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SLOPE STABILITY ANALYSIS IN OPENCAST MINES

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ABSTRACT
Slope stability and slope monitoring have become very common terms in opencast mines. Engineers, research scholars and scientists are inventing, innovating and publishing research articles on novel slope stabilization and slope monitoring ideas. The advent of Wireless sensors and IoT have drastically improved the standards of slope management. Considerably it has a major contribution to the cost reduction in the slope management system which lured small scale mining companies to adopt them. Although it is admirable that many mining firms have stepped forward to prioritize mine safety and embrace different wireless sensor networks (WSN) in slope management techniques, some flaws still exist that should be addressed. Many slope failures occur as a result of the collective influence of different aspects thus a combination of sensors that measures multi aspects of slope movement is indispensable. Acquiring acquaintance with several aspects of slope failure paves the way to enhance the slope monitoring system. So, in this paper, a detailed study of different factors affecting slope stability, slope monitoring and method of slope stability are discussed.

Keywords- components of slope; Mine safety; opencast mines; slope stability; slope design; slope instability.

1) INTRODUCTION
Slope failure is a phenomenon when the self-retaining ability of a slope is deteriorated and root the slope to collapse. One of the leading causes of mine fatality is slope failure, slope stability related issues significantly affect all aspects of mining. It is expected that almost one million American dollars' worth of losses occurs in a mine for each incident caused by slope failures excluding the halt of mining works during the investigation process. In the early days, it was used to be mostly the underground mines to mine minerals from the ground. As the requirement for minerals like coal enlarged the surface mines evolved because of their very own various advantages. Slope stability difficulties amplified when the height and width of the benches became higher and wider to ply massive mine machinery to improve the run of mine but, it resulted in unstable bench slopes. Then it has become requisite to study and understand the slope parameters that trigger off slope failure, slope stability analysis and slope monitoring are efficient tools to restrain the direct and indirect losses of slope failure. In the mid-19s, the period of the birth of mechanized mines, the knowledge about the factors affecting the slope stability learnt by the people can be perceived from Thornbury, describes that factors affecting the slope stability were classified into active and passive factors. The water circulation and anthropogenic factors were active factors and lithology, stratigraphic, topographic, geological structure were passive factors including climate. Mergers of different fields of study like rock engineering, earth science and others have yielded vast wisdom in this subject.

These slope failure accidents in Indian mines have taken place due lack of sound design of slopes and lack of monitoring. So, the coal industry has identified slope design, monitoring and stabilization as one of the thrust areas. Slope monitoring by cyclops was done to prevent failures, take remedial measures and to provide solutions against instability. The deformations are to be continuously detected and monitored, so that suitable preventive measures can be taken. Engineering of safe and stable slopes is of significant importance and is normally carried out by empirical, observational or analytical techniques.

2) OBJECTIVE
Here there are some objectives that we are going to give a brief explanation regarding the slope stability analysis in open-cast mines and the following objectives that we are going to addresses are:

1. To study about the factors that affecting the slope stability in opencast mine.
2. To study about the slope monitoring in open -cast mines.
3. To study about the methods for slope stability in open-cast mines.

3) TYPE OF FACTORS AFFECTING IN SLOPE STABILITY

The dependence of slope stability on several factors can be generalized as follows. One of the important basic parameters of a slope is the kind of material involved, intact rocks such as gneiss are stable in contrast recent volcaniclastic materials are highly unstable. The geometry of the slope material, for example, the dip direction of the layered rock towards the slope direction makes the slope more unstable. The weight distribution along the slope will put additional resistance towards sliding, weight distribution over the slope creates additional shear stress and triggers sliding. Groundwater decreases cohesion and raises the mass of the rock and pore water pressure in granular media. Impulsive forces from exterior sources like earthquakes and others cause severe effects on the slope. The brief factors that affect slope stability are discussed exclusively in the following.

A. Geological Structures

The slope monitoring systems, slope stabilization, slope stability analysis and other studies related to slopes are fastened to the geological structures or geological aspects of the slope. Slope stability evaluation procedures in empirical methods tend to ignore geological structure's critical role in controlling slope kinematics and stability. Geological structures of a slope decide the type or mode of the failure such as planar, wedge, circular and toppling failure. According to Saadoun, the most important geological structures are the amount and direction of dip, intraformational shear zones, joints, and discontinuities and faults in a slope. The number, orientation and distribution of Bedding planes, laminations, joints, pore spaces, cleavages, and faults are considered as the plane of weaknesses where the action of failure will occur, and also these factors control porosity, permeability and the amount of water that can enter the rock. Fig. 1 from Hudson & Harrison shows the important geological structures of a rock mass.

A.1. Incompetence of Rock:

Mechanically infirm rocks are inept at supporting steep slopes on either natural or engineered slopes that are susceptible to rotational slumping and mudflows when undermined by erosion or saturated with water. Mostly fine-grained sedimentary rocks such as siltstones, mudstones, shales and clays are typically incompetent rocks that cannot hold rock movement after certain slope angles and heights. Mechanically strong rocks such as sandstone, limestone, granite, basalt, gabbro and gneiss are typical competent rocks that are capable of supporting steep slopes.

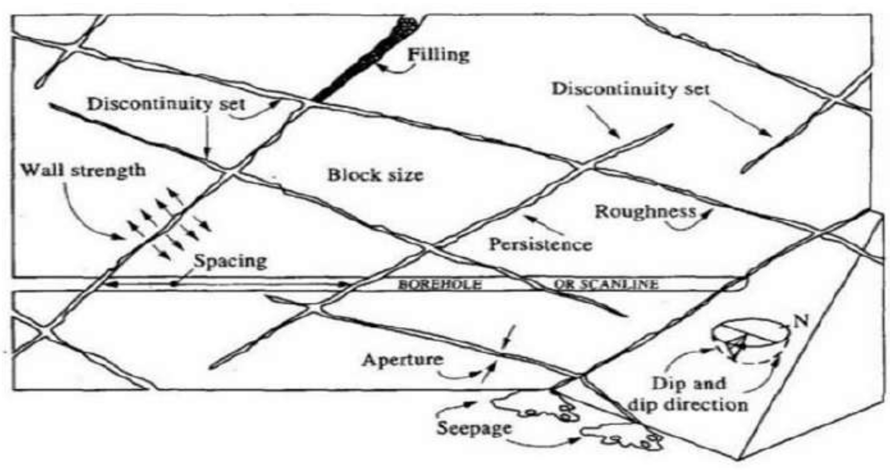

Fig. 1: Geological structure of a rock mass [1]

A.2. Tension cracks

These are formed due to the movement of the front face of a slope on its self-weight or as a result of any other external forces, that are found near the crest of a bench. These cracks are prone to propagate and disconnect the rock face from the body and in addition provide a thrust force when it is filled with water or gravel and soil. Park & Bobet performed experiments in which the sample rock specimen with a tension crack is subjected to uniaxial compression load and observed primary and secondary cracks propagation as the result. The primary cracks are initiated at the edges of the tension crack, coplanar and oblique are the two types of secondary cracks generated by shear and feature pulverized material on the failure surface.

A.3.Joints and discontinuities

Joints are fractures that are regularly spaced in a rock mass. Joints are formed by contraction while cooling, expansion while heating or relief of pressure as the overlying rock is removed by erosion. The individual joints and discontinuities are a major reason for the instability of a rock slope. Read & Stacey quote that the rock slope stability is extremely dependent on the spatial distribution of the slope and its configuration. When there is a joint or discontinuity in an intact rock, the joint tends to face the whole sliding force and creates a line of weakness that will fail eventually.

A.4.Groundwater and lithology

Groundwater causes adverse effects on the stability of the slopes by increasing the upthrust of driving water forces, it creates rubble at the bench toe that collapses the slope in due course. Groundwater greatly contributes to the reduction of the compressive strength of the rock by its physical and chemical effects on the pores of the rock. The attractive forces between particles prevent absorption of water unless groundwater pressure is overcome. A sudden change in precipitation levels or water flow may swiftly move a slope, and it accelerates the weathering process by penetrating fractures. Pictures that are shown in the Fig. 2 exhibit effects of groundwater saturation in rock slope, when the groundwater is at saturation level (Fig. 2 left) water fills the pores of the rock and friction between the grains holds the sediment together, but when it is liquified (Fig. 2 right) due to the pore pressure the water surrounds the grains and eliminates the contact between them and loses friction.

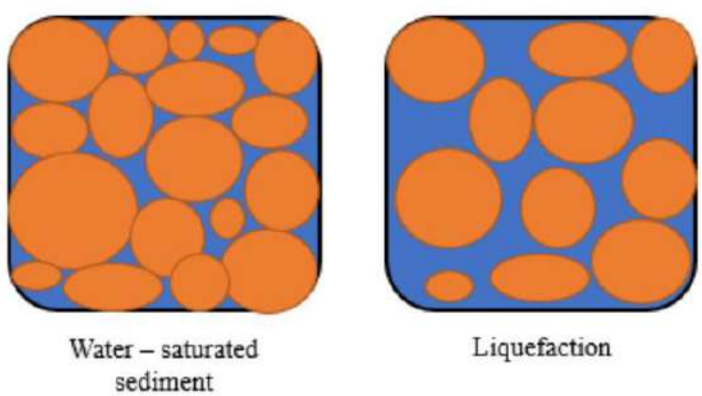

Fig. 2: Effect of groundwater saturation in the rock mass

B. Geotechnical Factors

In Turkey, using physical-based models Yalcin determined the influencing geotechnical factors that affect the slope stability, which are porosity, cohesion, angle of internal friction, plastic limit, void ratio, plasticity index, liquid limit, in-situ water content, and saturated unit weight and dry density. Kim & Song from Korea and Bicocchi from Italy similarly suggests dry density, porosity, permeability and internal angle of friction as the vital geotechnical factor. Mali in a research study concluded that relative compaction, porosity, in-situ water content, internal friction angle, slope angle and saturated permeability as the most relevant causal factor of slope failures.

B.1. Rock strength

The strength of the rock on slopes contrasts extensively. The rock strength is reliant on the material properties or the type of the rock, which refers to the chemical composition of the rock in terms of the minerals it is composed of. Rock type influences the types of weathering processes and resultant products that are likely to be occurring on a particular rock type. For instance, rocks like gneiss, granite and basalt are strong without non-consideration of factors like fracturing and layering, while metamorphic and sedimentary rocks like schist and dolo stone kind of rocks are weak in rock strength.

B.2. Shear strength

The ability of the rock mass to hold the slope in stable conditions is determined by the shear strength of the material. Rock mass on the slope is constantly pulled vertically downward by gravity. This vertical downward force can be resolved into two components, one is the shear force that drags the rock mass along the slope downwards and another one is the normal force pushing the rock mass into the slope itself. Rock mass to drift from the slope, the shear force has to overcome the shear strength of the rock mass. The shear strength of the material is dependent on various other factors like joints and discontinuities, cohesion, friction and density, but on the whole shear strength can be used to represent the stability of the slope. Fig. 3 from Chaulya exhibits the relation between shear stress and normal stress and how cohesion and friction have an effect on it.

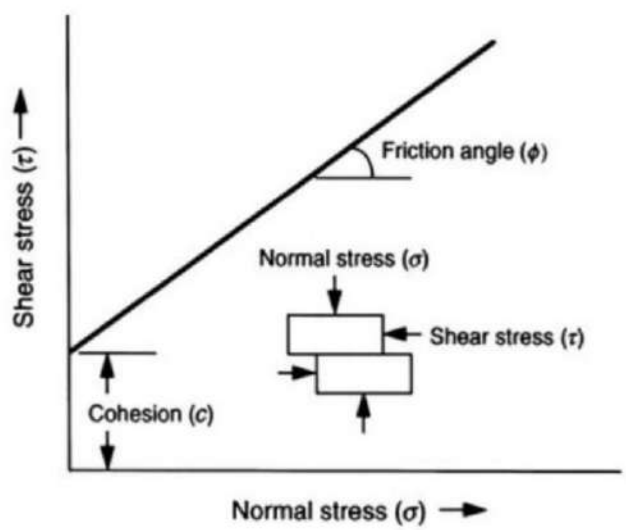

Fig. 3: Relation between shear stress and normal stress

B.3. Internal angle of friction

The internal angle of friction is the measure of the ability of a slope of rock to bear shear stress. It is the angle measured between the resultant force and the normal force that is achieved when the failure occurs in response to shear stress. Higher internal angle of friction results in a higher factor of safety and lower slope stress, strain and displacement. Typically, the coefficient of sliding friction is the measure of a rock or soil's ability to withstand shear stress. Particle roundness and size affect the coefficient of sliding friction. It is also affected by quartz content.

B.3. Cohesion

When rock is sheared at zero normal pressure, it generates a measurable resistance that is measured in pascals, this force of resistance per unit area is the apparent cohesion. A higher value of cohesion results in a higher factor of safety and lower slope stress, strain and deformation of the slope. Cohesion is a characteristic property of rock or soil, that measures the resistance of the rock or soil to be deformed or broken by forces such as gravity. The slope that is less cohesion tends to be weaker in nature.

B.4. Slope Geometry

The necessary goal of a slope design process is to enable a safe and economic design for the mine bench, ramp or overall slope. Slope design of a mine that gets deeper and larger naturally concomitant high risk in size of failure and consequences. The three main parameters in geometric slope design are height, overall slope angle, and failure area. As slope height increases, slope stability decreases. By increasing the overall slope angle, the possibility of any failure occurring at the rear of the crests may also increase, and it should be considered so that local ground deformation can be avoided in the mine's peripheral area. Fig. exhibits some of the basic components of open-pit mining.

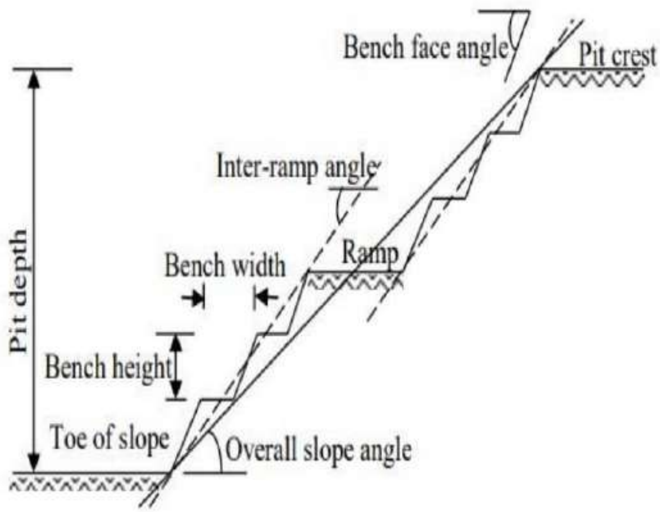

Fig. 4· ıematic openpit diagram [6]

B.5. Angle of slope

One of the most important factors contributing to slope instability is slope angle. The slopes of different study areas can differ based on their morphology. The greater the angle of a slope, the more unstable it is. Since the risk of landslides is higher on steeper slopes, it stands to reason that the other factors are identical. This parameter has been used to zone the risk of landslides in different studies because of its importance in landslide zonation. Surfaces with an angle of less than 10% also do not slip. According to DGMS, the overall slope angle of any mine should not be greater than 45°. As the curvature of the slope has a deep effect on slope stability, it should be avoided in slope design.

B.6. Height and width of the bench:

The bench height and width are determined based on various factors like loading machine bucket capacity, cutting height of the bucket, production parameters, pit slope stability etc. according to Li the height and width of the benches are designed higher because of the following reasons.

(i) Higher and wider benches facilities plying of large machinery that means more production.

(ii) Maintenance time will be reduced.

(iii) Supervision and other operation will be easier.

(iv) Facilitates the blasting of bigger blocks that will yield more production. But the problem associated with higher and wider benches is the safety issues.

The factor of safety is the common measure of slope stability in open cast mines. Generally, for open cast mines, the safety factor used is in the range of 1.2 – 1.4. According to the DGMS (tech.) circular no. 03 of 2020, guidelines for scientific study under regulation 106 of coal mines regulation, 2017, the minimum factor of safety to be considered for design of pit, bench & dump slope shall not be less than 1.50 for permanent slope and 1.30 for other slopes.

C. OTHER SOURCES OF SLOPE DISRUPTION

C.1. Soil erosion

There are two aspects of erosion to consider. In the first case, there is widespread erosion, such as river erosion at cliff bases. The second type of erosion is caused by groundwater or surface runoff. Erosion changes the geometry of a potentially unstable rock mass in the first type. The removal of material at the toe of potential slides reduces the restraining force that may stabilize the slope. The erosion of joint filler material or weathered rock can effectively reduce interlocking between adjacent rock blocks.

C.2.Seismic effects

During a seismic event, there is an added layer of pressure that can cause the rock to fracture. Unconsolidated masses are less likely to friction when they have jarred apart. During earthquakes, liquefaction may occur, and landslides are one of the major hazards. Particularly at the plate boundaries, where the most unstable parts of the earth are formed. Here, high relief and steep slopes are seen as well as the formation of new folds in the mountains. Although many open pit operators are familiar with the back break, most of them only consider the visible damage that occurs behind the rows of blast holes.

C.3.Equipment and mining methods:

The method of mining and mining equipment decides the period slope face exposed as a slope. The slopes are creepy and offer deformation and strain with respect to exposure duration. Benches of deeper and bigger mines ought to stand still year together and it is obvious that different type of surface mining method applies different approaches towards this issue. In general, there are four methods of advance in surface mines, advancing down the dip strike cut, advancing up the dip strike cut, dip cut along the strike and open-pit working. Advance with dip cuts are oblique to the strike that is used to reduce the strata stress and it often reduces the time and length of face exposure and during excavation. The open-pit mining method is largely used in steep seams, this method offers larger slope heights and that are more prone to bulk or slab mode of failure. The accumulation of mining equipment on the benches of an open-pit mine increases the surcharge, which in turn leads to a downward force pulling the slope face and causing instability.

4) TECHNIQUES OF SLOPE MONITORING

For monitoring mine slopes there are various monitoring techniques from simple visual inspection to complex GPS and radar scanning. All these techniques can be classified into conventional and modern-day techniques, as presented in Figure 2.

A. Conventional Techniques

Conventional or traditional monitoring techniques involve physical examination and mapping of tension cracks along the slope face.

A.1 Visual Inspection

All mine personnel are involved in slope monitoring directly or indirectly. The initial stage in slope monitoring is a visual inspection, which is the foundation of any monitoring programme. Mine workers search for any evident signs of deformation and then report them for a more thorough examination and monitoring. Routine inspections of active mine slope and dumps slopes is done by mine management. Last visit observations are compared with the current data.

A.2 Surface Monitoring

Cracks at the surface are a strong indication of instability. Existing cracks are highlighted to distinguish them from the new cracks. The movement of points on the surface in relation to one another can be calculated by measuring the separations between two cracks with a survey tape or rod or extensometers. Total stations require a survey network of several prisms or monitoring stations set on the slope at regular intervals. Using the movement of prisms, the relative motions of the target prism at the monitoring locations aid in identifying the deformation and key failure zones.

Because they relieve humans from tedious, continuous work, surveying robots or robotic total stations are increasingly being used to monitor buildings and terrain. With the advent of long-range, high-accuracy total stations, slope monitoring with prisms has nearly become a real-time solution. Robotic total station networks include a built-in photogrammetric camera and GNSS receivers to provide automated, accurate, efficient, and cost-effective survey solutions.

Digital photogrammetry has been used to study slopes by comparing images for decades and has recently evolved to include 3D models from terrestrial images. The digital image processing tools available now allow for the automated collection of discontinuities and related information, eliminating the risk of human bias and enabling the survey of inaccessible locations and steep rock faces. Earlier, robotic total stations and now, with the introduction of Remote Sensing technologies, slope monitoring has become more accurate.

A.3 Subsurface Monitoring

Subsurface techniques like installing apparatus in long boreholes or transmitting signals into the rock mass are used. The movement along the weaker planes is collected as signals by sensors showing slope deformation status and even stress accumulation along the weaker zones. Extensometers map movement along a crack to distinguish an unstable rock mass from a stable segment of rock-mass. The weight linked to the wire moves as the earth accelerates along the fractures, and the displacement measurements are recorded in the monitoring device with digital outputs for downloading data. Inclinometers monitor subsurface motions and determine whether they are steady or accelerating, ensuring that deformations are within limits. Slope inclinometers measure the amount, depth, direction, velocity, and type of slope movement.

Also, servo-accelerometers are used as sensors within inclinometers to measure proper acceleration. Both an extensometer and an inclinometer measure the slope's relative movement. Piezometers are also being used for monitoring slope instabilities with groundwater issues.

B. Modern-Day Techniques

Ground-based radar devices and GPS are increasingly integrated into most large open-pit mines' slope monitoring and management programmes.

B.1 Remote Sensing Techniques

The Global Positioning System (GPS) is a navigation and positioning system that follows GPS satellites' electromagnetic signals. It measures the movements of slopes, landslides, and subsidence on a continuous periodical basis. The amount of deformation and slope movements are calculated by comparing the starting and ending positions of the GPS stations. An improvement to GPS called Differential GPS (DGPS) improves location precision in the range of operations of each system, from the nominal GPS accuracy of 15 m to roughly 1–3 cm.

DGPS offers real-time information on slope stability and deformation rates. GPS is also being used as a control point for monitoring mine slope stability in conjunction with photogrammetry, total station networks, and remote sensing pictures. However, GPS has environmental limitations such as vegetation and mountains and is not suitable for fast deformation scenarios.

LiDAR (Light Detection and Ranging) directs a laser beam at the area of monitoring, which provides a graphical/digital depiction of slope and their relative motions based on the journey time of the reflected radiation. They produce virtual replicas of the slope in minutes, similar to photographic images emphasizing crucial regions.

Modern LiDAR scanners can be placed on static and mobile surveying platforms and instantly give Digital Elevation Models (DEM). Time Domain Reflectometry (TDR) can instantly and precisely identify the deformation zone's relative magnitude, displacement rate, and position. Since 2002, the micro-seismic technique has been used in opencast mining to anticipate slope movements and failures.

Micro-seismic events caused by tiny rock movements are collected by data recorders and relayed to the processing system. The events are then analyzed to identify the zone of weakness, stress conditions, deformation mechanics, and deformation rate within the rock mass. Significant advancements in mine seismology information effectively reduce risks far before they occur.

Selecting a proper monitoring system depends on several parameters, such as area coverage, mode of operation, cost, and installation and maintenance concerns. Conventional methods are time-consuming and of low accuracy, and inclinometers, TDRs, extensometers, and LiDARs are not appropriate for real-time information and early failure prediction. The slope monitoring radar has radically revolutionized the evaluation of geotechnical risk in surface mines. In the last ten years, radar has developed into a cutting-edge technology for monitoring pit wall movements in surface mining with real-time slope monitoring. The radar beam emitted by the antenna scans the slope faces vertically and horizontally. The movements along the slope are tracked both quickly and constantly, in addition to broad area coverage in all-weather conditions.

In recent years, 3D imaging of the damaged surface has also been made available by radar monitoring. Radar can be either space-borne or ground-based depending on the application. Recently, Slope Stability Radar (SSR) advances have included broad areal coverage, remote operation from greater distances, and better spatial resolution. Movement and Surveying Radar (MSR) and Synthetic Aperture Radar (SAR)/ Interferometric

Synthetic Aperture Radar (InSAR) in open cast mines can detect both sizeable rapid slope failures and small slope deformation movements over time10. Radar systems provide long-range monitoring, broad aerial coverage, and customized aerial coverage with sub-millimeter precision and accuracy.

5) METHOD OF STABILITY

Due to the rapid development of computing efficiency, several numerical methods are gaining increasing popularity in slope stability engineering. The most popular method of slope stability estimation is shear strength reduction technique (SSR). Sainsbury et al. (2003) stated that the traditional definition of the Factor of Safety (FS) for slopes stability analysis was to calculate the factor of safety with respect to the soil/rock shear strength. The factor of safety of a slope can be computed with a finite element or finite difference code by reducing the rock shear strength in stages until the slope fails. The resulting factor of safety is the ratio of the actual shear strength to the reduced shear strength at failure. This method is called the shear strength reduction technique and is described by Dawson et al. (1999). Hoek (2009) pointed out that the shear strength reduction method is now widely used in open pit slope stability studies because it includes all the benefits of limit equilibrium analyses and it allows the user to study slope displacements that are critical in the evaluation of open pit stability. The shear-strength reduction technique was used first with finite elements by Zienkiewicz et al. (1975) to compute the safety factor of a slope composed of multiple materials.

The best suited numerical method of analysis for slope stability is continuum modelling. If rock mass of slope can be represented as an equivalent continuum, continuum models should be used to solve these types of problems. Therefore, many analyses begin with continuum models. If the slope under consideration is unstable without structure, there is no point in going to discontinuum models. In continuum models, the displacement field will always be continuous.

The location of the failure surface can only be judged by the concentration of shear strain in the model. The slope can be simulated in 2D or 3D by numerical modeling. It depends on many factors such as time required for simulation, critical parameter, requirement of simulation, field condition and computer configuration. Most design analyses for slopes assume a two- dimensional geometry comprising a unit slice through an infinitely long slope under plane strain conditions, i.e. the radius of both the toe and the crest are assumed to be infinite. However, three-dimensional analyses are required when the direction of major geological discontinuities do not strike within 200–300 of the dip of the slope or the distribution of geo- mechanical units varies along the dip of the slope. This also becomes necessary when the slope geometry in plan cannot be represented by two-dimensional analysis, which assumes axisymmetric or plain strain condition.

Numerical approach to slope stability analysis is preferred over traditional limit equilibrium methods due to the following advantages

(a) No assumption needs to be made in advance about the shape or location of the failure surface. Failure occurs `naturally' through the zones within the soil mass in which the soil shear strength is unable to sustain the applied shear stresses.

(b) Since there is no concept of slices in the numerical approach, there is no need for assumptions about slice side forces. Numerical method preserve global equilibrium until failure is reached.

(c) Numerical methods are able to monitor progressive failure including overall shear failure.

6) CONCLUSION

Slope monitoring and slope stability analysis are crucial tools to control or prevent slopes from failure. It is not viable to monitor or evaluate the slope stability exclusive of brief knowledge about the parameter that affects the stability of the slope. This study discussed the major factors and the key parameter of the slope stability by classifying and differentiating them into four sections Geological structures, Geotechnical factors, Slope geometry and other sources of disruption. The information organized in this paper will find it’s important in slope designing, fabricating apt slope monitoring systems and slope stability evaluation studies in opencast mines.

Many slope failure incidents in Indian coal mines have taken place due to uneconomic and lack of sound design of slopes. Diligent monitoring and safe design by qualified geotechnical engineers at mine sites is crucial. According to the computation, the failure surface that grows from the crest of the pit and reaches toe of pit at the time of failure. When a slope fails it can provide a useful source of information on the conditions in the slope at the time of failure as well as an opportunity to validate stability analysis methods. Because the slope has failed, the factor of safety is considered to be unity or less than unity (1.0) at the time of failure (Duncan and Wright, 2005).

Therefore, it is recommended maintain well-developed drainage system in and around the mine to avoid entry of rain/surface water in the slope and continuous intensive slope monitoring to detect any instability well in advance. It is also recommended to provide perforated pipes in sub-horizontal holes to depressurize the ground water. There should not be any flow of water or garland drains in and around the pit which reduces the cohesion and angle of internal friction of the friable strata leading to the slope failure. Additionally, dewatering of potentially unstable zones is also important to minimize hazards related to high wall failures. Conduct of slope stability assessment in Indian coal mines is mostly based on empirical and observational approach. Hence, efforts should be made by statutory bodies to have more application of analytical numerical modelling in this field to make slope analysis and design scientific.

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