

DESIGN OF OPTIMUM SLOPES FOR SAFETY AND CONSERVATION IN OPENCAST MINES – AN APPRAISAL

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1. INTRODUCTION

Presently, due to ever-increasing demand of minerals for the country, it is very much required to have the opencast mines at a greater depth. Increasing depth also increased the severity of slope stability problems of the opencast mines. Unlike the previous quarrying practices at shallow depths, now-a-days, study the stability of slopes of working benches and waste-dumps of opencast mines and analyzing their stability has become a challenge for the mining community. For the purpose, besides design of slopes by modeling or analytical methods, it is pertinent to utilize various techniques for monitoring the slopes to understand the status of its stability and early detection of instability of slopes for opencast mines. Many fatal accidents due to slope failures in Indian mines indicate the urgent need of conducting slope monitoring for the working benches as well as dumps. With increasing depth of surface mining excavations, the problem of stability of slopes is becoming a major concern for the mining engineers (as shown in Figure 1). In mountainous regions, landslides are a major safety hazard, particularly in the rainy season. Stability analysis of the benches & design of slope parameters, Design of ultimate pit limits, inter-ramps, and safety berms, Design of barrier between water bodies and the open pit, Design of spoil dumps. Monitoring of slopes and landslide hazards are important. working benches of a typical coal mine is shown in Fig 1.



Figure 1: Benches in a typical opencast mine

Slope stability is a major problem in opencast mines. Slope stability in a large scale open pit mining operation is a matter of concern for the mine management so as to establish safety throughout the life of the mines. Again the profitability of the open pit mines is dependent to a large extent on the use of steepest pit slopes possible, provided they do not fail during the life of the mine. Steep slopes do need a great amount of analysis so that the whole operation is safe and profitable. Now days the open pits are whether large or small scale industries reaches more depth results unstable it is major concern in designing the unstable slopes. The most common methods used for designing the slopes are by conventional methods such as (Limit equilibrium, Kinematic analysis) methods and Numerical methods, convenient methods can be applicable for different mode of failures.

Instability of rock slopes may occur by failure along pre- existing structural discontinuities, by failure through intact material or by failure along a surface formed partly along discontinuities and partly through intact material. Although certain fundamental failure modes are recognized, the mechanisms of slope failure are

varied and complex. Such mechanisms are governed by the engineering geology conditions of the rock mass, which are almost always unique to a particular site. An understanding of failure mechanisms requires a knowledge of the physical, mechanical and strength properties of the intact material and discontinuities which make up the rock mass, as well as the structural geology and hydrogeology. These engineering geology parameters also must be evaluated with respect to the slope geometry to determine failures which are kinematically possible. Only after obtaining a reasonable appreciation of the possible failure modes can a rational mechanical stability analysis be carried out. Both two-dimensional and three-dimensional failure mechanisms should be considered in assessing the design of rock slopes. Simple analyses methods are used initially to identify those possible failures which could control slope stability. More complex and detailed analyses usually are required for a few critical failure modes which could control stability, or where a more complex type of failure mechanism is envisaged. Complex failure mechanisms are usually identified when assessing previous slope failures. More detailed information concerning slope geometry and engineering geology parameters must be acquired where analyses must be more rigorous.

2.0 SURFACE MINING DOMAIN – PRESENT CHALLENGES

The important technical changes that have taken place over the past two decades were discussed in details by Khare (2007) including rope shovels, hydraulic excavators, dragline, dumpers, and drills. Bucket wheel excavators of 1400 liters capacity are used in Neyveli for excavating both the OB and lignite. Studies have been made to introduce the system in some other mines also. Vastar lignite mine GIPCL is another mine besides Neyveli. In some other instances the material is blasted to make it diggable by the bucket wheel excavators. Continuous surface miners are now available and many mines are using them such as Koyagudem in Singareni collieries. Several models of these machines are available WIRTGEN surface miner, EASI miner, KRUPP surface miner, VOEST ALPINE surface miner. The manufacturers claim that rock with Uniaxial compressive strength up to 150 MPa can also be cut by such machines. In pit crushing and conveying also called semi-continuous mining system are shovel-crusher conveyor system makes use of continuous conveying using belt conveyors. The OB and coal are crushed before putting them on conveyors. This technology has been successfully used in open cast –II Ramagundam area of Singareni Collieries Company limited. OB bridges and long boom spreaders these machines take the OB right across the mine and dump it in the areas where the coal has been extracted.

Most common surface mining domain is mining of developed pillars in thick seams, seams with disturbed coal band or as a fire project with pillars on fire (Singh, 2007). As the past pillar mining was extensively in quality coal seams, common operating domain of such surface mines is over Ramgundam to Wardha, Talcher to Bokaro and Jharia coalfields. Level of mechanization and achievement in terms of production and productivity in such cases has been invariably poor said to be because of the disturbed condition of the seams or strata. The Jharia coalfield presently working 32 open cast mines is typical example of production and productivity in such workings. May be of interest to note that all the mines are making huge profit in spite of such a low production and productivity as the mining is limited to coking coal. Many a time lower virgin seams of poor grade coal are left untouched, covered by burden or left as waste pit. Clear decoaled blocks or blocks mined up to the optimal depth are rare and the optimistic view of their future mining at later stages has prevented the reclamation and resettlement of the area.

External dumping a common scene has resulted in degradation of land, silting of farms, pastures and water streams. The scenes in giant planned surface mines is a bit encouraging in respect of reclamation but the plantation of trees – good as fuel and useful as CO₂ sink is not the end. India with lowest per capita land holding (0,20He) in the world and 70% population depending over the agriculture needs proper utilization of valuable soil during reclamation. Genetic engineering is developing species suitable for wasteland and the reclaimed dump is no inferior for future cultivation of suitable crops. This may be done only by the farmers and not by the professional miners. Remining of such blocks may involve rehandling of external dumps or mining of backfilled dumps. This unwanted operation along with lowering of coal quality in lower seams may make such operation uneconomical or may affect the limiting depth of surface mining. Surface mining of power grade coal mostly in virgin patches likely Singrauli, Rajmahal and Korba etc has been a big relief to the nation

in terms of 10-20Mt mass production from different pits. Reclamation and rehabilitation, production and productivity in some of the fields have been to fair satisfaction because of very favorable stripping ratio- often 0.5 to 2.5.

3.0 SLOPE STABILITY PROBLEMS

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 effect 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. In this chapter we will try to study the different types of the slope failure, factors affecting them, stability analysis technique and software available and which are developed. It is critical to pay attention to the pore water pressures as they tend to increase over time. This means that cheap, undrained shear strength tests are only useful if looking at very short term stability. The geological sequence and history must be known so we are sure if there are existing tectonic shears. Excavations are more susceptible to the effects of tectonic shears than embankments because embankments raise the normal effective stresses on potential sliding surfaces, and these offset the increased levels of shear stress they imposed.

3.1 The Economic Impacts Associated With An Unstable Slope

1. Loss of production.
2. Extra stripping cost for recovery and handling of failed material.
3. Cost of cleaning of the area.
4. Cost associated with the rerouting the haul roads.
5. Production delays.
6. Risk of production delays.

The stability of slopes is basically judged by the factor of safety. Factor of safety is defined as the ratio between the resisting forces to the distributing forces. Resisting forces depends on cohesion and angle of friction, while the Distributing force is related to gravity and ground water condition. If the factor of safety is greater than unity then the slope is stable but if it drops below unity the slope becomes unstable.

4.0 FACTORS AFFECTING SLOPE STABILITY

(a) geological discontinuities

1. nature of occurrence
2. orientation and position in space
3. continuity
4. intensity
5. surface asperities
6. genetic type
7. gauge

(b) properties of rock mass

(c) ground water and hydrology

1. direct effect of water pressure
2. indirect effect of water pressure

(d) mineralogy, lithology and weathering

1. fundamental consideration for different rocks
2. consideration of mineralogy and lithology

- 3. adverse physical and chemical processes
- (e) regional stresses**
 - 1. evidence of high horizontal stresses
 - 2. effect on surface excavation
 - 3. potential areas of high horizontal stresses
- (f) time**
- (g) slope and pit geometry**
- (h) blasting**
 - 1. pre splitting
 - 2. post splitting

5. INPUT PARAMETERS AND LIMITATIONS FOR SLOPE DESIGN

To improve the open pit slopes with flexible design criteria that could be easily adapted to changing geologic conditions, a series of design concepts were developed. Each concept consists of a basic slope type, and specific slope design criteria. Basically for designing slopes required the collection of data, the use of appropriate design methods, and implementing of excavation method and stabilization/protection measures suitable for the particular site conditions. In developing the slope design concepts, some basic slope parameters first need to design the slopes. These includes fixed criteria, such as bench height increment and minimum catch berm width (which were based on the size of the mining equipment and regulatory requirements), and more subjective consideration, such as the overall design factor of safety and acceptable level of risk. In some cases more than one slope design concept has applicable. For example, artificial supports were an alternative that provided a steeper slope design than a conventional approach, this alternative slope design provides with additional flexibility.

Rock slope stability analyses are routinely performed and directed towards assessing the safe and functional design of excavated slopes (e.g. open pit mining, road cuts, etc.) and/or the equilibrium conditions of natural slopes. In general, the primary objectives of rock slope stability analyses are:

- To determine the rock slope stability conditions;
- To investigate potential failure mechanisms;
- To determine the slopes sensitivity/susceptibility to different triggering mechanisms;
- To test and compare different support and stabilization options; and
- To design optimal excavated slopes in terms of safety, reliability and economics

5.1 Methods of Rock Slope Analysis

Conventional methods of rock slope analysis can be generally broken down into kinematic and limit equilibrium techniques. In addition, analytical computer-based methods have been developed to analyze discrete rock block falls (commonly referred to as rockfall simulators). All limiting equilibrium techniques share a common approach based on a comparison of resisting forces/moments mobilized and the disturbing forces/moments. Methods vary, however, in the assumptions adopted in order to achieve a determinate solution. Graphical analysis using stereonet techniques can also be carried out using block theory techniques to assess critical keyblocks. Critical input Parameters , and limitations are presented in Table 1.

Table 1: Critical input Parameters and limitations

Analysis method	Critical input parameters	Advantages	Limitations
Stereographic and Kinematic	Critical slope and discontinuity geometry; representative shear strength characteristics	Relatively simple to use and give an initial indication of failure potential. Some methods allow identification and analysis of critical keyblocks. Links are possible with other analysis	Only really suitable for preliminary design or design of non-critical slopes. Need to determine critical discontinuities that requires engineering

		methods. Can be combined with statistical techniques to indicate probability of failure and associated volumes.	judgement. Must be used with representative discontinuity/joint shear strength data. Primarily evaluates critical orientations, neglecting other important joint properties.
Limit Equilibrium	Representative geometry and material characteristics; soil or rock mass shear strength parameters (cohesion and friction); discontinuity shear strength characteristics; groundwater conditions; reinforcement characteristics and external support data	Wide variety of software available for different failure modes (planar, wedge, toppling, etc.). Mostly deterministic but increased use of probabilistic analysis. Can analyse factor of safety sensitivity to changes in slope geometry and material behaviour. Capable of modelling 2-D and 3-D slopes with multiple materials, reinforcement and groundwater profiles.	Factor of safety calculations give no indication of instability mechanisms. Numerous techniques available all with varying assumptions. Strains and intact failure not allowed for. Do not consider <i>in situ</i> stress state. Probabilistic analysis requires well-defined input data to allow meaningful evaluation. Simple probabilistic analyses may not allow for sample/data covariance
Rockfall Simulation	Representative slope geometry; rock block sizes and shapes; coefficient of restitution	Practical tool for siting structures. Can utilise probabilistic analysis. 2-D and 3-D codes available	Limited experience in use relative to empirical design charts.

The main approaches for slope stability analysis are model studies and limit equilibrium methods. The model studies include physical and mathematical models. Physical models have been used quite extensively to simulate the behaviour of full scale structures (Hoek, 1971). Equivalent material models give valuable information regarding various parameters of open pits in complex geo-mining conditions. The most important factors which affect stability of the slopes are geological factors, hydrological factors, rock types, physico-mechanical properties, etc.,. The stability of slopes depends upon the presence and nature of geological discontinuities within the rockmass. The potential failure surfaces are guided by the structural weaknesses, e.g., fault zone, fold axis, joints, bedding plane and foliation planes (Kutter, 1974).

Ground water can cause slope instability in different ways. Slopes, which are stable in dry season, may become highly potential for failures during rainy season. Water pressure on the joints is probably more responsible for slope failure than all other causes. Hence, a thorough investigation of the hydrological characteristics of the region is necessary before any surface mining operation (Piteau, 1970; Morgenstern, 1971). It is the water pressure, not quantity of water, that causes slope instability (Hunt, 1986). The water pressure at critical locations in the rockmass should be determined or assumptions on the flow conditions have to be made (Hoek & Bray, 1981). It is not very easy to calculate the water pressure behind the slope face precisely. However, due to its importance an engineering judgement is required to select the most likely ground water conditions during the life time of the mine for slope stability analysis (Hoek & Londe, 1974). Patton and Deere (1970) concluded that where joints are open, water pressure can not develop. However, in the rather tightly closed joints, water pressure can develop and increase against the slope face to cause

instability. Geotechnical field investigations include collection of geological data, joint mapping to identify the discontinuity trends and nature, and collection of all relevant information related to the slope design analysis. Acceptability criteria and various analysis methods are presented in Table 2.

Stability of the slopes is evaluated from empirical, analytical and numerical techniques. In homogenous, isotropic ground conditions, the factor of safety can be determined for predefined failure modes using limit equilibrium method. Some design charts are available, which are useful to analyse only simple types of predetermined failures, but not for determining the slope angle which depends on the rock mass stability, particularly the unfavourable joints. Accordingly, this project was taken up with an objective to develop design charts and design guidelines to determine slope angles for different slope heights in different rock mass conditions, which can be readily used by the practicing engineer. For the detailed studies, ten mines, namely Nanjankulam (ICL), Tirodi (MOIL), Dongri–Buzurg (MOIL), Pandalgudi (MCL), Medapalli (SCCL), Jayanthipuram (MCL), Pandarathu (MCL), Majhgawan (Panna, NMDC), Rampura-Agucha (HZL) and Malanjhand (HCL) mines, were selected (*Jayanthu et al, 2002a and 2002b*).

5.1.1 Limit equilibrium analysis

The limit equilibrium analysis for slope stability estimates the factor of safety against shear failure along a predetermined surface. Factor of safety is the ratio of stabilising forces and destabilising forces existing on the failure surface under study. The shear strength is mobilised to resist the shearing stress caused by the gravitational forces. The failure surface can be planar, circular or non-circular. Different failure surfaces are analysed to identify the surface with minimum factor of safety. Circular failure analysis is done using Bishop's method for the whole slope to assess deep seated failures, and for slopes covering a few benches to assess the local failures. On the other hand, non-circular failure analysis is done using Sarma's method, which mainly checks the possibility of failure through different rock types. For the benches in the selected mines, two dimensional limit equilibrium analysis was performed for plane, non-circular, circular and toppling failures. For this purpose, software named GALENA, originally developed by BHP Engineering, Australia (GALENA, 1990) was used.

5.1.2 Numerical modeling

The limit equilibrium method, however, does not take into account the in-situ stress existing in the rock medium. The excavation in a mine will alter the stress state, and the deformation caused by the induced stress may be excessive. In order to study the effect of in-situ stress on the stability of the slopes, stress analysis using numerical modeling was performed in some of the cases. The numerical analysis was performed using UDEC (Universal Distinct Element Code), of Itasca Company, USA (UDEC, 1993). This is a discontinuum numerical technique first proposed by Cundall (1971). In this the rock mass is simulated as an assemblage of blocks which interact through corner and edge contacts. Discontinuities are regarded as boundary interactions between blocks, and joint behavior is prescribed for these interactions. The method utilizes explicit time stepping algorithm which allows large displacements and rotations and general non-linear constitutive behaviour for both rock matrix and the joints.

In general numerical models can be classified into two categories; discontinuum and continuum models. Although discontinuum models can be more useful for simulation of real life situations, it requires more sophisticated input data and processing time. However, as a preliminary analysis tool, continuum models are most commonly used for analysis and then a detailed analysis with calibration would be carried out for more reliable estimation of the stresses and deformations in a model. Some of the finite difference and distinct element codes of two and three dimensional numerical models such as of FLAC (Fast Lagrangian Analysis of Continuum) are used for understanding stability of slopes in a typical case study. Stability analysis for a typical opencast coal mine is presented in Fig 2. It shows the factor of safety exceeding 0.59, and considered as unstable. It was also observed that the slope in the field was unstable and collapsed recently. Further analysis is in progress for design of safe slope with varying bench heights and angle of the slope and benches in the site specific condition. Generally, if the factor of safety for the slope under analysis was above 1.2, then it was considered stable, and if it was less than 1.2, then the slope was considered to be potential for failure. In cases where the mining has to be carried out fast and the benches have to stand only for a short time, then the cut-off value for the safety factor could be 1.1; with constant and systematic monitoring, the safety factor of even 1.05 could be allowed.

In other hand Numerical modeling is used to design the critical slopes (Table 3) , which will give the better solutions for any type of the problematic slopes in the opencast mine. In comparison, non-numerical analysis methods such as analytic, physical or limit equilibrium may be unsuitable for some sites or tend to oversimplify the conditions, thus the Numerical analysis can evaluate multiple possibility of geological models, failure modes, and design options. Equilibrium is satisfied only on an idealized sit of surface. With numerical models, a full solution of the coupled stress/displacement, equilibrium and constitutive equation is made, given a set of properties the system is found to be either stable or un stable.

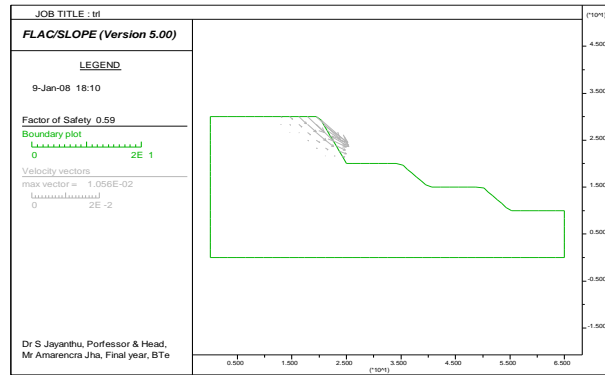


Fig 2: Stability analysis of a typical opencast mine in a Numerical model (Factor of Safety = 0.59)

Table 3: Advantages of various numerical modeling methods

Analysis Method	Critical Parameters	Advantages	Limitations
Continuum Modelling (e.g. finite- element, finitedifference)	Representative slope geometry; constitutive criteria (e.g. elastic, elastoplastic, creep, etc.); groundwater characteristics; shear strength of surfaces; insitu stress state.	Allows for material deformation and failure (factor of safety concepts incorporated); can model complex behaviour and mechanisms; 3-D capabilities; can model effects of pore pressures, creep deformation and/or dynamic loading; able to assess effects of parameter variations; computer hardware advances allow complex models to be solved with reasonable run times	Users must be well trained, experienced and observe good modelling practice; need to be aware of model and software limitations (e.g. boundary effects, meshing errors, hardware memory and time restrictions); availability of input data generally poor; required input parameters not routinely measured; inability to model effects of highly jointed rock; can be difficult to perform sensitivity analysis due to run time constraints.
Discontinuum Modelling (e.g. distinct- element, discrete- element)	Representative slope and discontinuity geometry; intact constitutive criteria; discontinuity stiffness and shear strength; groundwater characteristics; in situ stress state	Allows for block deformation and movement of blocks relative to each other; can model complex behaviour and mechanisms (combined material and discontinuity behaviour coupled with	As above, user required to observe good modeling practice; general limitations similar to those listed above; need to be aware of scale effects; need to simulate representative discontinuity geometry (spacing, persistence,

		hydro - mechanical and dynamic analysis); able to assess effects of parameter variations on instability.	etc.); limited data on joint properties available (e.g. jkn , jks).
Hybrid Modelling	Combination of input parameters listed above for stand-alone models.	Coupled finite- /distinction element models able to simulate intact fracture propagation and fragmentation of jointed and bedded rock.	Complex problems require high memory capacity; comparatively little practical experience in use; requires ongoing calibration and constraints

6. CASE STUDIES – APPLICATION OF MSMR

6.1 Nanjankulam Limestone Mine, India Cements Ltd.

In the footwall quartzite benches at this mine, a cohesion of 60 kPa and friction angle of 37.7° was sufficient for stability against planar mode of failure. This condition was applicable for a bench height of 10 m and bench slope angle of 90° under saturated condition for a discontinuity angle ranging between 40° and 80°. The factor of safety for this was between 1 and 2. For a discontinuity angle between 40° and 50°, the required cohesion was 50 kPa. It was seen that for a block in a bench to be stable under fully saturated condition, it was required to have minimum 50 kPa cohesion. Detailed analysis of the slopes at Nanjankulam mine revealed that the wedges formed by different intersections in the footwall require minimum 15 kPa and maximum 25 kPa of cohesion for the wedges to be stable. In the hangwall, the wedges require minimum 10 kPa and maximum 20 kPa of cohesion for them to be stable. It was observed that cohesion of 25 kPa was sufficient for any wedge geometry located on any wall. Based on two-dimensional numerical analyses, the following slope angles were designed, which were the same for both the footwall and the hangwall :

bench height		10 m
individual bench face angle	80°	
berm width		3.25 m
overall slope angle		47°

6.2 Pandalgudi Limestone Mine, Madras Cements Ltd.

Based on the kinematic and simple stability analysis, detailed limit equilibrium analysis was carried out. It was seen that in the footwall, some of the blocks were potential to fail by plane failure. The analysis was performed for different block geometries, which were kinematically possible to slide. These blocks were back-analysed using design friction angle to get some idea about the cohesion mobilized during failure. In the hangwall, the blocks were potential to fail by wedge failure. Therefore, the analysis was performed for different wedge geometries that were kinematically likely to slide. The wedge geometry was back-analysed using design friction angle to get some idea about cohesion mobilized during failure. The stress analysis of the open pit excavation was performed using UDEC, considering the rock mass as an equivalent continuum by reducing the strength and stiffness parameters of the intact rock using RMR. The analysis was performed by discretizing the model region by triangular finite difference mesh. The region near the pit enclosing a distance of 50 m was discretized heavily to model the stress concentration. The displacement vectors showed a definite mass flow pattern. The displacement along the boundary shows movement upwards and towards the opening. The maximum displacement vector was 2.36 cm observed on the footwall and hangwall. No plastic and or tensile failures were observed. The analysis did not show any abnormalities.

Based on the different types of analysis performed, the slope angles were designed as :

bench height (maximum)	10 m
bench width (minimum)	2.5 m
overall slope angle	43.5° for footwall, and 43° for hangwall
bench face angle	57° in the footwall (if the dip of joint set 1 was other than 57°, the bench face angle at those locations should be along the dip of joint set 1) 66° in the hangwall

6.3 Jayanthipuram Mine, Madras Cements Ltd.

The slope stability analysis was carried out using Bishop's simplified method and Sarma's method. From the field monitoring, it was found that the ground water level adjacent to the river was about 4.5 m, which may be higher in the worst situations. Keeping this in view, the slope was assumed to be completely saturated (worst possible condition). The rock mass properties estimated from the laboratory test results and the in-situ conditions were used in the analysis. For the top 5 m, soil properties were used. Different possible surfaces were analysed and the least factor of safety determined. The rock mass cohesive strength of 150 kPa and rock mass friction angle of 25° was used in the analysis.

The analysis was carried out for different depths, considering different overall slope angles for both circular and non-circular failure surfaces. Based on the least factor of safety values obtained, the following recommendations were made for different pit depths (applicable to both footwall and hangwall):

<u>Depth of the pit (m)</u>	<u>Overall slope angle (°)</u>
20	75
40	65
60	45
80	35
100	28

6.4 Pandarathu Limestone Mine, Malabar Cements Ltd.

There was a wide variation in geology of the pit. Therefore, a minimum safety factor of 1.3 was considered in this mine. The analysis were performed by varying the overall slope angle and pit depth. The joint data was analysed using hemispherical projections. Kinematic analysis showed that the benches in the gneiss were not potential for plane, toppling or wedge failures, but non-circular failures could be expected. So the analysis was carried out for both circular and non-circular failures, and accordingly slope angles were designed for different pit depths. These slope angles can be applied to gneiss portions in any of the four zones (North, South, East or West).

Depth (m)	Overall slope angle (°)
20	80
30	70
40	60
50	50
60	45
70	40
80	35
90	30

Slope Mass Classification

The strata comprising the slopes can now be classified in terms of stability using the MSMR values as follows :

Class	MSMR	Description	Stability
II	> 50	Good	Stable
III	31 – 50	Normal	Partially stable
IV	< 30	Bad	Unstable

For specific expected type of failure and the required support measures, the original SMR approach as given by Romana may be used. The individual bench angle (S_b) and the overall slope angle (S_o) can now be obtained from MRMR as follows :

$$S_b = 22 * \ln (\text{MSMR}) - 18$$

$$S_o = 14 * \ln (\text{MSMR}) - 16$$

7. SLOPE DESIGN CRITERIA:

On the basis of the engineering geology model and slope stability analysis, the general range of bedding orientations, within which each of the basic slope type is applicable, is accessed for each structural domain. In a given structural domain where bedding dips in the same direction as the slope, for example type I or II slopes may be applicable for bedding dips of less than 25 degree, type II slope for bedding dips up to 40 degree and for III or IV dips in the range of 40 degree to 90 degree. Where bedding dips in to the wall in between the 70 degree and 90 degree, type V or VI may be applicable. Type VII may be applied where bedding dips in to the walls at flatter than about 70 degree and where bedding strikes obliquely or normal to the slope, type VIII slope may be applicable.

For each applicable slope type and range of bedding orientations, design criteria are then developed which specify geometrical parameters such as bench height, bench face angle, berm width, spacing of artificial supports, etc as appropriate. These criteria are usually based on result of stability analysis and basic slope design criteria's are described in Table 4.

Table 4. Basic slope design criteria and its application

Basic slope type	General orientation of bedding	Application	General criteria	comments
I Benched (bedding undercut)	Dips shallowly out of slope	Footwall slopes not subject to major plane failure if bedding under cut but minor plane or stepped failure may occur	Benches designed to limit size of and provide catchments for potential minor or stepped failure	Slope angle steeper than the bedding dip is feasible. Unbenched slope is acceptable.
II unbenched	Dips shallowly to moderately in same direction as slope.	Footwall slopes not subject to buckling, ploughing, bilinear or other slab type failures.	Bench faces excavated parallel to bedding. Bench height designed to limit size of potential slab type failures, berms designed to contain	No assess to slope rock fall protection may be required

			minor slab type failure	
III Benched (bench face parallel to the bedding)		Footwall slopes subject to major buckling, ploughing, bilinear or other slab type failures	Bench faces excavated parallel to the bedding. Bench height designed to limit size of potential slab type failures. Berms designed to contain minor slab type failure.	May be used in conjunction with type IV to increase bench height and reduce berm width
IV Unbenched supported	Dips moderately too steeply in the same direction as slope.	Footwall slopes subject to major buckling, ploughing, bilinear or other slab type failures	Slope excavated parallel to the bedding. Support spacing or length designed to prevent major slab type failures.	May be used in conjunction with type III to limit amount of artificial support and provide berms for access rock fall catchments.
V Benched	Dips steeply in to slope	Footwall or hanging wall slope subject to toppling.	Single benches generally preferred. Benches faces inclined to reduce over turning moments. Berms designed prevent	May be used in conjunction with type VI to increase bench height, bench face angle, and slope angle and bedding berm width.
VI Benched supported	Dips steeply in to slope	Footwall or hanging wall slope subject to toppling	Double bench may be suitable support spacing or length designed to prevent toppling bench faces inclined reduce overturning moments. Berms designed to prevent toppling of multiple benches.	Artificial support allows higher benches steeper bench face angles and steeper overall slope.
VII Benched	Dips shallowly to moderately in to the slope.	Footwall or hanging wall slopes subject to stepped failures.	Benches designed to limit size of and provide catchments for minor stepped failures.	
VIII Benched	Endwall slope subject to stepped failures.	Benches designed to limit size of and provide catchments for minor stepped failures.		

The design criteria will vary depending on the critical failure mechanism and basic slope types. For example in the case of I, IV, VIII slopes, design criteria may consist of fixed bench height, bench face angle, and berm width designed to limit the size of possible failure and bench crest break back, provide access to slope and provide catchment for small failures, rock falls and raveling debris. In the case of type III and IV slopes which may be applicable over a wide range of bedding orientations, bench height and berm width may vary, depending on the slope angle. For type V and VI slopes, variable bench face angles and bench height may be applicable as described. Typical design bench height criteria for bench foot wall slope as illustrated below. In this example bench heights are limited by two different kinematically possible failure mechanisms which control design over different range of bedding dip. Analysis results are presented in terms of range of conditions which may occur in the slope. Possible design criteria are illustrated for two cases representing optimistic and conservative design respectively.

In some cases, more than one basic slope design concept may be suitable for a given range of bedding orientations. In this regard, comparison of relative cost and operational flexibility may be required to determine the optimum slope design.

8. D.G.M.S. RULES FOR SLOPE AND HEIGHT OF THE BENCHES:

In alluvial soil, morum, gravel, clay, or other similar soft ground, the sides shall be-

- (i) sloped at an angle of safety, not exceeding 45 degree from the horizontal, or such other angle as the regional inspector may permit by an order in writing, and subject to such conditions as he may specify there in; or
- (ii) kept benched, and the height of any bench shall not exceed 1.5m, and the breadth thereof shall not be less than the height.

However, in coal mines, the regional inspector, and in metalliferous mines, the chief inspector, may, by an order in writing, and subject to such conditions as he may specify there in, exempt from the above provisions, any working in the case of which special difficulty exist which, in his opinion, make compliance with the provisions not reasonably practicable. To bring uniformity, the regional inspector should have this power in metalliferous mines also.

In metalliferous mines, where float ores or other mineral is worked by manual means on a sloping face the face shall be benched and the sides shall be sloped at an angle of not more than 60 degree from the horizontal. The height of any bench shall not exceed 6m, and the breadth thereof shall be not less than the height. Wherever, however the type of ore body consist of comparatively hard and compact rock, the regional inspector may by an order in writing and subject to such conditions as he may specify there in, permit the height of the bench to be increased up to 7.5m, while its width is not less than 6m. In any excavation in any hard and compact rock, or in prospecting trenches and pits, the sides shall be adequately benched, sloped or secured so as to prevent danger from the falls of the sides. In coal the sides shall be either kept sloped at an angle of safety, not exceeding 45degree from the horizontal, or the sides shall be kept benched, the height of each bench not exceeding 3m, and the width thereof being not less than the height.

The chief inspector may, by an order in writing and subject to such conditions as he may specify there in, exempt from the above provisions, any working where special condition exists which, in his opinion make compliance with the above provisions not reasonably practicable. Such special conditions may be

- (a) surface features
- (b) geological disturbances
- (c) Mine boundaries etc.

When determining the slope of any pit or quarry face, consideration should be given to the nature of material excavated, the extent to which the material is cemented or consolidated, the height of the face, the type and size of the equipment being used, and the amount of the protection this equipment gives to the operator and other employees. Table 5 gives the Maximum permissible bench slope and bench heights:

The regulations are not sufficient to cover all geological conditions, e.g. faults, folds, wash-outs, strata surcharged with water under pressure, etc. the following factors, responsible for slope stability are considered carefully in arriving at suitable bench dimension:

- (a) nature of rock forming bench
- (b) wetness of the pit
- (c) presence of planes of weakness
- (d) irregularity of mineralisation

Table 5: Maximum permissible bench slope and bench heights:

Sl.no	Type of rock or mineral	Maximum slope from horizontal and maximum bench height permitted
1.	Sand	26 degree slope and no limit of bench height
2.	Kankar, loose soil, morum, gravel, marl, shingle, clays, and other dump materials	33 degree slope and 3m bench height
3.	slate, shell, laterite	45 degree slope and 6m height
4.	coal	75 degree slope and 6m height
5.	lime stone or sand stone	75 degree slope and 10m height

9. CONCLUSIONS

Over the decades, rock slopes have been characterized using the empirical approaches for preliminary assessment of the stability of a natural or man made slope in a rock mass. In the present ten case studies in opencast mines, the SMR values and the classes categorized by SMR did not correspond with the actual slope conditions prevailing at the mines. The MSMR came into existence as a modification in SMR. It was found that in all the case studies the description and category of the slopes obtained from MSMR was in conformity with the actual situations. When the above relation was used for the actual cases, the designed bench slope angles were within 10% variation as compared to the results of numerical / limit equilibrium analyses. It was established that MSMR of 50 and above indicates stable slopes and below 40 indicates instability. The slopes can be assessed for their stability even in the preliminary stages of development prior to mining, and for the future planning. The MSMR may be estimated based on surface joint mapping, assumed slope angles, and the likely inputs proposed for the mining. To make the system universally applicable and to widen the scope of the approach it is desirable to apply the MSMR in a large number of operating opencast mines.

The results of the above slope stability analyses were used to design the individual and overall slope angles at the mines. Generally, if the factor of safety for the slope under analysis was above 1.2, then it was considered stable, and if it was less than 1.2, then the slope was considered to be potential for failure. In cases where the mining has to be carried out fast and the benches have to stand only for a short time, then the cut-off value for the safety factor could be 1.1; with constant and systematic monitoring, the safety factor of even 1.05 could be allowed.

In view of the availability of the state of the art instrumentation in monitoring the slopes, and well accepted impetus on observational approaches in design of many structures in natural materials like rocks, the following action plan would lead to appropriate design of rock slopes:

- Preliminary design based on kinematic analysis and available empirical approaches—RMR, SMR etc
- Verification of stability by using numerical models, and modification of design
- Meticulous field monitoring of designed slope using state of the art modern instrumentation
- Modification of the design depending on the integrated results of kinematics, empirical, numerical and observational approaches.

Many slope failures or uneconomic overdesign of slope in recent times emphasizes the need of proper education to the concerned on the limitations and applicability of the existing guidelines and further studies required for the purpose. Therefore, it is required to create an appropriate task force including statutory, field, academic and

research agencies to reevaluate and formulate appropriate guidelines on design of safe and economic slopes in mines and other structures.

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