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A model study of slope stability in mines situated in south India

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ABSTRACT

Slope stability analysis is important in any opencast iron ore mine. A failure of slope in a working area of mine can give rise a significant economic losses and safety impact. The fundamental failure modes are varied and complex. Such mechanisms are governed by engineering geology condition of rock mass which are almost always unique to a particular site. Using the FLAC/Slope software stability of slope is analysis. The work was aimed at study of stability of slopes using numerical modeling, at the same time study the different failure mechanism. The purpose of this project is to learn and assess this FLAC/Slope software. As the study of the software is easy, it can be concluded that it is user-friendly. Based on parametric studies it can be concluded that slope angle plays a major role on slope stability. Safety factor varied from 0.63 to 1.37 for the depth of 10 m to 250 m for the slope angle of 45 degrees. It showed that with the increase in height of the bench or depth of the mine safety factor of the bench decreases indicating less stability of the concerned slope. At the depth of 100 m, the safety factor was found to be exceeding 1.2 for slope angle less than 35 degrees. Therefore, it is recommended to maintain the overall slope angle not steeper than 35 degrees, in the hypothetical mine conditions assumed in the project. At the depth of 150m, factor of safety is 1.02, and 1.01 for the slope angles of 35 degree and 40 degrees, respectively. This indicated that the slope may be maintained with more than 1.0 safety factor at flatter than 40 degree, ensuring continuous monitoring of the stability of slope through observational approaches. It is recommended that for improving the reliability of model results, calibrations of models with actual field conditions may be taken of through piezometric monitoring and measurement of slope moments in varying geomining condition at different mine sites.

Keywords: Slope stability, open pit mining, numerical modeling, rock mass strength, failure mechanisms.

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 (1). It is due to low gestation period, higher productivity, and quick rate of investment. On the contrary, opencast mining attracts environmental concerns such as solidwaste management, land degradation and socio-economical 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 (2). 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. 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 (3). 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.

Extensive literature review has been carried out for understanding the different types and modes of slope failures (4). 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 Raigarh in Chhattisgarh 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°.

In the geo technical field, stability analyses aim to support the safe and functional design of rock and soil slopes. Preliminary analyses can be carried out in order to determine the critical parameter of work stability. Parametric analyses allow one to asses physical and geometrical problem parameter influence on the slope stability (5). A rock and soil slope stability analysis allows one to evaluate: The optimal staged excavation or construction time sequence determination; the role, which design parameters such as slope angle and excavation or embankment height, play in the work stability; Consolidation work such as retaining walls, drainage system or rock bolting, which can stabilize slope (6).

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

Slope Geometry: Slope geometry is the important factor which affects the slope stability. The basic geometrical slope design parameters are bench height, overall slope angle and area of failure surface. Stability of slope decreases with increases in height and slope angle. 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 (7).

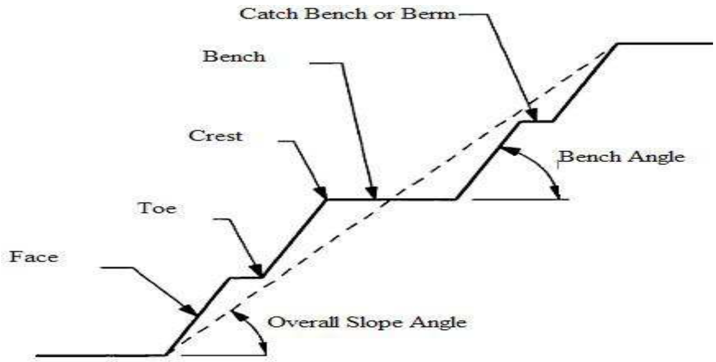

Figure1. Diagram showing bench angle, face, slope angle, toe and crest

Geological Structure: The main geological structure which affect the stability of the slopes in the open pit mines are:
1. Amount and direction of dip
2. Intra-formational shear zones
3. Joints and discontinuities
4. Faults

Instability of rock slope may occur by failure along pre-existing structural discontinuity, by failure through intact material or by failure along a surface formed partly along discontinuity and partly through intact material. Instability may occur if the strata dip into the excavations. Localized steepening of strata is critical for the stability of the slopes. Stability is hampered if a clay band comes in between the two rock bands. Bedding planes and Joints also provide surfaces of weakness (8).

Lithology and Ground Water: The rock materials forming a large pit slope determines the rock mass strength modified by discontinuities, folding, faulting, old workings and weathering. Low rock mass strength is characterized by ravelling, circular; and rock fall instability like the formation of slope in Massive sandstone restricts stability. Pit slopes having soil alluvium or weathered rocks at the surface have low shearing strength and the strength gets further reduced if water seepage takes place through them. These types of slopes must be flatter (9).

Ground water causes increased up thrust and driving water forces and has adverse effect on the stability of the slopes. Chemical and Physical 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 (10-12).

MATERIALS AND METHODS

In limit equilibrium method of analysis, static force is applied to analyze the stability of the rock mass or soil above the failure surface. If failure has already occurred, the geometry of the failure surface can be determined and the analysis of the failure can be done and is known as back analysis. If it is a design situation, however the failure surface is potential rather than actual, many potential surface may have to be analyzed to find the critical geometry before an acceptable slope geometry can be accounted for. In the case of plane failure, 3D wedge failure, circular failure, the material above the failure surface will be on the point of slipping when the disturbing forces due to gravity are just counterbalanced by the forces tending to restore equilibrium. The ratio of the two forces defines the factor of safety of the failure surface.

Stress Analysis Method: Failure does not necessarily occur along a well defined failure surfaces. The situation where the structural condition does not permit sliding along the discontinuity surface, crushing of the rock occurs at the points of the highest stress. Progressive failure of the rock mass can subsequently deform the slope and may cause the catastrophic failure. The objectives of the stress analysis method are to represent the rock mass by a series of structural elements (finite element method) or cells of constraint of materials (one finite different method) and perform an analysis to determine to stresses at points within the slope. The stress distribution can be examined to determine where rock failure is likely to occur, rock failure occurs when the stresses to which the rock is subjected more than its strength (13).

Numerical Modeling: Many rock slope stability problems involve complexities relating to geometry, material anisotropy, non-linear behavior, in situ stresses and the presence of several coupled processes (e.g. pore pressures, seismic loading, etc.). Advances in computing power and the availability of relatively inexpensive commercial numerical modeling codes means that the simulation of potential rock slope failure mechanisms could, and in many cases should, form a standard component of a rock slope investigation. Numerical methods of analysis used for rock slope stability may be conveniently divided into three approaches: continuum, discontinuum and hybrid modeling (14).

Continuum Modeling: Continuum modeling is best suited for the analysis of slopes that are comprised of massive, intact rock, weak rocks, and soil-like or heavily fractured rock masses. Most continuum codes incorporate a facility for including discrete fractures such as faults and bedding planes but are inappropriate for the analysis of blocky mediums. The continuum approaches used in rock slope stability include the finite-difference and finite-element methods. In recent years the vast majority of published continuum rock slope analyses have used the 2-D finite-difference code, FLAC. This code allows a wide choice of constitutive models to characterize the rock mass and incorporates time dependent behavior, coupled hydro-mechanical and dynamic modeling. Two-dimensional continuum codes assume plane strain conditions, which are frequently not valid in inhomogeneous rock slopes with varying structure, lithology and topography. The recent advent of 3-D continuum codes such as FLAC3D and

VISAGE enables the engineer to undertake 3-D analyses of rock slopes on a desktop computer. Although 2-D and 3-D continuum codes are extremely useful in characterizing rock slope failure mechanisms it is the responsibility of the engineer to verify whether they are representative of the rock mass under consideration. Where a rock slope comprises multiple joint sets, which control the mechanism of failure, then a discontinuum modeling approach may be considered more appropriate (15).

Discontinuum Modeling: Discontinuum methods treat the rock slope as a discontinuous rock mass by considering it as an assemblage of rigid or deformable blocks. The analysis includes sliding along and opening/closure of rock discontinuities controlled principally by the joint normal and joint shear stiffness. Discontinuum modeling constitutes the most commonly applied numerical approach to rock slope analysis, the most popular method being the distinct-element method. Distinctelement codes such as UDEC use a force-displacement law specifying interaction between the deformable joint bounded blocks and Newton's second law of motion, providing displacements induced within the rock slope. UDEC is particularly well suited to problems involving jointed media and has been used extensively in the investigation of both landslides and surface mine slopes. The influence of external factors such as underground mining, earthquakes and groundwater pressure on block sliding and deformation can also be simulated.

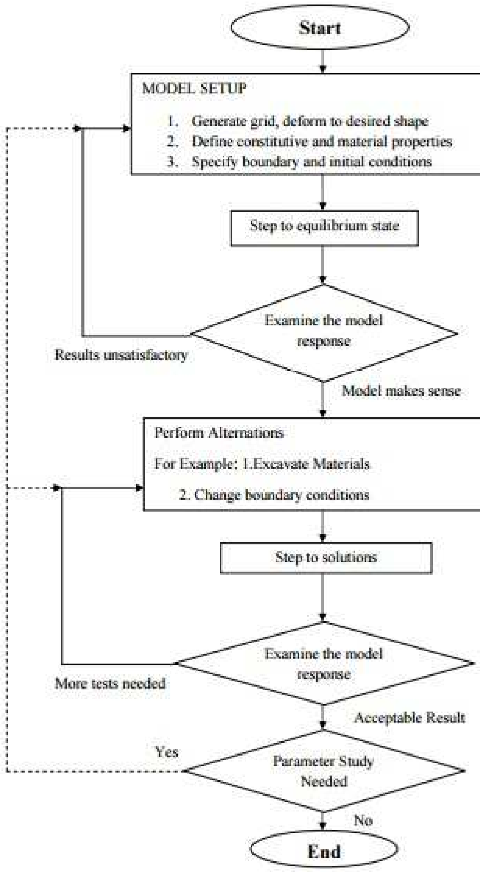

Figure2. Flow chart for determination of factor of safety using FLAC/Slope

Hybrid Techniques: Hybrid approaches are increasingly being adopted in rock slope analysis. This may include combined analyses using limit equilibrium stability analysis and finite-element groundwater flow and stress analysis such as adopted in the GEO-SLOPE suite of software. Hybrid numerical models have been used for a considerable time in underground rock engineering including coupled boundary-/finite-element and coupled boundary-/distinct-element solutions. Recent advances include coupled particle flow and finite-difference analyses using FLAC3D and PFC3D. These hybrid techniques already show significant potential in the investigation of such phenomena as piping slope failures, and the influence of high groundwater pressures on the failure of weak rock slopes. Coupled finite-/distinct-element codes are now available which incorporate adaptive remising. These methods use a finite-element mesh to represent either the rock slope or joint bounded block. This is coupled with a discrete -element model able to model deformation involving joints. If the stresses within the rock slope exceed the failure criteria within the finite-element model a crack is initiated. Remising allows the propagation of the cracks through the finite-element mesh to be simulated. Hybrid codes with adaptive remising routines, such as ELFEN, have been successfully applied to the simulation of intense fracturing associated with surface mine blasting, mineral grinding, retaining wall failure and underground rock caving.

General Approach of FLAC The modeling of geo-engineering processes involves special considerations and a design philosophy different from that followed for design with fabricated materials. Analyses and designs for structures and excavations in or on rocks and soils must be achieved with relatively little site-specific data, and an awareness that deformability and strength properties may vary considerably. It is impossible to obtain complete field data at a rock or soil site. Since the input data necessary for design predictions are limited, a numerical model in geomechanics should be used primarily to understand the dominant mechanisms affecting the behavior of the system. Once the behavior of the system is understood, it is then appropriate to develop simple calculations for a design process. It is possible to use FLAC directly in design if sufficient data, as well as an understanding of material behavior, are available. The results produced in a FLAC analysis will be accurate when the program is supplied with appropriate data (16).

Analysis Procedure: FLAC/Slope is specifically designed to perform multiple analyses and parametric studies for slope stability projects. The structure of the program allows different models in a project to be easily created, stored and accessed for direct comparison of model results. A FLAC/Slope analysis project is divided into four stages which is described below.

a) Models Stage: Each model in a project is named and listed in a tabbed bar in the Models stage. This allows easy access to any model and results in a project. New models can be added to the tabbed bar or deleted from it at any time in the project study. Models can also be restored (loaded) from previous projects and added to the current project. The slope boundary is also defined for each model at this stage.

b) Build Stage: For a specific model, the slope conditions are defined in the Build stage. This includes: changes to the slope geometry, addition of layers, specification of materials and weak plane, application of surface loading, positioning of a water table and installation of reinforcement. Also, spatial regions of the model can be excluded from the factor-of-safety calculation. The build-stage conditions can be added, deleted and modified at any time during this stage.

c) Solve Stage: In the Solve stage, the factor of safety is calculated. The resolution of the numerical mesh is selected first (coarse, medium and fine), and then the factor-of-safety calculation is performed. Different strength parameters can be selected for inclusion in the strength reduction approach to calculate the safety factor. By default, the material cohesion and friction angle are used.

d) Plot Stage: After the solution is complete, several output selections are available in the Plot stage for displaying the failure surface and recording the results. Model results are available for subsequent access and comparison to other models in the project. All models created within a project, along with their solutions, can be saved, the project files can be easily restored and results viewed at a later time.

RESULTS AND DISCUSSION

The final stage of problem solving is the presentation of the results for a clear interpretation of the analysis. This is best accomplished by displaying the results graphically, either directly on the computer screen, or as output to a hardcopy plotting device. The graphical output should be presented in a format that can be directly compared to field measurements and observations. Plots should clearly identify regions of interest from the analysis, such as locations of calculated stress concentrations, or areas of stable movement versus unstable movement in the model. The numeric values of any variable in the model should also be readily available for more detailed interpretation by the modeler. The above seven steps are to be followed to solve geo-engineering problems efficiently.

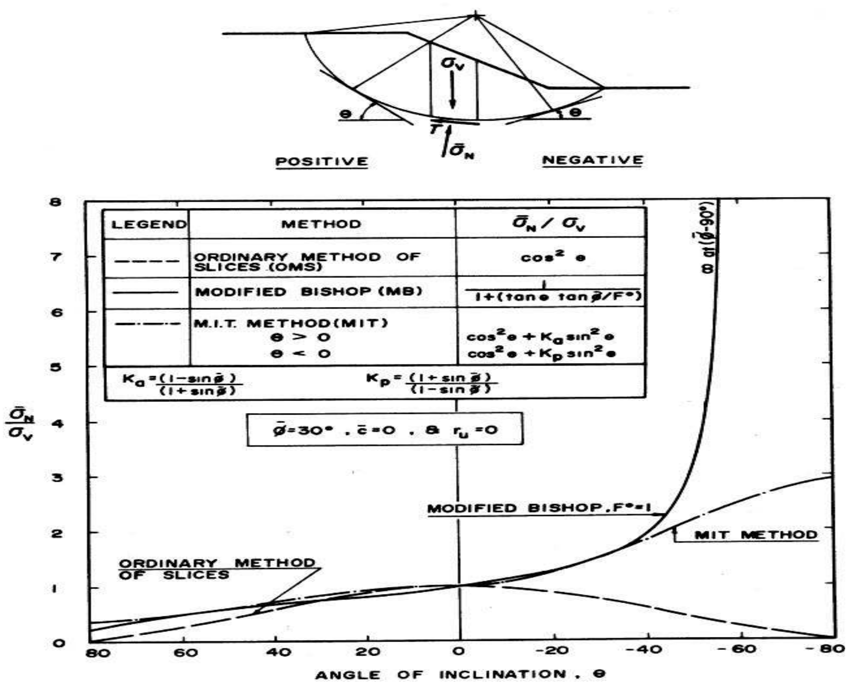

Figure3: Influence of base inclination of slice in two-dimensional slope stability analysis

Mechanism of Slope Stability: The stability of slopes has traditionally been treated as a problem in limiting equilibrium mechanics. A condition of failure is postulated along a known (or assumed) failure surface, and the necessary shear resistance of the soil to maintain equilibrium of the resulting free body is calculated. This shear resistance is then compared to the estimated shear strength of the soil to indicate the margin of safety of the slope.

Two-Dimensional Problems: A number of methods for the two-dimensional analysis of slope stability which are based on limit equilibrium techniques are presently available. For a description of these methods, the reader may refer to Fellenius, Taylor, Janbu, Bishop, Lowe and Karafiath, Morgenstern and Price, Spencer, and Janbu. Wright made a comprehensive study of some of these methods and compared their merits and shortcomings.

These methods differ from one another in one or more of the following aspects:
(i) The assumptions introduced to achieve statically determinacy.
(ii) The conditions of equilibrium which are satisfied.
(iii) The shape of the failure surface or the shape of the cut to be analyzed. The analysis performed herein is limited to circular arc models of failure.

Slope Analysis: SLOPE uses the graphical interface and it calculates the factor of safety. FLAC is the core of a new, user-friendly code that models slope stability problems under a wide variety of slope condition. These include: arbitrary slope geometries, multiple layers, pore pressure conditions, heterogeneous soil properties, surface loading, and structural reinforcement. SLOPE uses the same calculation method as FLAC with a simplified modeling environment that provides tools and facilities exclusive to slope stability analysis. The result is a code that offers rapid model development, proven analytical capabilities and fast solution reporting.

Tools within the SLOPE allow for rapid model development, including
- Creation of the slope geometry
- Addition of layers
- Specification of material either manually or from a database
- Positioning a planar or non-planar material interface
- Location of water table
- Application of surface loading at any location

➢ Installation of structural support such as soil nails or rock bolts.

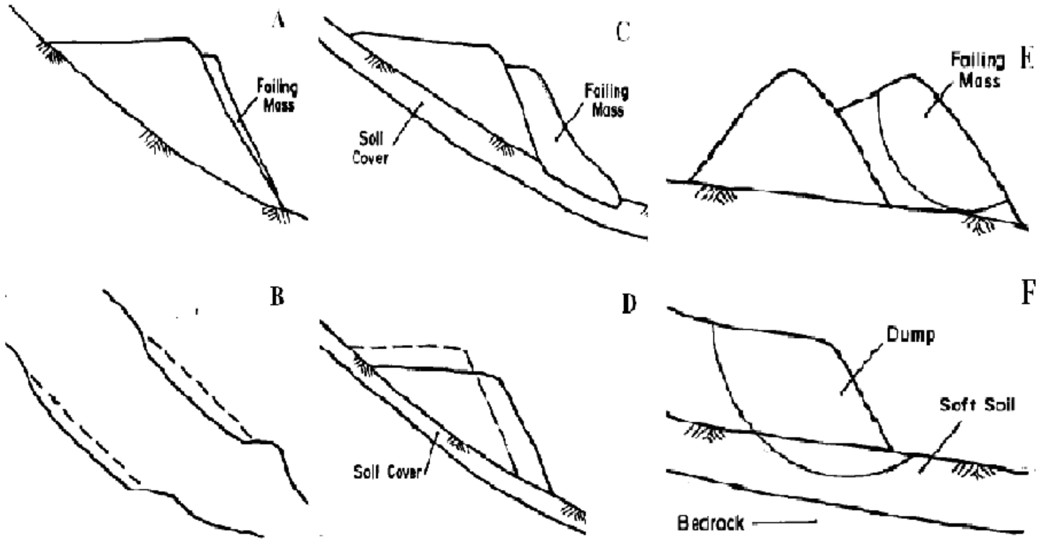

Figure4: (A) Surface or edge slide, (B) Shallow flow slides, (C) Base failure, (D) Block translation, (E) Circular arc failure, (F) Foundation circular failure

FLAC/Slope can be applied to a wide variety of conditions to evaluate the stability of slopes and embankments. Each condition is defined in a separate graphical tool.

1. The creation of the slope boundary geometry allows for rapid generation of linear, nonlinear and benched slopes and embankments. The Bound tool provides separate generation modes for both simple slope shapes and more complicated non-linear slope surfaces. A bitmap or DXF image can also be imported as a background image to assist boundary creation.
2. Multiple layers of materials can be defined in the model at arbitrary orientations and non uniform thicknesses. Layers are defined simply by clicking and dragging the mouse to locate layer boundaries in the Layers tool.
3. Materials and properties can be specified manually or from a database in the Material tool. At present, all materials obey the Mohr-Coulomb yield model, and heterogeneous properties can be assigned. Material properties are entered via material dialog boxes that can be edited and cloned to create multiple materials rapidly.
4. With the Interface tool, a planar or non-planar interface, representing a joint, fault or weak plane, can be positioned at an arbitrary location and orientation in the model. The interface strength properties are entered in a properties dialog; the properties can be specified to vary during the factor-of-safety calculation, or remain constant. Slope is limited to slope configurations with no more than one interface. For analyses which involve multiple (and intersecting) interfaces or weak planes, full FLAC should be used.
5. An Apply tool is used to apply surface loading to the model in the form of either a real pressure (surface load) or a point load.
6. A water table can be located at an arbitrary location by using the Water tool; the water table defines the paretic surface and pore pressure distribution for incorporation of effective stresses and the assignment of wet and dry densities in the factor-of-safety calculation.
7. Structural reinforcement, such as soil nails, rock bolts or geotextiles, can be installed at any location within the model using the Reinforce tool. Structural properties can be assigned individually for different elements, or groups of elements, through a properties dialog.
8. Selected regions of a Slope model can be excluded from the factor-of-safety calculation.

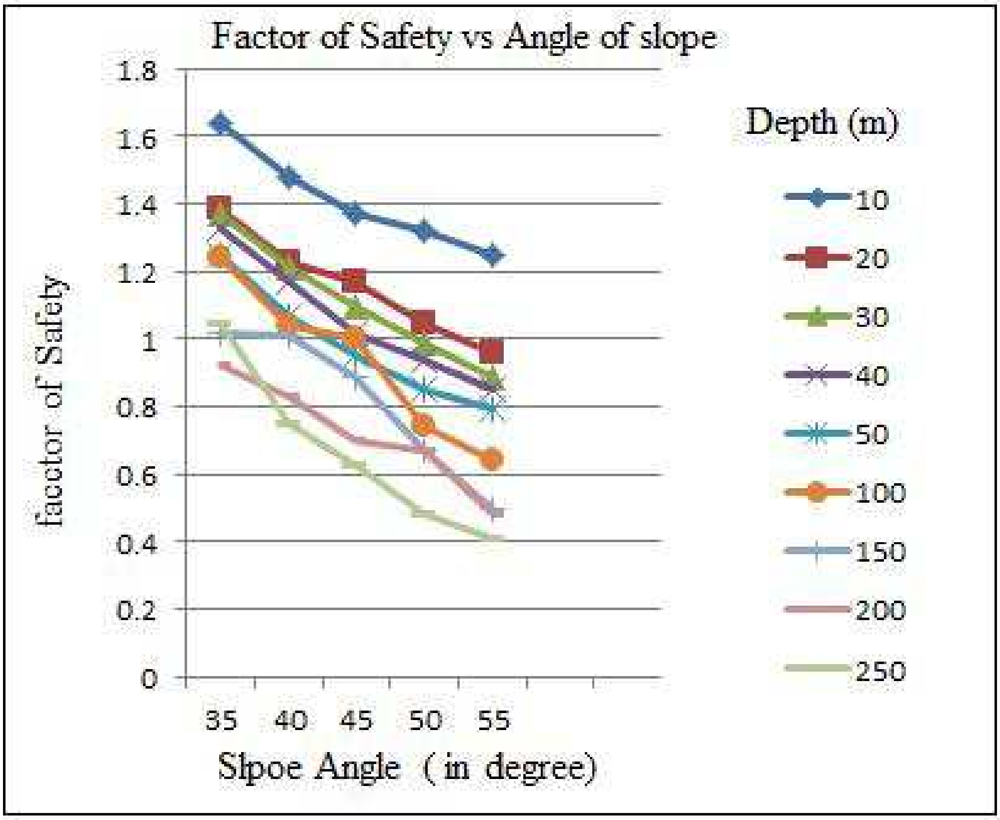

Figure5: Variation of Factor of Safety with Slope Angle for Different Depth

It is observed from the table that as the pit slope angle increases, the factor of safety decreases and the stability of the slope decreases. In total 45 model iterations were carried out, with different set of data on changing the slope angle with the increment of 5 degree from 35 degree to 55 degree to understand the effect on factor of safety. The result of the analysis has indicated that the factor of safety varied from 0.41 to 1.64 with 35 degree to 55 degree slope angles. The factor of safety 1.2 is considered safe. It was observed that the factor of safety changes with change in the resolution of numerical mesh while running the numerical model FLAC/slope. Factor of safety is quite approximate in coarse mesh while factor of safety converges to the possible value making it more accurate. Factor of safety calculation in coarse mesh as compared to fine and medium mesh is faster. So considering the time availability and requirement of modeler, the suitable mesh has to be selected.

Summary and Conclusion: Parametric studies were conducted by numerical model FLAC/SLOPE for varying slope angle and depth of the typical mine condition; following are the conclusion and recommendation based on the numerical modeling results.

1. Safety factor varied from 0.63 to 1.37 for the depth of 10 m to 250 m for the slope angle of 45 degrees. It showed that with the increase in height of the bench or depth of the mine safety factor of the bench decreases indicating less stability of the concerned slope.
2. At the depth of 100 m, the safety factor was found to be exceeding 1.2 for slope angle less than 35 degrees. Therefore, it is recommended to maintain the overall slope angle not steeper than 35 degrees, in the hypothetical mine conditions assumed in the project.
3. At the depth of 150m, factor of safety is 1.02, and 1.01 for the slope angles of 35 degree and 40 degrees, respectively. This indicated that the slope may be maintained with more than 1.0 safety factor at flatter than 40 degree, ensuring continuous monitoring of the stability of slope through observational approaches.
4. It is recommended that for improving the reliability of model results, calibrations of models with actual field conditions may be taken of through piezometric monitoring and measurement of slope moments in varying geomining condition at different mine sites.

From the above study following conclusions can be drawn:

- It has been found out that most of the overburden dump is concentrated by sandy samples as their size ranges from 0.075-4.75mm.
- The dumps were designed in four trials with different slope angles to check the best safety factors.
- The safety factors vary from 1.47 to 1.16 from which we have selected the most stable dump considering both the dump height and safety factor.
- From trial 1 the dump with slope angle of 32° was found to be the stable and dumps with slope angles greater than 32° are not stable. From trial 2 the dumps with slope angles lees than 29° were found to be stable. From trial 3 the dumps with slope angles lees than 27° were found to be stable. . From trial 4 the dumps with slope angles lees than 28° were found to be stable.
- The dump with three decks of height 30 m is at slope angle 29^0 with safety factor 1.20 is selected as stable and most effective.

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