

An Overview of Slope Failure in Mining Operations

Peter Kolapo ^{1,*}, Gafar Omotayo Oniyide ², Khadija Omar Said ³, Abiodun Ismail Lawal ², Moshood Onifade ⁴  and Prosper Munemo ⁵ 

¹ Department of Mining Engineering, University of Kentucky, Lexington, KY 40506, USA

² Department of Mining Engineering, Federal University of Technology, Akure 340100, Nigeria; gooniyide@futa.edu.ng (G.O.O.); abiodunismail18@yahoo.com (A.I.L.)

³ Department of Mining and Mineral Processing Engineering, Taita Taveta University, Voi 80300, Kenya; skhadijaomar@gmail.com

⁴ Department of Civil and Mining Engineering, University of Namibia, Ongwediva P.O. Box 3624, Namibia; lonifade4@gmail.com

⁵ Department of Mining and Mineral Processing Engineering, Manicaland State University of Applied Science, Mutare P.O. Box 7001, Zimbabwe; munemoprosp@gmail.com

* Correspondence: peter.kolapo@uky.edu

Abstract: The primary aim of every twenty-first century mining operation is to extract as much ore as possible in a safe and economical manner. Failure in mine excavation occurs when the shear stress acting on the rock is greater than the shear strength of the rock mass. The stability of rock slopes in open-pit mine and quarry operations is extremely important from both economic and safety points of view because unstable slopes can result in the loss of human life and damage to properties. This paper presents an overview of several case studies of slope failure in mining operations and explains various modes of failure in rock slopes, as well as factors that influence the stability of slope walls. With the aim of enforcing the importance of monitoring and evaluating slope stability in mining, both linear equilibrium and numerical modeling techniques were reviewed to elaborate their importance in designing stable slopes. In addition, the process of slope failure was discussed, and key signs of failure were indicated. In an effort to prevent mines from experiencing the hazards of slope failure, this study reports previous work performed in determining slope failure and the current state-of-the-art models, which entail the integration of analytical methods with artificial intelligence techniques. This innovation would help overcome the drawbacks of conventional prediction techniques that are cumbersome and ambiguous.

Keywords: slope failure; in situ; shear stress; rockmass; mining; factor of safety



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1. Introduction

The stability of slopes in open-pit mining operations and quarries is extremely important from both economic and safety points of view. The stability of rock slopes entails the design of safe, economical, and functional excavated slopes to attain equilibrium conditions of natural slopes [1]. It is generally accepted that during the design of a stable slope, a proper understanding of the geological processes, such as stratigraphy, weathering, geomorphology, petrography, and earthquakes, is necessary. The most significant structures that influence the stability of slopes are joints, bedding planes, and the intersection of joints, faults, and shear zones [2].

Instability in rock slopes can be harmful and could result in the loss of human life and damage to basic properties. Failure in slope occurs as a result of the downward movement of materials due to the effects of gravity. However, it is assumed that the sliding of a rock slope will take place where there is an intersection of joint sets. Failure of rock mass is inevitable when the shear stress is greater than the shear strength of the rock [3]. However, failure of slope walls depends on some activities such as cracking of rock mass, weathering, increase in pore pressure, presence of decomposed clay rock filling materials, leaching,

increase in water permeability, strain softening, and change in groundwater dynamics, which causes an increment in shear stress [4]. Therefore, the nature and behavior of the rock mass must be well-understood to ensure that the design of a pit wall remains stable for the life of the mine while extracting as much ore as safely and economically as possible [5].

The most common mode of failure in rock slopes is a plane failure. This type of failure happens when the angle of a structural discontinuity plane such as a bedding plane is smaller than the slope angle and greater than the angle of friction of the discontinuity surface [6]. Moreover, the water forces acting along the potential failure plane can also destabilize the slope. According to Wang and Niu [7], the dynamic loading and surcharge forces are other factors that contribute to the driving force that causes failure in rock slopes. The plane failure is influenced by factors such as the geometry, groundwater conditions, dynamic loading, potential failure plane characteristics and surcharge conditions [8]. However, the presence of major structural features such as faults, major joint planes, and unfavorably oriented bedding planes may also have a significant influence on the stability of the slope.

Over the last few decades, there have been significant advances in slope stability research works that investigated the causes of slope failure and factors that can trigger failure in slope. These factors are categorized by Sha [4] as internal and external factors. The internal factors that can affect the stability of a sloping wall include the mineral composition of the rock, rock types, and geotechnical and structural strengths. In addition, environmental factors such as earthquakes, rainfall, and weathering that can reduce the strength of the rock mass are also categorized as internal factors, while the external factors are mainly caused by human activity [9].

The increase in mineral demand in the 21st century has without a doubt compelled the expansion of mining operations globally, which has resulted in the extraction of minerals in larger capacities and deeper levels. However, it is important that these operations are conducted in a safe and economical manner. Therefore, this means that competent designs and techniques should be adopted to support the ever-growing mining capacities. Despite the analysis of slope stability using conventional techniques, mines are still experiencing slope failures, which have proven to be catastrophic and expensive. Therefore, this requires a better understanding of slope failure and the development of accurate prediction models to forecast this hazard before it occurs. Therefore, this study reports the application of slope stability evaluation techniques using linear equilibrium and numerical modeling, as well as the mechanism of slope failure. Additionally, the common factors known to affect slope stability are discussed, together with the various slope failure cases recorded globally. Last but not least, the application of artificial intelligence in predicting mine slope failure is reviewed, together with recommendations to improve prediction modelling.

Instability and Rock Mass Failure in Slopes

Unstable strata in rock slopes can lead to rock mass movement and cause harmful incidents that can affect mining operations and loss of ore reserves. Consequently, it can result in the premature closure of mines. Nicholas and Sims [9] reported the risk associated with slope failures in mining operations. These ranged from the loss of equipment to loss of reserves or mine closure and, in the worst cases, loss of life. Hustrulid et al. [10] argued that instability in rock mass slopes is largely caused by mining activities such as rock drilling, blasting, and the use of heavy machines. Similarly, Read and Stacey [11] indicated that the presence of groundwater, slope design, complex geology, discontinuities on rock mass, and mining operations are factors that affect the stability of rock slopes in mines. According to Eberhardt [12], the most common factors that influence the stability of rock slopes are redistribution of in situ stresses, complexity in geology, anisotropy and inhomogeneity of the rock materials, pressure pores and seismic loading. Similarly, Stacey and Swart [13] reported that the effects of blasting and groundwater are the only two major significant factors that control the stability of slopes. In addition, they indicated that blasting can

cause ground vibration that in turn may have a significant influence on the stability of the highwall.

Practical experience in the design of rock slope projects has demonstrated the importance of having a robust design. The basic parameters to be considered in the design are height, overall slope angle, and area of failure surface, as shown in Figure 1 [14]. There is a correlation between the height and stability of the slope wall; the slope stability decreases with the increment in the height of the wall. Similarly, the slope needs to be steeped to minimize the amount of waste rock mined, thereby reducing mining costs. However, the economic effect of steeping a slope is that some portion of the waste material will be mined but the slope will be stabilized [5].

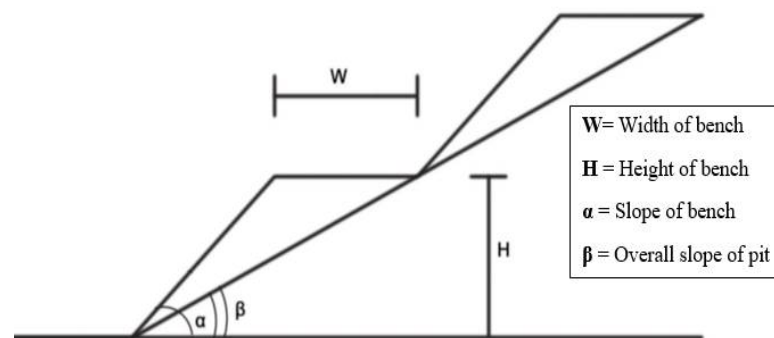


Figure 1. Design parameters in rock slope (Adapted from [14]).

The design of rock slopes is a major challenge in open-pit mines as it requires knowledge of the geological structure, lithology, and geotechnical properties of the rock mass [11]. It is necessary to determine the optimum design parameters to be able to evaluate all geotechnical materials before creating a slope. Read and Stacey [11] diagrammatically illustrated the design process of a rock slope in Figure 2, which is grouped into five stages, namely: models, domains, design, analysis, and implementation stages. Prior to the implementation of the design, the site investigation and data play important roles in evaluating the economic viability and stability of a rock slope. Furthermore, if predictions have been made that slope failure will occur, it is very important that the structural characteristics of the rock mass be considered. However, at the early stage of the design, data from the site can be obtained during geological exploration, which provides information on the strength of the rock mass, deformability properties, and geological structure and highlights the presence of major planes of weakness. These parameters could also be used to predict slope stability. Typical samples, as reported by Simataa [5] from a site investigation as shown in Figure 3, are selected for laboratory testing to determine the mechanical properties of a rock mass.

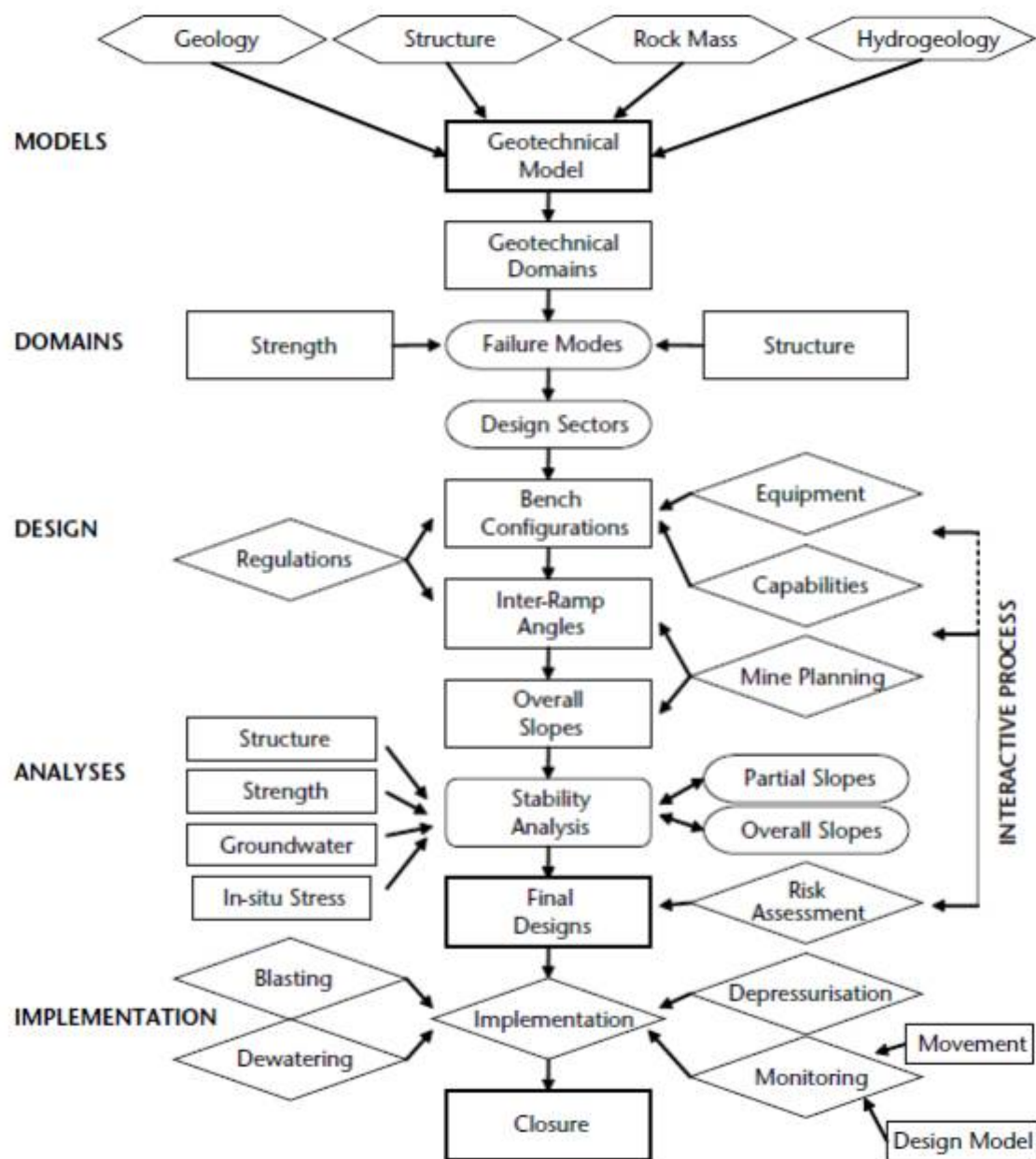


Figure 2. Rock slope design procedure (Adapted from [11]).



Figure 3. Core logs from borehole drilling during site investigation (Adapted from [5]).

2. Evaluation of Slope Stability in Mining

Failure of rock slope occurs when excess loading shear stress in a rock mass is re-distributed and the load exceeds the strength of the rock. The shear strength of a rock mass plays an important role in the stability of the rock mass. Therefore, factors that tend to change the shear strength must be taken into consideration during the design as these factors may have an overriding influence on the stability of the slope. According to Abramson [15], failure starts in the rock slope from a single point and propagates to the entire rock mass. According to the study by Eberhardt et al. [16], during slope failure simulations, their model suggested that in the absence of triggering events, the strength reduction and progressive failure in a rock mass are attributed to causes of failure in the rock mass.

Over the years, a number of researchers have conducted research on the evaluation of slope stability. However, numerous methods were proposed, but only two major techniques, namely the limit equilibrium method (LEM) and numerical analysis (deformation analysis), are commonly used to evaluate the performance of rock slopes' stability [17,18].

2.1. Limit Equilibrium Method (LEM)

Hoek et al. [19] stated that the LEM has been available for more than 25 years and can be considered as a reliable slope design tool. The LEM approach is based on evaluating the applied forces and the strength of the ground. This method has been the most popular technique used in estimating the stability of a slope in geotechnical engineering [20]. In addition, Duncan et al. [21] described the LEM as the procedure used to calculate the shear strength of the ground against some factors causing the shear stresses. In general terms, the factor of safety (FOS) of a slope is described as the ratio of strength to the stress load. In a potential failure surface, the resisting force (strength of the rock mass) could be compared against the driving force. The balance between the shear stress acting along the potential failure surface and the strength conditions of the rock mass also describes the FOS.

According to Fleurissen and Cojean [22], if the calculated FOS is greater than 1, this shows that the strength of the rock mass exceeds the stress; thus, the slope is stable. In the case where the FOS is united, then there is an equal chance of failure or stability of the slope. However, when the FOS is less than or equal to 1, this shows that the stress exceeds the strength; hence, the slope is unstable. This shows that the calculated value of FOS determines an average value for the slip surface. The stability conditions for wedge stability analysis are presented in Table 1.

Table 1. Stability condition analysis for wedge failure (Adapted from [23]).

Calculated FOS	Stability Condition	Recommended Action
$FOS > 2.0$	Stable	None
$1.0 < FOS < 2.0$	Marginal	Analyse stability rigorously
$FOS < 1.0$	Unstable	Revise design or stabilise

According to the study reported by Simataa [5], the strength of LEM lies in its ability to evaluate the sensitivity of stability using various input parameters, the simplicity of the component and, most importantly, the experience of the geotechnical engineers acquired over the years in estimating FOS. Similarly, the engineer must have an in-depth knowledge of the limitations of the method. For instance, LEM can become inadequate when there is internal deformation in rocks, such as the presence of microcracks, brittle fracture, extension strains and liquefaction of the weaker soil layer [24]. In a complex scenario, computerized codes and software can be utilized to further analyze the stability conditions of the slope.

The LEM can be combined with other geotechnical analysis methods, such as the Mohr-Coulomb, failure criterion to assess the initiation of failure in slopes to the worst credible scenario. In this approach, it is assumed that the shear strength of the rock along the potential failure zones is controlled by linear (Mohr-Coulomb) or non-linear relationships

in between the shear strength and the normal stress on the failure surface, which is defined by FOS [24]. However, the LEM is so fast that it can make thousands of FOS calculations, while the numerical modelling method takes a longer period to estimate just one FOS [8,25].

Despite the advantages of LEM in analyzing the stability of slopes, there are still some limitations reported by Ceryan et al. [26], as stated below.

- (a) In estimating the stability of slopes, if the movement of rock mass is detected, the LEM approach cannot estimate the impact of such movement on the overall stability [27];
- (b) LEM is restricted to the evaluation of slope stability with simple problems, such as providing little insight into the slope failure mechanism [12];
- (c) LEM can only identify the onset of slope failure. Complex rock slope stability problems associated with in situ stresses, such as the geometry of the slope, pre-pressure and seismic loading, require a continuum-mechanics-based numerical modeling approach [28].

2.2. Numerical and Mathematical Modeling Method of Slope Stability Analysis

The numerical modeling method of analyzing instability in rock slopes has offered solutions for complex scenarios. The design of open-pit mines often involves complexities as a result of inherent geological conditions that can be too cumbersome for the conventional LEM to solve. The numerical modeling approach can be applied in such cases for the simulation of potential rock slope failure mechanisms and to carry out a comprehensive rock slope investigation [29]. However, many researchers have applied computational tools, such as PLAXIS 2D, FLAC 3D by Itasca Consulting Group Inc and Phase2 from Rocscience Inc., for such cases.

Over the years, the advancements in technology and high computing software tools have brought about the introduction of computer codes and computational tools that can provide more comprehensive and reliable slope stability analyses for geotechnical engineering. The two most commonly used numerical methods are the finite element method (FEM) and finite difference method (FDM) [30]. The shear strength reduction is the most widely used approach for performing FEM in slope analysis [31]. Hammah et al. [32] conducted a study on the principle of systematical reduction in the shear strength of materials by FOS and computed the FEM models of the slope until deformations were unacceptably high. The FOS in the numerical simulation methods was calculated using the shear strength reduction techniques that relate the existing strength to the limit equilibrium strength [26].

In the numerical modeling approach, slopes are divided into elements. The split elements are modeled with the stress–strain relationship and deformation properties of the slope to predict the behavior of slopes. The boundary conditions are defined, and the numerical modeling software is able to determine FOS and predict the displacement of rock mass that will take place during failure [26]. Similarly, a study by Chiwaye [8] reported that numerical software is capable of calculating FOS using the shear strength reduction techniques. The calculated FOS determined by the numerical modeling approach is usually equal to or slightly less than that of the conventional LEM.

According to Eberhardt [12], the numerical method of analyzing slope stability can be categorized into two approaches, viz., continuous and discontinuous modeling. The continuous computer codes assume that the material is continuous throughout the body. This technique is used to analyze slopes that are massive, have weak strata, are heavily fractured and have soil-like rock masses [32]. However, with this technique, the discontinuous surface does not form with the continuous modeling and it is impossible to have after failure analysis. In addition, discontinuities inside the rock mass cannot be modeled clearly [33]. On the other hand, the discontinuous modeling approach is applicable if the stability of the slope is governed by a joint bounded blocks or intact deformation [34]. During modeling, the model treats the rock slope as an arrangement of deformable blocks [12]. However, the discontinuous modeling requires the geometry of the discontinuities, shear strength of the rock, groundwater characteristic, in situ stress condition, and the intact

constitutive criteria as the input parameters [8,29]. Nonetheless, of the capabilities of the discontinuous modeling approach, some shortcomings are associated with this method. Chiwaye [8] acknowledged that modeling of rock mass with discontinuous methods requires a representative of the discontinuity geometry. A study by Stead et al. [29] reported that both continuous and discontinuous computer codes can be used to analyze various failure modes in rocks but are most suitable for rocks with complex translation or rotational instabilities where failure brittle fracturing, internal yielding and shearing are present.

The main advantage of the numerical approach in analyzing slope stability is to predict the deformation analysis (stress–strain distribution), which may be used in the interpretation of slope behavior [10]. In addition, Hammah et al. [32] stated that numerical modeling has two major advantages; firstly, the ability of models to compute deformation and displacement of a rock mass and the proficiency of the method to process more sophisticated and complex problems than LEM. Secondly, numerical models can analyze complex geometries, simulation of stages in excavation and the influence of stress field conditions and groundwater seepage on the stability of the slope.

Recent studies have shown that the application of geomechanical parameter modeling of rock slopes is another approach to conducting stability analysis of geotechnical structure in slopes. Ground properties such as the cohesion and friction angle are the most used parameters that are required for the modeling [34]. The modeling of geomechanical parameters has been widely used by a great number of researchers to predict the stability factor and effects of the geomechanical structure of rock slopes. Lei et al. [35] applied the discrete fracture network (DFN) to model a couple of geomechanical properties of natural discontinuity rocks. Additionally, four copulas, that is, the Gaussian, Plackett, Frank, and Number 16 copulas, were used by Tang et al. [34] to model the dependence structure between cohesion and friction angle. The outcomes of the model were employed to construct the joint probability density function of cohesion and friction angle.

Similarly, Ahmad et al. [36] used Tree Augmented Naïve Bayes (TAN) to develop a Bayesian belief network to create seven nodes (unit weight, slope stability, slope angle, pore pressure ratio, slope height, cohesion, and internal friction angle) that represent parameters such as the “slope geometry”, “geomaterial shear strength” and “water condition” to predict the slope stability. In another study by Haghshenas et al. [37], a meta-heuristic algorithm, that is, Harmony Search (HS) algorithm and K-means algorithm, was used to determine a clustering analysis that will highlight whether a slope will be stable or fail. Additionally, to develop a slope engineering geological model framework, an algorithm model was introduced by Huang et al. [38] to evaluate decision-making in slope management. This model was developed from soft set theory and fuzzy soft set theory. A probabilistic approach was applied in complex anisotropic rock masses to model a factor of safety in Figueredo et al. [39]. The study made use of a series of stochastic simulations that provided scenarios for the failure moment, and a factor of safety close to 1 was obtained.

The study by Tugelbayeva [40] developed prediction models for describing dynamic behaviors of non-uniform media and structures to solve non-stationary issues in rigid bodies. The study developed mathematical models to determine mechanical processes utilizing explicit finite-difference techniques for explaining finite-difference techniques for solving partial differential equations and a numerical solution method using integral transformation. The study analyzed wave propagation with a cavity lying on an elastic foundation under dynamics loads from the surface overlying the cavity. The study utilized discontinuity decay for analyzing stress–strain variables. Analysis of the results proved that the models can be used to design and assess geomechanical features in mineral deposits [40]. Another study by Nemirovsky and Tyrymov [41] utilized mathematical modeling of a deformable body to calculate stress–strain conditions of layered rock mass with an overlying mountainous.

3. Process and Mechanisms of Slope Failure

The mechanisms of slope failure from a stationary hillside to an active slide imply that there is either an external force that triggers the failure process, or the shear stress is greater than the strength of the ground. In most cases, the downward movement of rock mass occurs very suddenly and most of the time, it is not just one cause that results in failure [42]. A combination of factors may influence the failure mechanisms in slopes. The redistribution of excess loading of the shear stress triggers the downward movement on sections of rock slope, especially where the shear stress exceeds the strength of the rock mass [5]. The study by Eberhardt et al. [16] suggested that in the absence of any triggering event, degradation in the strength of the rock mass may result in progressive failure, but subject to a time-dependent mechanism. Wyllie and Mah [43] categorize the mode of failure in rock slope into four classes as shown in Figure 4. These include plane failure, wedge failure, rotational and toppling failure.

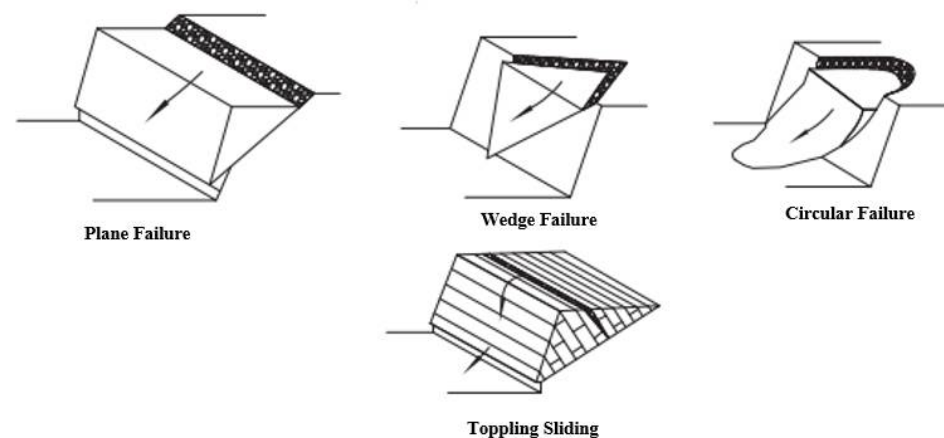


Figure 4. Classes of failure in rock slope (Adapted from [44]).

3.1. Plane Failure

Plane failure occurs when the discontinuity striking approximately parallel to the slope face and dipping at a lower angle intersects the slope face to enable the slope to slide [24]. This failure involves the rock slope downward and outward movement along a gently undulating surface or sliding [45]. When there is a potential plane failure, it will be evident as the bedding plane strikes parallel to the slope and dips out of the slope. In such conditions, there will be a lack of confinement, which will trigger planar failure in the slope. Kliche [45] and Simataa [5] in their studies agreed that planar failure is likely to occur when pre-existing joints are striking parallel to the slope and also when the dip is less than the slope angle as shown in Figure 5. In practice, the lack of lateral confinement in rock slopes will lead to planar failure. This type of failure is common in slopes that have convex designs where the direction is parallel to the strike of the weak planes. Planar failure can be limited to benches or areas of the pit with adverse geometry or the structures that strike perpendicular to the slope face, and thus allow a planar slide to occur. One of the major contributing factors in planar failure is the presence of groundwater, which causes the stability of the slope to deteriorate when there is temporary groundwater pressure, especially during heavy rainfall.

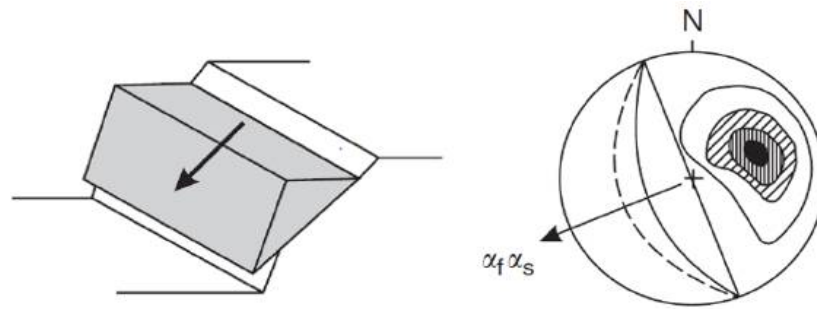


Figure 5. Pre-existing joints dipping out of slope face and striking parallel to the face (Adapted from [44]).

Wyllie and Mah [43] improved on the conditions reported by Hoek and Bray [46] and suggested the conditions that must be satisfied for planar failure to occur as follows:

- The strike of the plane of weakness must be within $\pm 20^\circ$ of the crest of the slope;
- The toe of the failure plane must daylight between the toe and the crest of the slope;
- The dip of the failure plane must be less than the dip of the slope face and greater than the angle of internal friction of the failure plane;
- The upper end of the sliding surface either intersects the upper slope or terminate in tension cracks;
- Release surfaces that provide negligible resistance to sliding must be present in the rock mass to define the lateral boundaries of the slide.

3.2. Wedge Failure

Wedge failure occurs as a result of the intersection of two or more discontinuities that lead to the formation of a tetrahedral failure block, which could slide out when the angle of inclination of the line is greater than the internal angle of friction along the discontinuities [5]. When two discontinuities hit obliquely across the slope face, the rock resting on these discontinuities will slide down the line of intersection, as shown in Figure 6.

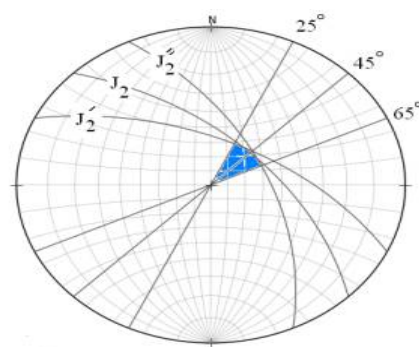


Figure 6. Plot of intersection of three joint sets on Stereonet dipping out of slope face (Adapted from [47]).

Wedge failure has a high tendency of being the most commonly experienced failure mechanism in rock slope [48]. The stability analysis of a wedge failure is one of the main components in the design of a competent bench face angle–height configuration. The stability evaluation will include large wedges, which could influence the stability of the overall slope, and joint planes, which could link up and affect the stability of the bench or even the ramp.

Hudson and Harrison [49] reported that wedge failure is inevitable in rock slope under the following conditions:

- (a) When the line of intersection of two discontinuity planes associated with the potentially unstable wedge is daylighting on the slope plane;
- (b) When the dip of the slope exceeds the dip of the line of intersection of the two discontinuity planes associated with the potentially unstable;
- (c) When the line of intersection of the two discontinuity planes associated with the potentially unstable wedge must be such that the strengths of the two planes are reached.

Low [50] argued that there are four classes of failure modes for a wedge, namely:

- (a) Sliding along the line of intersection of both planes forming the block;
- (b) Sliding along plane A only;
- (c) Sliding along plane B only;
- (d) A floating type of failure.

In evaluating the stability of wedge failure in rock slope, one of the most rapid and convenient methods is the use of stereonet. The stereonet has widely been used to examine the kinematic feasibility of wedge failure, i.e., the type of sliding that is likely to occur when there is intersection of two or more major planes. However, the method cannot be used to determine the actual FOS but can be estimated from the geometry of the wedge, the strength of each plane and the water pressure [43]. Moreover, the application of a friction stability chart is another rapid method to check the stability of two-plane wedges. In this approach, the chart only considers the frictional strength on the plane of weakness while ignoring the cohesion and water pressure. When using the friction method, the calculated FOS value must be greater than 2; a slope with FOS less than 2 is regarded as potentially unstable [43]. In using the stereonet approach to determine the stability of wedges, great circles for the planes of weakness are plotted on the stereonet by considering the shear strength on the weakness planes. Similarly, the slope designer must also consider the frictional strength using a friction circle.

3.3. Circular Failure

Circular failure is most common in soil and deeply weathered or closely fractured rock. Coates [51] stated that circular failure is experienced in continuum slopes with highly jointed or weak rock mass, as shown in Figure 7. However, circular failure can also be experienced in hard rock [52].

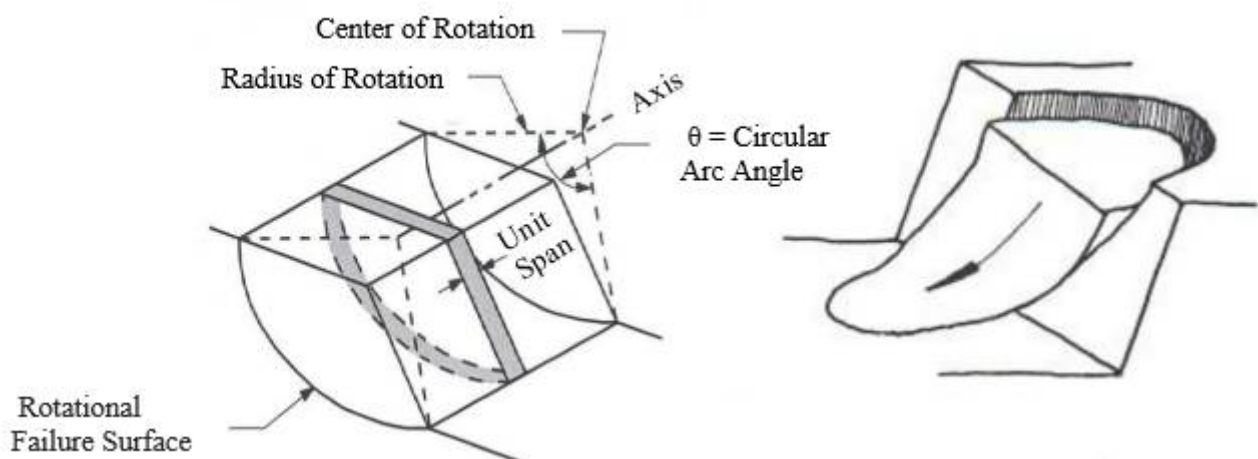


Figure 7. Rotational failure mode and circular failure mode in slopes (Adapted from [5]).

In weak strata such as soil or deeply weathered rock, the circular failure is defined by a single discontinuity surface but will tend to follow a circular path [53]. However, if the failure surface is curvy, it helps to prevent the extension of tension cracks at the upper ground surface [5]. The result of Sjöberg [54] investigations indicated that it might be difficult to conduct numerical simulations of rock slopes in large scales. Sjöberg [55] also

managed to carry out a model study of circular failure which showed that circular failure occurs in six (6) stages, as shown in Figure 8. The six stages are explained below:

- (a) Elastic displacement is caused by the removal of rock material during mining activities;
- (b) Yielding commences at the toe and spreads upwards as more material is removed or as a result of mining to a new and critical slope height;
- (c) Accumulation of shear strain at the toe of the slope will progress upward;
- (d) When failure surface is developed, the slope will start showing some displacements, which can be tracked if there is a good monitoring system in place;
- (e) Slope fails with time with larger displacement starting from the toe;
- (f) When failure occurs, the failing mass can slide away from the slope.

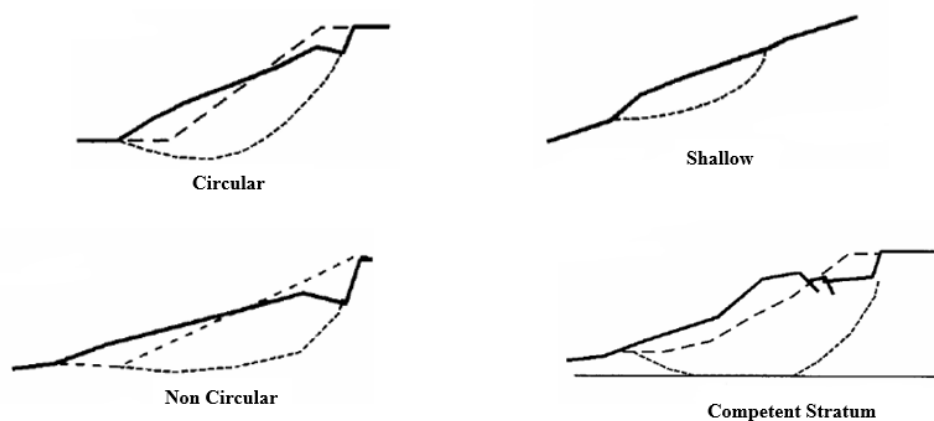


Figure 8. Mechanics of rotational and compound failure in rock slope (Adapted from [56]).

Kliche [45] reported that most circular failures in homogenous materials such as fills, highly jointed rock slopes, and constructed embankments are aggravated by water intrusion. Gundewar [24] classified circular failure into three (3) categories based on the area that is affected by the failure, namely: slope failure, toe failure, and base failure. Slope failure happens when the arc of the rupture surface meets with the shape above the toe of the slope. Toe failure occurs when the arc of the rupture meets with slope at the toe, while base failure occurs when the arc of the failure passes below the toe and into the base of the slope. In most cases, base failure materializes when the strata below the base are softer than the soil above the base.

3.4. Toppling Failure

Toppling failure happens in slopes with joint sets that are vertical or nearly vertical. Kliche [45] reported that this type of failure occurs when there is a mass movement where the weight of the vector of a rock block resting on an inclined plane falls outside the base of the block. The failure is triggered once joint sets are disturbed; the slope will collapse from a small to large size, as shown in Figure 9 [57]. The movement of the failed slope in toppling is characterized by the downslope overturning, through rotation and flexure of blocks with steep discontinuities [5]. Moreover, boulders from the upper bench face may bounce off and over benches to pose a hazard at lower levels. In the area where toppling is potentially identified, the bench should be sufficiently wide to ensure that boulders cannot be bounced over the crest.

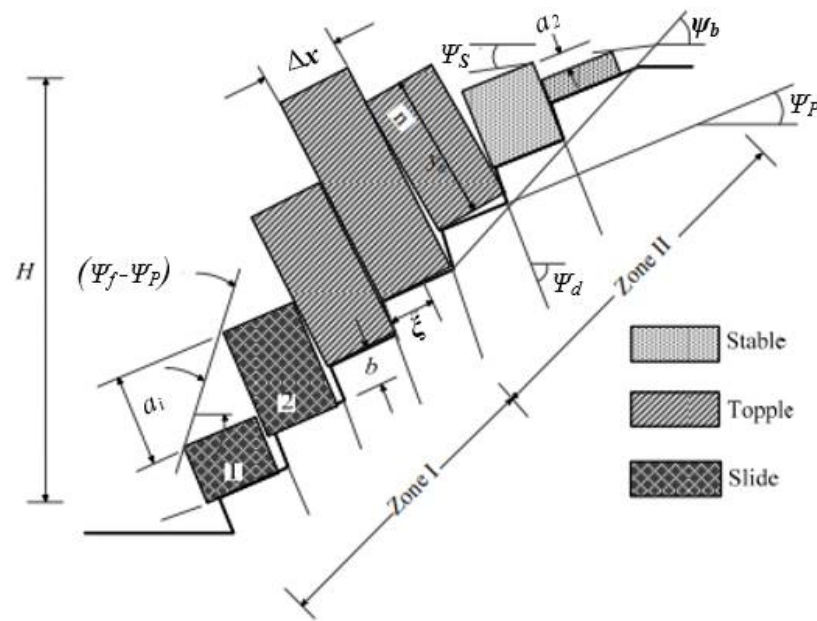


Figure 9. Geometry model of toppling slope failure (Adapted from [57]).

In major toppling instability, there will be a long warning period with noticeable events such as progressive development of tension cracks adjacent to the crest of the slope. However, there will be sufficient time to implement stabilizing measures or to evacuate the area before failures occur. The potential for small toppling failure could be sudden from bench faces, which represents a hazard during mining activities such as drilling, charging and mucking operations. According to the study reported by Sjöberg [55], the following conditions have to be satisfied in order for toppling to occur:

- (1) The joint sets must dip relatively steeply into the slope and must be able to slip relative to each other;
- (2) The rock mass must be able to deform substantially for toppling to have room to develop;
- (3) The tensile strength of the rock mass must be low to allow a tensile bending failure at the base of the toppling columns.

4. Factors Affecting Rock Slope Stability

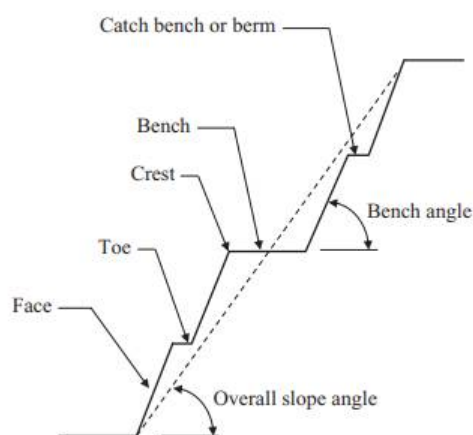
Many factors have a significant influence on the stability of rock mass slopes. Some of these factors are taken into account when analyzing the stability of slope so that their effects can be included on a quantitative judgment basis, while some factors are not considered during stability analysis. The most important factors that affect the stability of slopes in both hard and soft rocks are slope geometry, geological structures, groundwater, lithology, cohesion, and angle of internal friction, effects of blasting and mining method, and equipment used [24]. Similarly, Chiwaye [8] pointed out some factors as sources of uncertainty that lead to the failure of rock slopes, as presented in Table 2.

4.1. Slope Geometry

The geometry of slopes in open-pit mines and quarries plays a significant role in controlling the stability of the slope. Slope geometry is described as the basic slope design parameters that comprise the height, overall slope angle and area of failure surface [53]. The study reported by Chauhya and Prasad [58] indicated that the basic geometrical slope design comprises parameters such as the overall slope angle, bench height and surface area, as shown in Figure 10. The stability of the slopes decreases with an increase in the height of the pit wall and slope angle.

Table 2. Sources of uncertainty in rock slope failure.

Slope Aspect	Sources of Uncertainty
Geometry	Topography Geology/Structures Groundwater surface
Rock mass Properties	Strength Deformation Hydraulic conductivity
Loading	In situ stresses Blasting Earthquakes
Failure Prediction	Model reliability

**Figure 10.** Schematic diagram showing open-pit bench slope parameters (Adapted from [58]).

The overall slope angle plays an important role in the stability of the slope. An increase in the slope angle can increase the chance of failure occurring in the rock slope. Ideally, the overall rock slope at 45° should be considered safe and stable in open-pit mines [14]. Similarly, the curvature of the slope also influences the stability of the wall. The design of convex pit wall structures should be discouraged as it has effects on the stability of a slope. Planar failure is more likely to take place when the slope geometry is convex in a plan, i.e., the plan shape of slopes affects the potential for failure and the effects of failure. Several studies [46,59–62] have shown that geometry has a significant effect on the stability of slopes. The result of the study reported by Zhang et al. [63] showed the effects of curving surface (different geometry) slopes on the FOS and the stability of a 3D slope. In general, a curving slope surface on a steep slope shows more significant influence than that of a gentle slope.

In addition, the relationship between the curvature and slope height of the wall influences the stability of the slope. In most cases, if the radius of curvature in a concave slope is less than the height of the slope, the slope angle can be 5° to 10° steeper than conventional slope stability analysis. On the other hand, for convex slopes where the radius of curvature is lesser than the slope height, the slope angle should be 5° to 10° flatter than the conventional ones. The majority of natural and excavated slopes are not infinite in the plane; most of them are either concave or convex in configuration [46] most especially in open-pit mines where the curvature of the pit walls can affect the stability angle of the slope [64]. According to Wines [60], the stability of concave slopes is more than that of a straight slope. Due to the lack of confinement and effects of the side resistance in convex slopes, the potential failures are structurally controlled, and the stability of convex slopes is often less than that of straight slopes.

The relationship between the radius of curvature and the height of the slope is another factor that is used in the stability analysis of slopes. When the radius of curvature of a concave slope is less than the height of the slope, the slope angle can be 10° steeper than the angle suggested from the conventional stability analysis [46]. Similarly, the ratio of the curvature radius to the height due to an increase in the lateral pressure causes an increase in the stability of a slope [64]. However, practical experiences have shown that concave geometry is the most widely used type of curvature design of slope geometry, most especially in open-pit mines, narrow long pits, circular pits and in the wall at the end of the pits [60].

4.2. Geological Structure

This is an important factor to be considered in evaluating various factors that influence the stability of slopes. It is essential, not only from a safety but also from an economic point of view. A wrong approach to geological conditions during design and operations can have severe consequences in mining operations. Geological structures include fault, joints, presence of bedding plane and intra-formational shear zones that influence the stability of a rock slope. In most cases, geological structures, also known as discontinuities, control the type of failure that will take place in the rock slopes. The properties of the discontinuities include roughness, orientation, and persistence and mineral infillings such as clay material present in between rocks play important role in the stability of the rock slope. For instance, the joint orientation (dip and the dip direction) can be used to predict the mechanism of failure that will occur. The intersection of discontinuities such as joints and fractures in rocks results in instability and accidental falling of rock blocks in rock mass as a result of the actual strength of the in situ rock mass being less than the strength of the intact rock [8,61]. These discontinuities are usually several sets occurring at different directions, which causes separation in rock mass into discrete and interlocking pieces. However, intersection of discontinuities causes a reduction in the shear and tensile strength of the rock, resulting in sliding along the structural plane [65].

The geological structure and strength of rocks have a significant influence on the mechanical properties of the rock. According to Liu et al. [66], the mechanical properties of the ground depend on different factors such as stone content, rock shape, rock distribution and bonding strength. In most cases, the mechanical properties serve as input parameters for evaluating the stability of slopes and to understand the characteristics of a rock mass [67].

The initiation of tensile and shear failure in rock mass often leads to instability of rock slopes, which usually occur as a result of response from several factors, such as temperature and insolation [68], seismic loading [69], weathering [70] and precipitation [71]. In underground excavations, the rock in the roof behaves oppositely, where there are overhanging and threatening blocks or slabs remaining in their position because of the strength initiation of discontinuities, which are mainly arising from the rock bridges [72]. However, results from investigations revealed that rock bridges significantly increase with the shear strength of individual incipient rock discontinuities, especially when they are under constant normal stiffness boundary conditions [73]. The intersection of joints in rock masses results in the formation of discrete blocks with variable geometries, especially when the discontinuities are not fully continuous [74].

The main geological structures known to influence slope stability include direction of dip, intra-formational shear zones, joints, discontinuities and faults. Slope failure may occur due to failure along the structural discontinuities of intact zones or along surfaces formed close to discontinuities [75,76]. In addition to that, dip direction affects slope stability especially when the dip direction of the strata of discontinuity is similar to slope dip direction with an angle of the strike of less than 20° , which consequently triggers failure from the toe zone. Furthermore, slope failure is promoted when seepage occurs from beneath the ground into the strata, which lubricates the rock mass and consequently triggers material failure in the upper zones, leaving a planar surface [77]. Additionally, in zones where the rocks have weathered, the infiltration of water into the sediments increases

pore pressure, alters the degree of saturation, and compromises the shear strength of rock mass leading to failure [78]. The density of slope material has considerable implications on its stability, as a very low density promotes water seepage into the rock mass, while a high-density limits infiltration [79].

4.3. Groundwater

Groundwater opens up the little cracks and activates the force on blocks and wedges that cause instability of slopes in rocks. The water pressure on potential failure planes reduces the normal stresses across planes, which in turn reduces the frictional strength on these planes. Consequently, it increases the thrust and driving forces, which in turn controls the stability of the slope.

Unusual ingress and distribution of groundwater can enlarge the spacing between joints, which can result in the failure of rocks when subjected to gravitational forces. According to Simataa [5], when the tension crack in the rock mass is filled with water, there will be a linear increase with depth and total force, as shown in Figure 11. From Figure 11, Z is the depth of the tension crack, W represents the weight of the wedge rock, U is the uplift force due to water pressure on failure surface, V is the water pressure in the tension crack, and (φ) represents the angle of internal friction of sliding. It is assumed that the water moves in between the tension crack and the base of the block, which causes distribution along the base of the block. The distribution of water becomes an uplift force U , which reduces the normal force acting across the surface.

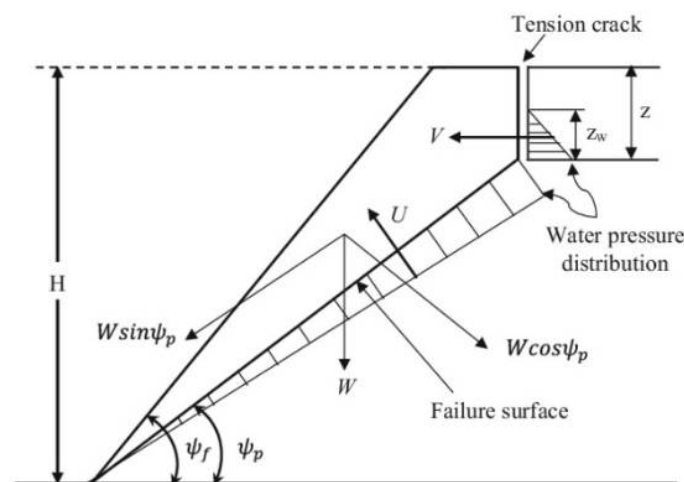


Figure 11. Effects of water pressure in a crack (Adapted from [80]).

According to Liu and Li [81], the ingress of water is one of the factors that triggers landslides. Based on statistics, over 90% of landslide and slope failures are caused by water-related issues. The outcome of their investigations revealed that water seepage, rainfall, and water level fluctuations are the major mechanisms of landslide failure.

Prakash [53] stated that the presence of groundwater alters the property of the rock and reduces the normal effective stress and alters rock strength parameters such as cohesion and friction. Moreover, the effects of the groundwater pressure and transient flow of water within the rock and soil affect the pore pressure conditions, strength, and deformation behavior of the rock [17]. Additionally, the presence of water pressure within the rock enlarges the rock pores, which decreases the compressive strength, particularly where confining stress has been reduced.

There are various computer codes used to analyze and assist in assessing groundwater pressure. Numerical modeling techniques such as FLAC/FLAC 3D, UDEC/3DEC, and PHASE2 are capable of performing coupled hydro-mechanical analyses [8]. This numerical modeling software can predict pore pressure drops due to volumetric expansion associated

with the excavation of a pit. However, modeling of groundwater pressure and expansions with numerical modeling software is cumbersome.

Hydrogeological conditions of the rock mass influence slope stability, which normally manifests through ground seepage from an underground water aquifer, surface water, or precipitation from stormwater or snow thaw. The influence of groundwater on slope failure can generally be experienced in three major avenues. To begin with, the presence of water in the rock mass creates hydrostatic pressure, which tends to lift present rock blocks, thereby posing lateral pressure on present discontinuity planes. Consequently, the imposed lateral pressure reduces plane resistance against sliding, as well as the shear strength through a reduction in normal stress on the discontinuity plane, which loosens rock blocks, resulting in slope failure. Furthermore, depending on the nature of the groundwater, such a condition may alter the physical and chemical compositions of discontinuity fillings, thereby reducing the shear friction and ultimately leading to slope failure [82].

4.4. Lithology

The lithology of rock mass is an essential factor that influences the failure process of rock slopes in open-pit and quarry operations. In most cases, the physical characteristics of the rock mass show the potential areas that are prone to failure. The mineral constituents forming the rock control the mechanical properties and the behavior of the rock mass and also determine the strength of the rock mass [14,83]. McNeilly et al. [84] stated that the porosity, mineralogy, density, and degree of cementation are the rock properties that can influence the strength of rock. The mineralogy dictates the rock type, strength of the rock, color and other properties of the rock. According to Yasir et al. [85], the strength properties of the rock increase with the degree of cementation. The mineral composition and the physical properties of the rock mass affect the strength of the rock, thus influencing the stability of the slope. In the design of rock slope, pit high wall that contains weathered rocks or alluvium rock materials will have low shear strengths and a high propensity to further weathering through erosion. Despite the roles cohesion and frictional angle play in the stability of rock slope by opposing the effects of the magnitude of the shear stress, there are some limitations of these strength parameters. In most cases, the estimated value of these parameters contains errors during calculations that influence the uncertainty in the result [86]. Likewise, Sullivan et al. [87] stated that the friction angle is influenced by the grain sorting, grain size and grain angularity, while the chemical bonding and cementation also affect the cohesion.

4.5. Cohesion and Angle of Internal Friction

Rock strength properties such as cohesion (c) and angle of internal friction (φ) are used in evaluating the FOS of rock slopes during the design stage. The shear strength is a key mechanical characteristic of rock–soil related to slope stability assessment. The cohesion and friction angle values are used to describe the shear strength of the rocks. These parameters are determined in the laboratory through a triaxial compression test. The angle of internal friction in a rock defines the ability of the rock to withstand shear stress [53]. However, the particle size of the rock affects the angle of internal friction; i.e., the larger the particle size, the larger the angle of internal friction. In addition, high water content, undercutting slopes, ground vibration, and alternating expansion by wetting and contraction by dryness of water reduce the strength of cohesion in a rock mass.

The cohesion and friction angle of rock–soil aggregates are influenced by the particle size distribution characteristics and other conditions, especially the water content [88]. However, the lower the cohesion in a rock mass, the lower the stability of the slope, and the higher the internal frictional angle of rock, the higher the slope wall will be. Therefore, it is necessary to evaluate the cohesion and the angle of internal friction from the core specimen during site investigation to determine whether the slope will be stable or not. In analyzing the stability of the slope both in rock and soil, the cohesion and the angle of internal friction must be taken into account as these properties control the shear strength of the rock [89].

4.6. *Blasting*

Poor blasting in open-pit mining operations is detrimental to rock slope stability, not only due to blasting-induced vibrations but more largely because the rock behind the slope face can be fragmented and loosened [5]. The ground vibration that occurs as a result of poor blasting causes redistribution of stresses in the rock slope, which eventually leads to a dynamic acceleration of materials, which in turn causes instability in the slope plane [14]. Similarly, the effects of poor blasting largely result in the creation of discontinuities such as fractured zones, faults, joints, and fissures in rock slopes [90]. Poor blasting reduces the cohesion and creates the potential for ingress of water, which causes further loosening of the rock mass.

Another implication of poor blasting is that it reduces the bench-face angle and eventually leads to ground vibration that could potentially cause failure in a rock mass [53]. During blasting operations, natural cracks and fractures in a rock mass structure are extended by additional stresses induced by the blasting, and therefore the shear strength of the rock mass is significantly reduced, thereby causing instability of the rock mass.

Over the course of detonation, seismic waves are produced, which spread in the form of a stress wave within a rock mass. The effects of this distributed seismic wave on the geometry of a slope will produce vertical and horizontal constant acceleration that will result in an unstable slope. When the stress wave is higher than the tensile strength of the rock, there may be potential damage of the rock mass as a result of seismic waves, elastic vibration and elastic stress waves caused by poor blasting and the presence of fracture zones, thus leading to slope instability and other damages. However, a combination of the effects of poor blasting with the external loading can also create a surcharge on the crest of the benches.

4.7. *Mining Method and Equipment Usage*

In mining operations, the surrounding rock mass around excavation develops deformation due to changes in the in situ stress field conditions. During excavation, natural slopes may face deformation as a result of the reduction in shear strength, which can lead to slope failure [91]. The rock mass movement may continue if no solutions are implemented on the cut slope. The overall slope stability must be considered when selecting mining methods and equipment usage. Similarly, the state of in situ stress field conditions described by the magnitude and orientation of the principal stress must be taken into account during the excavation process [92]. In the open-pit mining method, the highwall slopes are designed to be steeped due to the increase in slope height that is prone to the buckling mode of failure [53]. Additionally, the movement of heavy equipment during mining for mine haulage and other operational equipment such as rigs give rise to an increase in surcharge, which in turn increases the forces that trigger the downward movement of the slope.

4.8. *Stresses on Slope*

The presence of field stress conditions in rock masses has a significant influence on the stability of a slope [93]. The in situ field-stress condition of a rock mass can be used to investigate the behavior of slopes regarding the height of the wall and provide a summary of several failures. Although the impact of in situ stress fields can be less significant in small slopes, it has to be considered for the design of a very large slope. The advantages of using the stress analysis approach to evaluate the stability of slope include modeling of the excavation sequence, modeling of deformation, modeling of water pressure and flow in the rock mass and modeling of the progressive development of yield and failure zones. However, the stress can be advantageous as it provides confinement to the rock mass [94]. The confinement assists in stabilizing the slope. Hoek et al. [19] stated that the lateral stresses during rock excavation have an important influence on the stability of the slope. At high confinement conditions, most of the joints reach their residual aperture, and

as a result, the stiffness of the rock is no longer affected by the increment in the confining stress [95].

The presence of discontinuities in rocks influences the shear strength, which in turn determines the stability properties of the rock mass. The effects of discontinuities (geological structures) significantly influence the load condition of the rock mass. Notably, natural discontinuities such as joints and faults are evident in rocks that influence the mechanical behavior of the rock and also create stress in the anisotropy, heterogeneity and scale effects. The mechanical properties of a jointed rock mass are controlled by the geometry and properties of the discontinuities. Additionally, the physical properties of discontinuities such as friction, compressive strength, weathering and the presence of infilling materials (clay) affect the mechanical behavior of the rock mass. This is more reason why the joint network and other geological structures reduce the strength of the rock mass and increase the deformability of the rock. Therefore, it is important to investigate the properties of joints to be able to accurately determine the stability factor of slopes. Moreover, knowing the joints network will enable a safe and economic design of the slope and stability analysis [96]. The nature of the jointing, such as their orientations, length, the distance between joints and joint spacing, also influence the stability of slopes.

During site investigation, discontinuities are classified according to how they are formed. In most cases, discontinuities with the same category usually have the same properties in terms of their shear strength property, which can be used to predict the stability conditions of the excavation. Evaluation of joints network and the strength properties can serve as the guide for designing a stable slope and other rock engineering applications. It is assumed strength properties of jointed rock masses depend on the properties of the intact rock pieces and the freedom of the pieces of the slide and rotate under different stress conditions. Ryan [97] stated that the strength of jointed rock masses depends on the strength of the joints, the strength of the intact rock locks between the joints and the degree of interlocking between the rock blocks. For instance, in jointed rock masses, it is expected that the water pressure in the joints will continue to increase and dissipate faster than the pore pressure of the intact rocks, most especially in rocks where the porosity and permeability are low.

In slope stability analysis, the joints are too many to be taken into account individually; thus, an approximate property is usually considered. Other influences of discontinuities are represented by the shape, the block size and the strength of the rock mass. Likewise, the importance of taking into account joint conditions in the rock mass is that the joint information is used to highlight the failure mechanisms as well as the failure intact between joints [98]. According to Cundall et al. [99], the compressive strength of the rock is the best described property of the rock against shearing under confined conditions. Recently, the advancements in technologies have brought about accuracy in the method of predicting slope stability in jointed rock masses. The availability of various computer programs can simulate different stability scenarios in jointed rock masses. However, the application of computer programs such as the finite element method (FEM) and the discrete element method (DEM) have proven to be effective in analyzing slope stability. These approaches make use of the shear strength reduction (SRR) methods to determine the stability factor in a jointed rock mass. However, to use the computer programs for jointed rock mass, it is necessary to consider the joint patterns to obtain an adequate representation of real rock configuration. That is, when all the joint components are considered in the model, it is possible to predict the slope failure mechanism and joint movement that can influence the sliding of the rock mass.

5. Slope Failure in Mining Operations

Slope stability is a crucial consideration in the management of mining operations as slope failure compromises the economical and safety aspect of production. Due to the increase in demand for mineral resources and the invention of more sophisticated mining methods as well as machinery, most mines are designed to reap more resources from

deeper or steeper mines. Such mines have a higher angle of inclination, which make them more susceptible to slope failure. Slope failure can lead to injury of personnel, damage of mine machinery, and disruption of operations, which all negatively impact the mining performance. In order to prevent such a hazard from occurring, it is imperative that extensive geotechnical studies are conducted to ensure that FOS is within a tolerable range (>1) far from failure. In cases where the FOS is very low, more attention should be given to monitoring such slopes to prevent slope failure.

Slope failures are common in open-pit mines and become unavoidable as excavation is becoming deeper and, as such, more difficult to manage. A review of existing failed slopes around the globe provides a better understanding of the failure modes and factors to be considered in controlling the mechanisms that trigger mass movement of materials in slope engineering [55]. Mitigation of slope failure risk requires an in-depth understanding of structural geology, rock mass properties, influence of groundwater pressure and other external forces in the area [100]. Failure in rock slopes occurs due to many reasons, which have been discussed earlier in this paper. During excavation, stripping excavation walls are required to be as steep as possible for operational efficiency. Failure may occur if the slope design is over steeped [101], although most failures in open-pit mines are triggered by fracture and shear on existing defects. Structures inside the rock mass interact in different ways as the rock deforms, and thus affect the general behavior of the rock. In addition, understanding the in situ stress field pattern is critical in understanding the deformation processes in open-pit mines. For instance, mining of ore using open-pit mining methods expose the surface and the rock adjacent to the pit wall; therefore, it becomes unconfined in the direction normal to the slope face over large areas [102].

When a rock mass comprises blocks separated by joints, shear zones and bedding planes, sliding on multiple discontinuity sets as well as tensile and shear failure are bound to occur [103]. For instance, the report of the slope failure that occurred at Yanqianshan iron mine in China confirmed that the eastern part of the slope collapsed as a result of deformed strata in the area [104]. The collapsed area comprises of eight build-up stages that are represented by actions from point (a) to point (g). These stages are classified as a cave rock zone, cracking zone, toppling zone, and sliding, as shown in Figure 12. Based on the report of the investigations, the process of initiation and development of failure zones were categorized into three stages: (i) overlaying area above the goaf, (ii) initiation of the collapsed strata sliding into the pit to form a small landslide and (iii) a large landslide occurring as a result of mining activities and creeping of rock that triggered the mass movement in the northeastern phyllite slope. The disturbance produced by underground mining activities initiated the potential sliding body on the northern phyllite slope and the retaining wall structure gradually tended towards instability.

Similarly, another slope failure was reported in Western Macedonia in Northern Greece as a result of sliding along the sub horizontal direction, unfavorably sloping as shown in Figure 13. From the analyses, the stability was governed by the interface between lignite and an underlying stiff presence of plastic clay or a marl layer that are very close to the bottom of the slope where there is a significant amount of stress. Based on the study reported by Zevgolts et al. [105], some factors such as groundwater conditions, pit geometry and shear strength of the critical interfaces between clays and lignite influenced the stability of the slope.

In addition, a massive landslide at the Grasberg gold and copper mine in Indonesia, which forced the pit to suspend operations, was reported by DTE [106]. In October 2003, a fatal accident happened at the southern wall of the open-pit mine, which collapsed and claimed the life of eight people and injured another five people. This incident moved 2.3 million tons of rock and mud down the slope, thereby engulfing mineworkers and heavy equipment. Similarly, a rock mass slippage happened in the year 2000 at the same mine when the overburden was washed by heavy rainfall into Lake Wanagon [107]. The main cause of material movement was attributed to ingress of groundwater from a nearby water table, coupled with an abnormally high rainfall season.

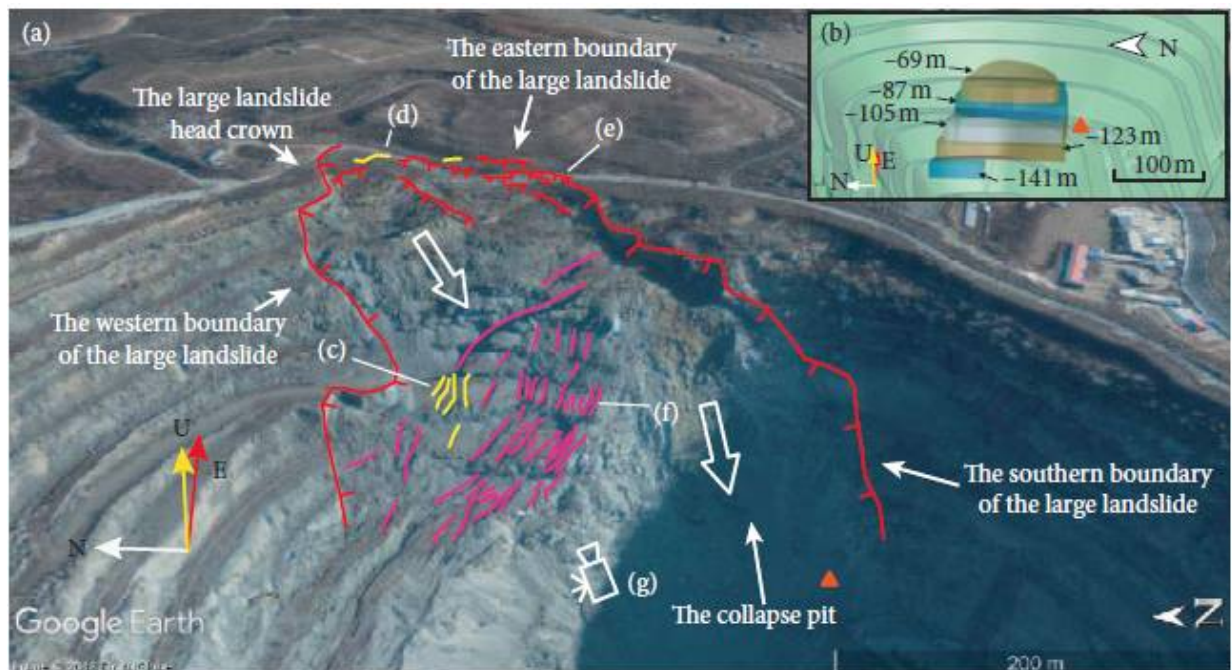


Figure 12. Image of collapsed phyllite materials in the northeastern slope (Adapted from [104]). (a) cracks initiation point (b) location of the mining area (c) Tension cracks from the western boundary of the landslide (d) Initial collapse area (e) Tension crack at the eastern boundary of the landslide (f) Collapsed pits (g) Google Earth monitoring technique.

Sliding of portion of Lava Lignite mine



Figure 13. Sliding portion of lava lignite mine in Greece (Adapted from [105]).

Recently, another landslide happened at the Gamsberg mine located in the northern Cape Province in South Africa. The open-pit mine is operated by Vedanta zinc interna-

tional (VZI), which currently produces 40,000 tons of ore per month [108]. According to Petley [109], the landslide incident that occurred at the south pit of Gamsberg was described as a “geotechnical failure”. According to the report, eight mine workers were rescued after the incident, while two people were still missing at the time when the report was published. The failure happened across the road that provides an access ramp. The incident appears to have occurred above the access ramp, but the debris reached the pit floor, as shown in Figure 14. After the failed slope, Vedanta Zinc International (VZI) suspended all mining-related activities at Gamsberg to carry out a proper investigation into the slope failure.



Figure 14. Image of Gamsberg mine landslide (Adapted from [109]).

Another notable incident of slope failure in mining was the movement of the Chiquicamata slope in Chile, which was triggered by an earthquake [110]. In this study, the authors stated that the mass movement progressed at a more or less steady rate until it fell in 1968. However, the kinematics of the slope movements were not clear but seemed to involve load transfer from the north block to the south block dominated by discontinuities. However, due to the presence of discontinuities, the cohesion that was supposed to prevent the movement of the slope was quite small, with little intact rock. The failure started from the north, i.e., the upper part of the slope, to the south block, which is the toe of the slope, as shown in Figure 15.

Possibly the largest landslide of all time was the event that took place at Kennecott Utah copper’s Bingham Canyon Mine in the United States of America. This open-pit mine is regarded as the largest man-made excavation in the world, which measures 1 km deep by 4 km wide [111]. The Bingham Canyon landslide occurred on 10 April 2013 in the canyon open-pit copper mines, causing a massive movement of the upper half of the northern pit wall. The slide filled the mine floor with thick debris, as shown in Figure 16. Before the incident, the geotechnical surveillance teams and mine operators were fully aware of the instability and evacuated the mine workers and equipment from the unstable zones. Thus, no fatalities or injuries were recorded. According to Pankow et al. [112], the seismograph showed that the landslide was triggered by several small earthquakes. Six days after the landslide event, 16 additional seismic events were detected in the mine area. The study by Hibert et al. [113] indicated that the slide caused the onset of the mobilization of the second slide at a higher elevation.



Figure 15. A large scale image of some portion of Chiquicamata slope (Adapted from [1]).



Figure 16. Image of landslide at Kennecott Utah Copper's Bingham Canyon Mine (Adapted from [112]).

The failure mechanisms driving the instability and causes of failure are presented in Table 3.

Table 3. List of failed mine slopes.

Country	Location	Names of Mining Company	Mode of Failure	Causes of Failure	Sources
Botswana	Central District	Letlhakane mine	Toppling	Presence of tension crack formation, crack widening and extension	i
Canada	British Columbia	Afton Mine	Wedge, Toppling and circular failure	Multiple failures occurred as a result of intersection of discontinuities	j, r, a
	British Columbia	Brenda Mine	Toppling	Intersection of joint sets	q, a, j
	British Columbia	Cassiar Mine	Toppling	Presence of shear zones, faults and sets of discontinuities	j, k
	British Columbia	Highland Valley Copper	Toppling	Steeply dipping joints, increase in groundwater pressure and melting of snow	t
	British Columbia	Lonex Pit at Highland valley	Toppling	Groundwater condition, Steeply dipping faults	o
	British Columbia	Higmont	Planar	Structural discontinuities, precipitation, run off, poor quality and low strength rock mass	o
	Vancouver	Island Copper	Wedge and Toppling	Large fault zone passing through a weaker rock mass	l
	Quebec	Jeffrey Mine, Asbestos	Wedge and Planar	Intersection of several thick shear zones and smaller scale discontinuities	t, c
	British Columbia	Nickel Plate Mine	Wedge	Steeply dipping joint sets and faults	t
	Mongolia	Changshan hao open-pit	Wedge and Toppling	Presence of faults and joints	s
China	Shazhenxi	Qianjiangping	Planar	Increase in water level, poor geological structure and continuous rainfall	h
Norway	Hange i Dalane	Tellness Dagbrudd	Wedge	Heavy rainfall	n
Mexico	Calama, Antofagasta	Chiquicamata	Toppling	Presence of fault zones	f, p
Spain	Seville	Aznacollar Mine	Complex	Presence of tension cracks, Heavy rainfall, groundwater pressure	g
Sweden	Kiruna	Kirunavaara	Rotational	Presence of tension cracks	u

Table 3. Cont.

Country	Location	Names of Mining Company	Mode of Failure	Causes of Failure	Sources
United States of America	Utah	Bingham Canyon Mine	Rotational, Planar	Rise in water table, fractured rock mass with minor joints and larger fault structure	t, v
	Nevada	Carlin Trend	NA	Presence of wider fault zones and clay infillings	v
	Arizona	Cyprus Bagdad and Sierrita	Toppling	Presence of steeply joint sets	j
	Nevada	Liberty Pit	Wedge	Intersection of joint sets	c
	Nevada	Veteran—Tripp Pit	Wedge	Intersection of faults, presence of clay gouge in fault zones	m
	Nevada	Kimbley pit	Wedge	Presence of flat sipping fault, High water pressure	b
	Arizona	Twin Butes	Toppling	Numerous faults and several joints	c
South Africa	Limpopo	Palabora Mine	Wedge	Presence of faults and set of joints	t, d
	Mokopane	Sandsloot open pit	Planar and Wedge	Presence of set of joints	e
Zambia	Chingola	Nchanga Open Pit	Wedge	Intersection of joint sets, abnormally rainfall, weathering	u

Source codes: a: Blackwell and Calder [114]; b: Blake [115]; c: Brawner [116]; d: Brummer et al. [117]; e: Bye [118]; f: Call et al. [119]; g: Golder Associates UK Ltd [120]; h: Jian et al. [121]; i: Kayesa [122]; j: Martin [123]; k: Martin and Mehr [124]; l: Mathis et al. [125]; m: Miller [126]; n: Nilsen and Hagen [127]; o: Newcomen and Martin [128]; p: Rapiman [129]; q: Pritchard and Savigny [130]; r: Reid and Stewart [131]; s: Ren et al. [132]; t: Stacey [133]; u: Sjoberg [54]; v: Zavodni and Mccarter [134].

However, events of landslide and rock slope failure in underground mining environments have not yet been fully researched [18]. In most cases, slope failure in underground mine spaces happens during the transition from open-pit to underground mining methods. The transition from open pit to underground usually happened to exploit minerals from deep ore deposits. When mine deposits start from the shallow subsurface and extend to a great depth, sequential use of open-pit and underground mining is an efficient and economical way to maintain mining productivity.

An example of a failed slope during the transition to underground mining was reported by Brummer et al. [117] for Palabora mine in South Africa. Parabola mine was changing their method of extraction from open-pit to the underground block caving method as the ore extraction was getting deeper, which was no longer economical for the mine. During the transition, there was a failure at the north wall which, is evident by the daylight caving of the zone as a result of intersections of four main faults crossing the pit and three dominant joint sets present at the mine [117].

6. Factors Required in the Design of a Stable Slope

The essence of strengthening a rock slope is to prevent rock mass movement and premature closure of mining operations. When making an attempt to stabilize a rock slope that is prone to failure, many solutions are opened to the geotechnical engineering team to decide what to do. According to Niroumand et al. [135], the method used in preventing slope failure includes a change in geometry, rock–soil drainage, rock material nailing, turfing, shotcreting, geotextiles and the application of retaining the wall. Similarly, Roux et al. [136] applied techniques such as a regular collection of geotechnical mapping and logging data, the collection of laboratory strength test data, adherence to good housekeeping and the use of a hazard plan and evacuation procedure to achieve a stable slope. The study also implemented precautionary measures, such as surveying the actual excavation profile, measuring the change in groundwater level with a piezometer instrument, monitoring the seepage flow from the toe drains and face, measuring the damage caused by blasting to the rock mass behind the mine design line, inspecting the blast face and crests to allow removal of loose materials, and periodically installing bolt supports, as recommended by the geotechnical engineering team.

The study reported by Singh et al. [137] indicated that anchored tensioned rocks were installed, along with scaling and trimming of loose rock blocks, to prevent further slope failure. The study mentioned that shotcrete can be sprayed on the slope face with proper drainage galleries to prevent the development of pore water pressure. These techniques protect the slope from degrading agents such as rainwater and serves as part of an effort to strengthen and improve the ground conditions, which in turn increase the FOS and improve the stability of the slope. Another method to stabilize a rock slope involves the use of a leguminous tree planted on the rock slope to control hydrological factors such as erosion and run-off water that have the potential to trigger rock mass movement in rock slope engineering [138]. The outcomes of the study showed that the *Leucaena Leucocephala* leguminous plant has the capability to prevent slope failure in open-pit mining operations.

The use of an early warning system (EWS) is another approach to prevent the risk associated with slope stability. Roux et al. [136] confirmed that the installation of smart technologies such as extensometers aid in monitoring and checking the source of rock slope failures. In deeply weathered rock, the presence of cracks and faults are inevitable and need close monitoring. Extensometers and other smart systems can be installed in open-pit mines to monitor cracks and generate early warning systems. An extensometer integrated with other EWS was installed at Navachab Gold Mine in Namibia to give an early warning prior to failure. A study reported by Roux et al. [136] indicated that extensometers set off alarms an hour before failure. A similar study reported by Karam et al. [139] indicated that warning systems in mines should be installed in affected areas and serve as a guide to passive or active countermeasures. The EWS is designed to reduce threat, as shown in Figure 17.

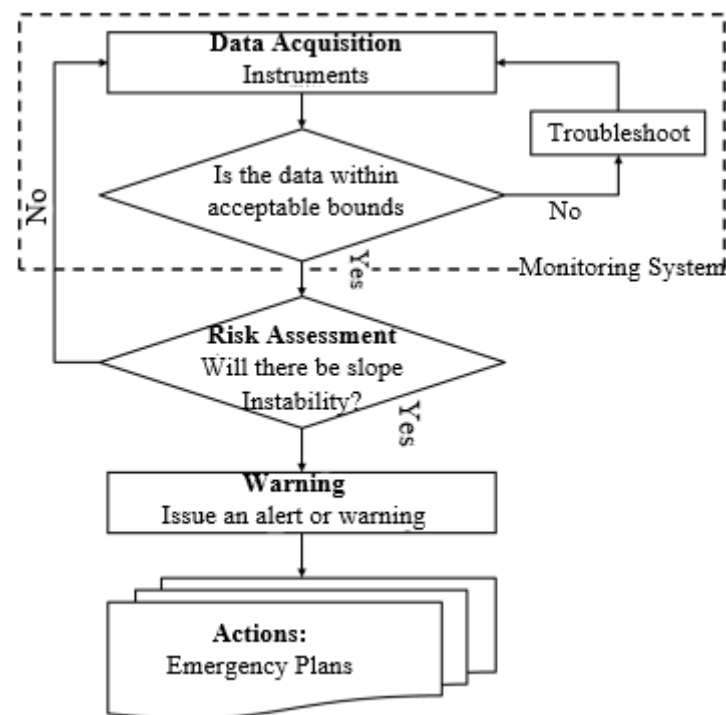


Figure 17. The flow chart for early warning system (Adapted from [139]).

6.1. Methods to Improve Slope Stability

There are several ways of achieving stability or strengthening rock slopes in mining operations. These include the construction of drainage and pump installation, slope monitoring, ground control with improvement in geological structures and the application of reinforcement.

6.1.1. Drainage Construction

Since water is one of the factors that promote failure in rock slopes, mine water management systems should be a priority. The presence of groundwater in open-pit mines often creates problems by reducing the stability of pit slopes. Most of the problems are caused by pre-pressure and hydrodynamic shock from blasting operations [140]. The presence of pore pressure on rock mass reduces the shear strength and seepage pressure, and water in the tension cracks causes an increment in the unit weight, which in turn increases the shear strength of the ground.

A number of researchers confirmed that drainage construction around the mines can reduce the impact and occurrence of groundwater in a mining environment. The three main objectives of drainage systems in mines are to keep working areas dry, stable, and safe, to ensure pit floor workability, and to lower the hydrostatic pressure and increase the effective stress of soil to improve stability [141]. Some of the drainage systems may include the construction of channels, water collection sumps and pump stations with pipelines to divert water from the surface. In addition, drains may be constructed within the surface to remove excess seepage. Hence, it is necessary for the geotechnical engineering team to know the hydrogeological conditions of the mine. This will assist in the selection of pumping systems required in the mine.

6.1.2. Slope Monitoring

Monitoring of rock slopes is necessary to determine how the rock structure behaves during excavation and if they are a threat to safety. This has been a key technique used to assess instability in rock slopes. The slope monitoring approach can be of value to provide information that is useful in data collection, recording and qualitative and quantitative anal-

ysis. The effectiveness of any monitoring system depends on the ability to give warnings before rock mass movement or failure takes place [142]. Traditionally, there are geotechnical instrumentations (piezometers, crack meters, tiltmeters, borehole extensometers, and stress meters) available for the monitoring of slopes in mining and civil engineering. Despite the contribution of these instruments in the monitoring of rock instabilities, they also have some limitations.

Over the years, there have been improvements in geotechnical monitoring instrumentations, which include the use of remote-sensed technological tools. These instruments are commercially available to monitor rock mass movement in a mining environment and are cost-effective. Examples of these are the integration of synthetic aperture radar (SAR) with optical images and interferometric SAR (InSAR), which are currently being used to characterize instabilities in slopes. Advancement in remote sensing technology systems has brought about differential synthetic aperture radar (DInSAR) with high-resolution image processing, which is also being used to monitor instabilities. Similarly, there is a ground-based radar monitoring instrument known as linear SAR (LISA), which is capable of assessing the deformation of an unstable area in slopes that are characterized by high radar reflectivity [139]. Other advanced geotechnical monitoring instruments are light detection and ranging (LiDAR) and optical satellite images.

6.1.3. Ground Improvement with Enhancement of Geological Structures

The interpretation of the data acquired during site investigation provides information about the structure of the rock mass, strength of the rocks, planes of weakness, and the range of their strengths. This will provide adequate information on the relationship between slope parameters, such as the spatial relationship, face inclination of the rock, and geometrical dimensions of each of the individual elements of a particular sector of the mine shell, such as ramp and geotechnical berm width, bench spill berm width, individual slope height, and slope angle, slope bench, etc.

Apart from the design parameters, the geotechnical engineering team must be familiar with the geology of the mine, i.e., the discontinuities and engineering properties of the rock mass that can influence the stability of the slope. Karama et al. [139] argued that gravitational load is the most important load affecting the stability of the mine and, notably, the shear strength of the ground, which confers major resistance to failure. To prevent further damage of the rock mass, the shear strength of the ground must be enhanced to strengthen and protect the ground. This strengthening can be completed with the application of backfill, rapid yielding properties, the construction of a retaining wall, the spraying of shotcrete, and application of reticulated micropiles.

6.1.4. Installation of Reinforcement Units

The application of reinforcement in rock slope is a viable approach to increase the stability of unstable slopes. The installation of various support systems increases the shear strength of rocks and reduces sliding effects along the slip surface [143]. The essence of reinforcement in weathered rock or soil is to stiffen the base and to reduce shear stress magnitudes. The two most commonly used support systems in rock slope and slope engineering measures are rock bolt fame and anchor cable fame [144]. These reinforcement tools have proven to be effective in resisting the shear stress in rock mass deformation by transferring the load to the bounded rock so that resistance is provided by the rock to balance the deformation. During the installation of bolts, the effects of the inclination angle of bolts must be defined by the designer of the slope for effective reinforcement. According to Sazzad et al. [145], the FOS of slopes increases with an increase in the angle of inclination. However, the FOS value depends on the overall angle of the slope. Therefore, the relationship between the slope angle and inclination angle for a maximum FOS should be enhanced, i.e., the positioning of the bolts is a key factor in reinforcement design. In addition, when installing a bolt to resist dip bedding slope, the failure mechanism and process occurring in such slope need to be considered. A great number of researchers have

acknowledged the effectiveness of bolts as reinforcement tools in controlling the movement of discontinuous layers that are subjected to shearing. The installation of rock bolts in unstable zones can be regarded as one of the major techniques used to improve and control the unstable ground in open-pit mines.

6.2. Role of Artificial Intelligence in the Management of Slope Failure As a Reflection on the Current State of the Art

The monitoring and evaluation of slope stability in mining operations is a crucial necessity to avoid potential damage to both the personnel safety and financial base of mining companies. Despite the effort to reduce slope failure, the geotechnical phenomenon is known to be complex, comprising numerous factors such as ground conditions, geological activities and human actions, which make the prediction of slope failure challenging [146,147]. More so, these factors are dynamic and ever-changing, making it cumbersome to continuously measure them. However, the invention of artificial intelligence (AI) has greatly aided engineers in forecasting possible slope failure using detailed analysis rather than solely relying on phenomenological models [148].

The study by Kothari and Momayez [148] compared the prediction performance of inverse velocity (IV) and the artificial neural network (ANN) model to forecast slope failure of an open-cast mine. Twenty-two datasets were collected using radar equipment, and we developed a double-layered feed-forward ANN in the MATLAB environment. The output from the study indicated that ANN prediction was 86% accurate compared to IV. A total of 82% of the slope failure predictions indicated that the slopes were safe, while 18% indicated that the slopes were unsafe. The unsafe predictions were approximated within 5 min before actual failure, proving that the ANN model gave a safer prediction compared to IV. Another study by Chebrolu et al. [149] utilized 46 datasets (23 obtained from wet slopes and 23 obtained from dry slopes) to predict the FOS of a slope using multi-gene genetic programming (MGGP) and multi-adaptive regression spline (MARS). Thirty-two datasets were used in training the models, and fourteen datasets were used in testing the models. Despite both models proving to have an accurate prediction, MGGP has a better prediction performance, with R-values of 84.38% in training and 85.71% in testing, compared to MARS with R-values of 81.25% in training and 85.71% in testing.

To establish an accurate prediction model for determining the slope failure of a mine in Vietnam, a study by Bui et al. [146] integrated the M5-rule and genetic algorithms to develop a novel prediction model that was then compared with conventional AI models, including ANN, support vector regression (SVR), the firefly algorithm (FFA), the imperialist competitive algorithm (ICA), artificial bee colony (ABC), and the genetic algorithm (GA). This study utilized bench height, soil unit weight, cohesion, angle of internal friction, and slope angles as input parameters to forecast the factor of safety against failure. The results of this study indicated that prediction performance from the M5-rules GA model gave the best accuracy due to its enhanced optimization prowess. Another study by Du et al. [150] utilized a ground-based interferometric radar (GB-SAR) to record 150 datasets in the Anjialing open-pit coalmine of China. Twelve input parameters (slope shape coefficient, deformation rate, reverse deformation rate, deformation amplitude, rainfall, temperature, atmospheric pressure, relative humidity, wind speed and direction, and groundwater temperature and level) and one output variable (deformation) were used to develop five prediction models. These models included backpropagation, NN, support vector machine (SVM), recurrent neural network (RNN), adaptive neural fuzzy inference system (ANFIS), and relevant vector machine (RVM). From this result, it was evident that not all models can be reliable in the prediction of slope failure due to high error values. The error values for each model were 4.122 mm for BPNN, 3.612 mm for SVM, 1.660 for ANFIS, 0.578 mm for RNN, and 0.442 mm for RVM. RVM had the lowest root-mean-square error value (RMSE) of 2.64, while BPNN had the highest RSME value of 4.58.

In addition, a study by Ferentinou and Fakir [151] developed a BP-NN model using 141 databases obtained from worldwide cases of surface mines and eighteen (18) input

variables, including environmental factors, rock quality, rock mass characteristics, rock stresses, hydraulic profile, presence of geological features, dimensions of slopes, blast design and previous instability occurrence. This study established slope stability indices, where all slopes were examined to predict failure. The results obtained indicated a mean square error value of 0.0001 converging at 98%, proposing the utilization of BP-ANN as a reliable tool to predict slope failure in feasibility studies. To evaluate and monitor the slope stability of open-cast mines, Luo et al. [147] developed a particle swarm optimization-cubist algorithm (PSO-CA) to forecast the factor of safety of a Vietnamese mine. This model used five input variables, including bench height, angle of slope and internal friction, cohesion coefficient, and specific weight of the material. The output from this model was then compared with the output obtained from the prediction of the same variables using SVM, classification and regression tree (CART), and k-nearest neighbor. Performance comparison of the models inferred that PSO-CA had the lowest error values (mean absolute error (MAE) of 0.009 and root mean square error (RMSE) of 0.025 and a high correlation coefficient R-value of 0.981. The SVM, CART, and k-NN produced poor prediction performance with MAE values of 0.014 to 0.038, RMSE 0.030–0.056, and R 0.917–0.974.

The reported studies that have utilized AI in determining factors of safety in mines have proven to be efficient and effective in accurately forecasting slope failure before the hazard occurs. Moreover, the models are endowed with the ability to handle large amounts of data at a given time and execute predictions at a high rate compared to conventional stability analysis techniques. The models are designed using various factors known to affect slope stability in order to map out FOS. Various AI models have been used to predict slope failure in mines, but limited studies have been conducted to compare and validate the most accurate model for such a task. Therefore, in order to establish the most robust, versatile, and reliable model, more comparative studies need to be conducted to improve prediction performance.

7. Concluding Remarks

Stability analysis of slopes in open-pit mines and quarries is extremely important from both economic and safety points of view. The effect of unstable ground cannot be over-emphasized as it may lead to the temporary or permanent closure of the mine depending on the level of damage. Instabilities usually occur where there is a presence of geological discontinuities such as fractures, cracks, faults, unfavorably oriented bedding planes, etc. Rock slope failures are triggered when the shear stress exceeds the shear strength of the rock mass. Several factors, such as geometry of the slope, groundwater condition of the rock, lithology, geological structures, cohesion and angle of internal friction, effect of blasting, mining method and equipment selection, have been declared to influence the failure of rocks. The effects of all these factors must be considered during the planning and designing stage of the mine, not only that these factors have effects on the design, but that they also influence the engineering judgement on the stability of the slope. Several techniques, such as construction of drainages, slope monitoring, application of reinforcement and improvement of geological structures, have been used over the years to improve and maintain the stability of the rock slope.

Advancements in technology have brought about improvement in slope monitoring techniques and provide an understanding of slope dynamics through the assessment of stability over time. The accurate prediction of slope failure is an important task in active open-pit mines in order to avoid slope failure so as to prevent injury to personnel and damage to machinery. When determining the stability of a slope, it is imperative to assess the factors affecting slope stability. Different studies have used different AI models with various input variables to predict slope failure in mining. These studies have reported the prowess of AI models as being fast, reliable in mapping out FOS and sturdy to handle large amounts of data at a given time. Despite the usage of such a model, there is a need for comparing the output of various AI models in order to determine the most accurate model for forecasting slope stability. In addition, various elements known to affect slope stability

should be captured and used as input variables to forecast slope stability and compare performance of different AI models.

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