Slope Stability Analysis in Open Cast Mines

B. Rajesh kumar1, S. Saravanakumar2, P. Nithiyanan3, Dr. S.P. Venkatesan4, G. Velurugan5
PG Scholar1, Assistant Professor2,3,5, Professor4
Department Mechanical Engineering (M.E Industrial Safety Engineering)
Excel College of Engineering and Technology, Komarapalayam, Tamil Nadu, India

Abstract:
The analysis of slope stability has received widely attention now days because of its practical importance. To provide steepest slopes which are stable and safe various investigations are ongoing. Stability is determined by the balance of shear stress and shear strength. If the forces available to resist movement are greater than the forces driving movement, the slope is considered stable. A factor of safety is calculated by dividing the forces resisting movement by the forces driving movement. A previously stable slope may be initially affected by preparatory factors, making the slope conditionally unstable. The field of slope stability encompasses static and dynamic stability of slopes of earth and rock-fill dams, slopes of embankments, excavated slopes, and natural slopes in soil and soft rock. Various methods are available for slope stability analysis. This paper aims an overview on various methods of slope stability on the basis of assumptions, Factor of safety calculation, soil conditions, soil types, applicability of output of the method with its limitations. This paper also aims to focus some new mathematical tools which can be applicable for stability analysis of slope.

I. INTRODUCTION

Slope stability analysis forms an integral part of the opencast mining operations during the life cycle of the project. In Indian mining conditions, slope design guidelines are yet to be formulated for different types of mining practices and there is a growing need to develop such guidelines for maintaining safety and productivity. Till date, most of the design methods are purely based on field experience, rules of thumb followed by sound engineering judgment. During the last four decades, the concepts of slope stability analysis have emerged within the domain of rock engineering to address the problems of design and stability of excavated slopes. In India, the number of operating opencast mines is steadily increasing as compared to underground mines. It is due to low gestation period, higher productivity, and quick rate of investment. On the contrary, opencast mining attracts environmental concerns such as solid waste management, land degradation and socio-economic problems. In addition to that a large number of opencast mines, whether large or small, are now days reaching to deeper mining depths. As a result, analysis of stability of operating slopes and ultimate pit slope design are becoming a major concern. Slope failures cause loss of production, extra stripping cost for recovery and handling of failed material, dewatering the pits and sometimes lead to mine abandonment/premature closure. A slope is defined as a surface of which one end or side is at higher level than another; a rising or falling surface. An earth slope is an un supported, inclined surface of a soil mass. The failure of a mass of soil located beneath a slope is called as slide. It involves a downward and outward movement of the entire mass of soil that participates in the failure. The failure of slopes takes place mainly due to, The action of gravitational forces, and Seepage forces within the soil. They may also fail due to excavation or undercutting of its foot, or due to gradual disintegration of the structure of the soil, Slides may occur in almost every conceivable manner, slowly or suddenly, and with or without any apparent provocation. Maintaining pit slope angles that are as steep as possible is of vital importance to the reduction of stripping (mining of waste rock), which will in turn have direct consequences on the economy of the mining operation. Design of the final pit limit is thus governed not only by the ore grade distribution and the production costs, but also by the overall rock mass strength and stability. The potential for failure must be assessed for given mining layouts and incorporated into the design of the ultimate pit. Against this backdrop, there is a strong need for good practices in slope design and management so that suitable corrective actions can be taken in a timely manner to minimize the slope failures.

1.1. About Organization
Jindal Steel Ltd. is an Indian steel making company based in Mumbai, Maharashtra. It is a subsidiary of Jindal Group. It is one of the fastest growing companies in India with a global footprint in over 140 countries. After the merger of ISPAT steel, Jindal Steel has become India's second largest private sector steel company.

1.2. Objective and Scope
The prime objectives of the project are addressed towards:
   a) Understanding the different types and modes of slope failures; and
   b) Designing of stable slopes for opencast mines using numerical models.

1.3. Research & Strategies
Extensive literature review has been carried out for understanding the different types and modes of slope failures. Numerical model FLAC/Slope was critically reviewed for its application to evaluation of the stability of slopes in opencast mines. Field investigation was conducted in Jindal Opencast Mine with 116 m ultimate pit depth at in Karnataka State. Laboratory tests were conducted for the rock samples taken during field investigation. Parametric studies were conducted through numerical models (FLAC/Slope) to study the effect of cohesion (140-220 kPa) and friction angle (20°-30° at the interval of 2°). Pit slope angle was varied from 35° to 55° at an interval of 5°.

1.4. Outline of report
Following the introductory chapter, a general description of the economics of open pit mining, slope stability, failure
modes and failure mechanisms, the assessment of slope stability and different methods of analysis are discussed in Chapter 2. In Chapter 3, numerical modelling (FLAC) has been described, starting with FLAC’s overview followed by summary of its features and finally analysis procedure. Application of numerical modelling is given through a case study of “Jindal OCP,” in Chapter 4. Chapter 5 deals with conclusion and scope for future work.

1.4.1 Qualitative Analysis
Qualitative analysis uses words and descriptive scales to determine the likelihood of each identified hazard and its consequences. This provides an estimate of the likely rate of occurrence of hazardous events and their severity, from which a measure of the risk may be obtained through a simple matrix format of the equation:

\[ \text{Risk} = \text{Likelihood} \times \text{Consequence} \]

The Risk associated with a proposed development is determined by combining the likelihood of the potentially hazardous events and the magnitude of their consequences. The process of combining consequences and frequencies gives appropriate weight to the range between small consequence events (which are relatively frequent) and events of major consequence (which are very infrequent).

1.4.2 Quantitative Analysis
Quantitative analysis is conducted using numerical data values for both likelihood and consequences. This data has been gathered from a variety of sources including mathematical risk modeling, extrapolation from experimental studies or past data. A quantitative analysis can be used to estimate:

- Thermal radiation distances;
- Explosion overpressure;

1.4.3 Risk Assessment
Risk assessment involves comparing the level of risk found during the qualitative and quantitative analyses to previously established risk criteria, thereby ascertaining if that level of risk can be accepted or not. Such decisions take into account the wider context of the risk and include consideration of the tolerability of the risks borne by external parties. Low and acceptable moderate risks can be allowed with minimal further treatment; however, they should be monitored and periodically reviewed to ensure they remain at this level. Higher level risks should be treated using safeguards.

1.4.4 Risk Treatment
A complete range of safeguards should be incorporated into the design and operation of the proposed development as prevention or protection measures for higher level risks. These measures may include plant design features, organizational safety controls, emergency and counter disaster principles and approval processes. Options should be evaluated on the basis of the extent of risk reduction and the extent of benefits or opportunities they create. In general, the cost of managing risks should be commensurate with the benefits obtained.

2.1 INTRODUCTION
In open pit mining, mineral deposits are mined from the ground surface and downward. Consequently, pit slopes are formed as the ore is being extracted. It is seldom, not to say never, possible to maintain stable vertical slopes or pit walls of substantial height even in very hard and strong rock. The pit slopes must thus be inclined at some angle to prevent failure of the rock mass. This angle is governed by the geo- mechanical conditions at the specific mine and represent an upper bound to the overall slope angle. The actual slope angles used in the mine depend upon (i) the presence of haulage roads, or ramps, necessary for the transportation of the blasted ore from the pit (ii) possible blast damage (iii) ore grades, and (iv)economical constraints.

2.2 Slope Stability
Slope stability problem is greatest problem faced by the open pit mining industry. The scale of slope stability problem is divided in to two types: Gross stability problem: It refer to large volumes of materials which come down the slopes due to large rotational type of shear failure and it involves deeply weathered rock and soil.

Local stability problem: This problem which refers to much smaller volume of material and these type of failure occur one or two benches at a time due to shear plane jointing, slope erosion due to surface drainage. To study the different types and scales of failure it is essential to know the different types of the failure, the factors affecting them in details and the slope stability techniques that can be used for analysis. The different types of the slope failure, factors affecting them, stability analysis techniques and software available have been described in the following sections:

Factors Affecting Slope Stability
Slope failures of different types are affected by the following factors:

2.2.1 Slope Geometry
The basic geometrical slope design parameters are height, overall slope angle and area of failure surface. With increase in height the slope stability decreases. The overall angle increases the possible extent of the development of the any failure to the rear of the crests increases and it should be considered so that the ground deformation at the mine peripheral area can be avoided. Generally overall slope angle of 45° is considered to be safe by Directorate General of Mines Safety (DGMS). The curvature of the slope has profound effect on the instability and therefore convex section slopes should be avoided in the slope design. Steeper and higher the height of slope less is the stability. Diagram showing bench, ramp, overall slope and their respective angles is given in Fig.1.

![Figure 2.1 overall slop angles](http://ijesc.org/)

IJESC, June 2021 28280 http://ijesc.org/
The main geological structures which affect the stability of the slopes in open pit mines are:
1. Amount and direction of dip
2. Intra-formational shear zones
3. Joints and discontinuities
   a) Reduce shear strength
   b) Change permeability
   c) Act as sub surface drain and plains of failure

4. Faults
   a) Weathering and alternation along the faults
   b) Act as ground water conduits
   c) Provides a probable plane of failure

Instability may occur if the strata dip into the excavations. Faulting provides a lateral or rear release plane of low strength and such strata plan are highly disturbed. Localized steepening of strata is critical for the stability of the slopes. If a clay band comes in between the two rock bands, stability is hampered. Joints and bedding planes also provide surfaces of weakness.

Stability of the slope is dependent on the shear strength available along such surface, on the orientations in relation to the slope and water pressure action on the surface. These shear strength that can be mobilized along joint surface depending on the functional properties of the surface and the effective stress which are transmitted normal to the surface. Joints can create a situation where a combination of joint sets provides a cross over surface.

Lithology

The rock materials forming a pit slope determines the rock mass strength modified by discontinuities, faulting, folding, old workings and weathering. Low rock mass strength is characterized by circular; raveling and rock fall instability like the formation of slope in massive sandstone restrict stability. Pit slopes having alluvium or weathered rocks at the surface have low shear strength and the strength gets further reduced if water seepage takes place through them. These types of slopes must be flatter.

Ground Water

It causes the following:
   a) Alters the cohesion and frictional parameters and
   b) Reduce the normal effective stress

Ground water causes increased up thrust and driving water forces and has adverse effect on the stability of the slopes. Physical and chemical effect of pure water pressure in joints filling material can thus alter the cohesion and friction of the discontinuity surface. Physical effects of providing uplift on the joint surface, reduces the frictional resistances. This will reduce the shearing resistance along the potential failure plane by reducing the effective normal stress acting on it. Physical and the chemical effect of the water pressure in the pores of the rock cause a decrease in the compressive strength particularly where confining stress has been reduced.

2.3. Mining Method and Equipment

Generally, there are four methods of advance in open cast mines. They are:
   a) Strike cut- advancing down the dip
   b) Strike cut- advancing up the dip
   c) Dip cut- along the strike
   d) Open pit working

The use of dip cuts with advance on the strike reduces the length and time that a face is exposed during excavation. Dip cuts with advance oblique to strike may often used to reduce the strata dip in to the excavation. Dip cut generally offer the most stable method of working but suffer from restricted production potential.

![Figure 2.2 more prone to large slab/buckling modes of failure](image)

3. SLOPE STABILITY ACCEPTANCE CRITERIA FOR OPENCAST MINE DESIGN

3.1. FOS & POF

The Factor of Safety (FoS) and Probability of Failure (PoF) are commonly used to find a compromise between the risk of open cast mine slope failure and economic return. Acceptable FoS and PoF criteria are typically selected by the geotechnical designer without explicit consideration of uncertainties, and with only a broad consideration of consequences. Some organisations may have defined acceptance criteria as part of their mine slope design guidelines, but more often the selected values will be based on some combination of the designer’s experience, project or site precedence, perceptions of uncertainty and likely consequences of failure, and pressure from mine management, consenting authorities or geotechnical reviewers. A new technique for selection of acceptable FoS and PoF for opencast mine slope design is presented based on the explicit consideration of uncertainties in the slope design, the consequences of slope failure, and the intended slope design life. It provides the ability to select defendable acceptance criteria for individual slopes, with easily-documentation, and to achieve a more consistent level of risk management across all types of slopes. Geotechnical mine slope design necessitates finding a compromise between the risks of slope failure and the cost of mining. The safety, environmental, and business risks associated with slope failure must be weighted up against mining costs for a particular slope design, and the design adjusted until an acceptable balance is reached. Unfortunately, comprehensive quantitative risk-based slope design techniques are still embryonic in their development, and while good progress has been made in recent years (Terbrugge et al., 2006; Steffen et al., 2008) the practical reality is that for the majority of mining projects we are budget-constrained to design slopes that can meet an “acceptable” level of stability or performance.
3.1. Some of the key differences are:

- Mine slopes are often much higher and the range of stresses equally impressive. Opencast pits often expose a wide range of geological materials from very soft soils to extremely strong rocks. This in turn requires a wide range of geotechnical skill sets.
- The location of proposed open pit and waste rock slopes can change rapidly at the whim of commodity economics, and this requires a broader and more versatile geotechnical model to deal with the changing slope risks.
- Geological structure is vitally important to pit slope stability, particularly below the weathering or soil horizon. Weak or deeply weathered rocks that fit neither standard rock mechanics nor soil mechanics models can present a significant challenge (Adams and Lucas, 2011).
- To the advantage of the geotechnical engineer, there is often a resource geology model and exploration drilling data set that can be used as the basis for a geotechnical model.
- Construction control in mining environments can be to a lower standard for both cut slopes and fills.

3.1.2. Factor of Safety

The Factor of Safety (FoS) is the ratio of capacity (of the slope to resist failure) to demand (placed on slope by driving forces such as gravity and seismic accelerations). A FoS of unity implies the slope is in a state of limiting equilibrium. Any miniscule increase in load or decrease in resistance will result in an unstable slope (FoS < 1). Conversely a FoS > 1, implies some margin of safety (MoS = FoS – 1) against failure. While the FoS is a direct output from LEM analyses, a broadly equivalent safety reduction factor (SRF) can be computed from finite element method (FEM) and other numerical analyses using the shear strength reduction method.

A key problem with the factor of safety is in its name. While there is no denying a broad positive correlation between the FoS of a slope and safety, there are a multitude of other factors that need to be considered, including the characteristics of the failure, the elements at risk, and the uncertainty in the modelling process. An extreme example of FoS misuse is shown in Table 1 from Sowers (1979), which effectively asserts a direct correlation between FoS and safety. This is not the case. For example, a one metre high slope in dry sand with a friction angle of 32° and a slope angle of 32° may have a FoS of 1.0, yet in unlikely to be considered unsafe. Likewise a massive deep-seated creeping paleo-landslide may also possess a FoS close to 1.0, yet the safety risk may be negligible. On the other hand, a 10 m3 rock wedge with a FoS of 1.0 and on the verge of falling onto a major highway would, without doubt, be considered a critical safety risk.

3.2. Slope Failure

Failure of a slope is an ambiguous concept with no common universally accepted definition. Failure has meanings of malfunction, collapse, disappointment, and disaster; as well as being the opposite of success. However, as Duncan (2000) rightly notes, not all slope “failures” are catastrophic. Some are better described as unsatisfactory performance or a minor irritation. Bench-scale slope failures, for example, are generally expected and can be acceptable when adequately managed by catch berms. Other terms such as “instability” or “movement” may imply less of a disaster, yet are still equally ambiguous; while terms such as “creep” or “collapse” can sometimes be used to describe the slope “failure” in a slightly more specific or intuitive fashion. A FoS of 1.0 describes the point at which the total demand on the slope exceeds the total capacity of the slope to resist failure through all materials on the defined failure path. A slope failure is, however, much more complex than it is modelled by the LEM. In practice, failure does not occur simultaneously along a single discrete basal surface, but rather localized material failure progressively develops into a larger slope failure. With the exception of purely structurally-controlled slope failure in a brittle rock mass, the internal deformation process also plays a large part in the development of slope failure.

Pit slope failures generally pass through several stages of movement, as shown in Figure 1.

1. Viscoelastic response
2. Primary Creep, which may eventually stabilize, or progress to...
3. Secondary Creep
4. Tertiary Creep (cracking and dislocation)
5. Collapse
6. Post collapse deformation

The first two stages or “initial response” include elastic rebound, relaxation and/or dilation of the rock mass Secondary creep and pre-collapse deformation is associated with yielding, softening, strength loss, localized failure and slip on structures within the rock mass. The exact part of the curve in Figure 1 described by FOS = 1.0 is controversial, although generally accepted to be somewhere between Secondary Creep and Collapse.

3.3. Modelling Limitations and Advantages of Limit Equilibrium Methods

Limit equilibrium methods (LEM) have been used for slope stability analysis since the dawn of geotechnical engineering. Increased computing power over the last few decades has enabled a move from simplistic geometries to powerful slip-surface search and optimization routines. Key limitations of the method include the inability to model progressive failure, internal deformation of the sliding mass, or post failure displacement of the slope. It assumes that shear displacement occurs along a unique sliding surface, and for this reason slope failure mechanisms such as active-passive wedge failures and flexural toppling that are clearly governed by internal shear displacement should only be modelled by LEM with extreme caution, and preferably only where calibrated by back analysis.
Despite these limitations, the LEM provides a valuable and cost-effective tool for assessing pre-failure stability, the sensitivity of the slope to changes in slope geometry, shear strength parameters, groundwater conditions and loading; and stabilization options such as buttressing, ground anchors and slope depressurization. For this reason, the LEM continues to be widely used within the mining geotechnical community.

3.4. Accounting for Uncertainty
The FoS is a deterministic concept and does not describe real-world uncertainty in the stability of the slope. Fortunately, there are tools available that can at least partially assist in this area:

- Sensitivity analysis is an extremely powerful yet simple technique to assess the influence that each input parameter (such as the friction angle, cohesion or piezometric pressure) has on the resulting FoS of the slope. It enables the designer to define the most important controls on slope stability.

- The process has been automated in common LEM software to assess uncertainty associated with material parameters, groundwater pressures and applied loads, yet it is still a painstaking task to assess subsurface spatial and geometrical uncertainties such as the location and orientation of weak discontinuities or weathering horizons.

- Probabilistic modelling is a technique used to carry uncertainty associated with input parameters through the analysis to produce a statistically distributed FoS rather than a single deterministic value. The resulting probability of failure (PoF) has become a commonly-used design acceptance criterion. Recent advances include the use of numerical analyses for probabilistic modelling.

3.5. Probability of Failure
The Probability of Failure (PoF) has been used and abused as a criterion for mine slope design over the last 40 years. The basic premise of the PoF concept is that a statistical distribution (probability density function) can be defined for each of the input parameters to a slope stability analysis. Using a process of stochastic simulation, it is possible to define a statistical distribution around the FoS. The PoF is defined as the percentage of results with FoS < 1. While the PoF is a nice concept, the author has become aware of some major issues with the value of this correlation introduces yet another epistemic uncertainty.

3.5.5. Computed vs total PoF:
Probabilistic modelling routines within commonly used software Slide (Rocscience) and Slope/W (GEO-SLOPE) allow the user to estimate the PoF associated only with material properties, groundwater pressures and external loads. The computed PoF does not account for other significant sources of uncertainty, and as a result may be much smaller than the total PoF of the slope. Unaccounted-for uncertainties in the computed PoF include spatial variability of material properties, unknowns in the structural geology model, temporal probabilities associated with rainfall and seismic hazard, computational model simplifications and implementation variation to design.

3.5.6. Lack of time dependency:
In the absence of time-dependent input variables, the computed PoF does not have a timescale. In order to calculate the annual PoF, the reference time is often assumed to be related to the design life of the slope. In reality, the PoF of a slope is likely to be related to the rate of stress redistribution, the rate of material strength degradation (eg. Via weathering and rock mass relaxation), and the temporal probabilities of triggering events such as rainfall or earthquakes. The preceding discussion suggests that major issues exist with the value of the computed PoF as an input to quantitative risk assessment. Some of these have been overcome via the quantitative event tree slope design procedures of Terbrugge (2006) and Steffen (2008). In a qualitative sense, the PoF remains a useful technique to rank the importance of various uncertainties, and to determine (for example) when a tighter input distribution (requiring more spend on drilling and lab testing) would justify a lower FoS and steeper slope, thus saving significant earthworks Money.

3.6. Current Practice for selection of Design acceptance criteria
The choice of an acceptable FoS for slope stability evaluation is said to require sound engineering judgement due to the multitude of factors that must be considered (Barnes, 1995). However, it is the author’s observation that acceptable FoS and PoF criteria are typically selected by the geotechnical...
designer without explicit consideration of uncertainties, and with only a broad consideration of consequences. Some organizations may have defined acceptance criteria as part of their mine slope design guidelines, but more often the selected values will be based on some combination of the designer’s experience, project or site precedence, perceptions of uncertainty and likely consequences of failure, and pressure from mine management, consenting authorities or geotechnical reviewers. Commonly referred to recommendations of acceptable minimum values of FoS and PoF for the mining industry tend to be based on a small number of published suggestions dating back to the likes of Hoek and Bray (1981). The general theme which has become industry standard is to present acceptable values that depend on the size of the slope and generic consequences (e.g. Table 2). However, this approach takes little account of specific consequences, and does not necessarily present a consistent level of risk management.

4. CONCLUSION

Commonly-used limit-equilibrium slope analysis methods, and associated FoS/PoF design acceptance criteria have many limitations that must be understood in order to use them effectively. Nevertheless, they remain as simple and powerful tools to evaluate mine slope stability, provided all the relevant uncertainties can be accounted for. It is recommended that deterministic FoS analyses are always backed up with a comprehensive sensitivity analysis. PoF analyses should be used with caution, particularly if the computed result is intended for use in a quantitative risk analysis. A new technique for selection of acceptable FoS and PoF for slope design has been presented based on explicit consideration of uncertainties in the slope design, the consequences of slope failure, and the intended design life. It provides the ability to select defendable acceptance criteria for individual slopes, with easily-documented logic, and to achieve a more consistent level of risk management across all types of slopes. The method described in this paper does not constitute unilateral endorsement of the FoS approach in all situations, but is rather intended to improve the current practice. Application of this methodology could be extended to civil earthworks, dams or highways, however in these environments, design criteria are often dictated more rigidly by approved codes and guidelines. Further improvements to this methodology will include tables to assist in the detailed description of slope failure scenarios, and improved descriptions and quantification of consequence and confidence levels.

5. REFERENCES

[2]. DGMS Circulars.
[3]. The influence and Evaluation of Blasting on stability in Open cast Mines
[4]. Rock Mechanic design in Mining & Tunneling.
[5]. Indian Mining and Engineering Journals.
[6]. Aitik slope stability study.
[7]. PIT Slope Manual.
[9]. Jindal safety manual
[10]. National Institute of Rock Mechanics. (NIRM)