining engineering, the technology deriving from the slope stability analysis would be used for benches and shafts design in surface and underground mining respectively.

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