Stability Assessment and Design of Open Pit Slopes of Limestone Mines in India

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***Abstract*—In India, open pit mines are the primary source of limestone mineral production. Limestone is utilized as a raw material in the manufacture of cement, a necessary construction material. Because the increased demand for limestone minerals grows year after year, deeper open pit mines are being developed to ensure improved production, productivity and mining safety. The improper design of pit slopes in some limestone mines leads to the failure of slopes, production and productivity losses, and safety issues in the mining area. The design of safe and stable rock cut slopes is required for a healthy working environment and the continuation of limestone production. This paper presents slope stability issues and solutions in two open pit limestone mines covering extensive geotechnical investigations, which are helped by result-oriented stability evaluation using empirical and numerical methods. Recommendations for suitable slope design helped for the exploitation of locked-up limestone reserves in an economic and safe way which may be useful for similar geo-mining conditions.**

***Keywords*—Open pit mine, limestone, slope stability, limit equilibrium method (LEM), safety factor**

I. Introduction

In India, open pit mines are the primary source of limestone mineral production. Limestone is a nonmetallic mineral that is utilized as a raw material in the manufacture of cement, a necessary construction material. The cement sector alone required around 76% of the limestone produced, while the iron and steel industries used 16%, the chemical industries 4%, and the sugar, paper, fertilizer, and ferromanganese industries 4%. Because the increased demand for limestone minerals grows year after year, deeper open pit mines are being developed to ensure improved production, productivity and mining safety. The safe working environment and uninterrupted production of limestone need the use of a safe and stable design. The existence of structural characteristics within the rock mass has a considerable impact on the stability of rock cut mining slopes. In such cases, the slope design must take into account the relative orientation of these elements. The optimal slope design is critical for achieving the twin goals of safety and economy. The process of creating the best slope entails finding a balance between the competing demands of safety and economy.

The basic goal of any rock excavation is to reduce the amount of rock extracted while still providing a cost-effective and safe environment for its intended usage. The primary goal of economically and safely designed rock cut slopes is to maximize the degree of inclination of the slope while ensuring stability. Stability assurance necessitates an understanding of the many causes of failure. Thus, a thorough understanding of the slope failure mechanism, as well as astute slope monitoring and management, is critical for reducing the likelihood of slope failure. As a result, the primary goal of slope stability evaluation is to design a stable, inexpensive, and low failure rate slope. The excavatability of the material for benching and subsequent slope stability are major problems in geo-mechanical engineering and are dependent on the material's physico-mechanical characteristics. This is true during both the design and construction phases. A variety of procedures have been employed to measure slope stability [1–4].

The analysis of rock cut slopes in an 'inhomogeneous' rock mass, together with rock mass classification methods, is often used to determine the strength and deformational characteristics of the rock mass. The rock mass categorization numbers Q [5], RMR [6], and Geological Strength Index [7] have been found to be related to the rock mass modulus, rock mass strength parameters, and the rock mass unconfined compressive strength. The relation between the geological strength index and Mohr-Coulomb strength parameters can be obtained using RocLab software [8], allowing for the simple estimation of rock mass cohesion and friction values using Hoek-Brown parameters. This programme also allows for the calculation of a rock mass's uni-axial compressive strength and modulus using correlation from empirical findings.

Slope stability evaluation in open pit mines at various stages of mining is crucial for safe and successful mining operations [9]. Geotechnical data and the physico-mechanical properties of the material are frequently used to generate slopes. The stability of the slopes is assessed using several empirical, analytical, and computational methodologies based on the rock mass attributes [10].

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Numerous experts have stressed the various aspects that play a significant impact on the overall behaviour of slopes. These parameters are classified as geological, material nature, slope geometry, geotechnical, hydrological, physico-mechanical characteristics, slope drainage, temperature, stress state, erosion, blasting influence, dynamic loading, and temporal considerations [11–23]. Plessis and Martin [24] used a similar approach. They did, however, calibrate the model using slope monitoring data to calculate the necessary cohesiveness and friction angle for the rock mass, and then utilized the model to evaluate the stability of the final cut. Singh and Dhar [25], Singh *et al.* [26] used a finite difference approach to analyze the stability of rock slopes based on rock mass categorization data for their rock mass input parameters. The 'plasticity indications' provided inside the software were used in the former, while the localized safety factor against the Mohr-Coulomb shear failure was used in the latter. LEM analysis was also performed in both circumstances, yielding similar signs of stability. Oztekin *et al.* [27] conducted a stability evaluation of rock cut slopes in the limestone for six different rock cut slopes with high angles of inclination ranging from 71° to 84°, and the safety factor was found to be between 1.19 and 3.83. Their research was performed assuming a circular slip surface and employing an automated grid search, which provides a slip centre grid from which alternative slip planes are examined.

The objective of this paper is to design an optimum final rock cut slope of a limestone mine's critical pit slope section under numerous geologically disturbed area (such as joints, faults and folds) with dump surcharge loading in the first case-1, and design a slope failure in limestone mine's pit slope in case-2 studying local geologic formations using core logging and joint mapping, characteristics of the rock mass, hydrologic conditions, and using the kinematic analysis and numerical software.

II. Case Study-1

The limestone mine is located in Telangana State, India. The lease area lies between latitude N $18^0$42’57.60” to $18^0$44’44.6” and longitude E $79^0$23’7.6” to 79^0 24’14.62”. The mine is in uneven topography with a near-plain land interspersed with mounds and hillocks. The plain land varies between 180m and 220m from the mean sea level in height. Site investigation and exploratory holes indicate the sequence that this area has cement-grade limestone deposits that form part of a sequence of sandstone, shale and various types of limestone. Limestone ore from this mine is mined by a fully mechanized open pit method with an annual production capacity of 1.78 million tonnes per annum. Removal of overburden and limestone in the mine is carried out through mining operations deploying a shovel-dumper combination. The hard strata in the mine are exploited by using drilling and blasting.

The limestone mine is working at a maximum depth of 90m and consists of eight benches with an inclination of about 70 degrees (Fig. 1). The mine consists of an active dump at the crest of the pit slope with a maximum height of 65m. Detailed exploration in the mine lease area revealed the presence of limestone ore reserves up to 110m depth. Deeper excavations become especially important as open pit mines reach greater depths due to land availability limits. The deposit is faced with numerous geological discontinuities (i.e., joints and faults). The slopes in the excavation are non-homogenous. The slope stability state in a limestone mine is typically governed by several factors such as rock/soil formation thickness, rock mass condition, the existence of major and minor faults, rainwater infiltration into the slope, and the existence of external loads on cut slopes.

Figure 1. A view of the open pit limestone mine [28].

A. Geotechnical Site Characterization

The regional geology of the area is dominated by the 2500-million-year-old granitic rocks which form part of the Archean granite-greenstone terrain of Eastern Dharwar Craton. The outcrop pattern of the Sullavai Group in the present area is defined by regional faults and the associated smaller-scale folds and faults. These faults and folds have influenced the distribution of cement grade limestone in the mine.

In the present lease area in the mine, the cement-grade limestone deposits form part of a sequence of sandstone, shale and various types of limestone. Together, they are correlated with the Sullavai Group. There are three limestone bands in the mine, namely, lower grey limestone, middle purple limestone and upper purple limestone. The limestone bands are sandwiched between sandstone in the northeast and between granites in the southwest. These are narrow linear bands, extending up to 8 km. They are intensely folded at places and are intercepted by minor faults.

The limestone beds are 30m to 50m in thickness, sometimes even 80m. The cement-grade limestone has 80% or more $CaCO_3$ content. The formations dipping varies from 70^0 in hills to 30^0 in plains due SW (strike NE-SW) but is folded at places. The beds are thinly layered (thickness of bands 10cm to 15cm), highly disturbed with close-spaced vertical joints, and gentle to highly folded structures (Figs 2–3). The geological sectional view of the open cut slope is given in Fig. 4.

The area experiences tropical climatic conditions, with the temperatures dipping from as low as 8^0C in winter to as high as 48^0C in summer. Groundwater observed the developing quarry excavation during field investigations at the limestone mine. Furthermore, while mining, constrained bedrock aquifers will be discovered throughout the developing quarry. The average rainfall of the area is approximately 1100 mm per year.

Kinematic analysis was used to show the potential for different modes of rock/soil slope failures (i.e., planar, wedge, and toppling failures) caused by the presence of unfavourably oriented discontinuities [28]. The analysis was based on Hoek and Bray's description of Markland's test. Kinematic analysis was performed with rock material friction angle, discontinuities measured, and orientation of slopes to identify any possible structurally controlled failure at the investigational locations. The kinematic analysis of the slopes shows that structurally controlled collapse will not occur on these pit slopes. The results of the field mapping (Fig. 5) and core logging were tabulated in Table I.

Figure 2. Two sets of joints in the benches of the mine [28].

Figure 3. Joint filled with ferruginous material in the benches [28].

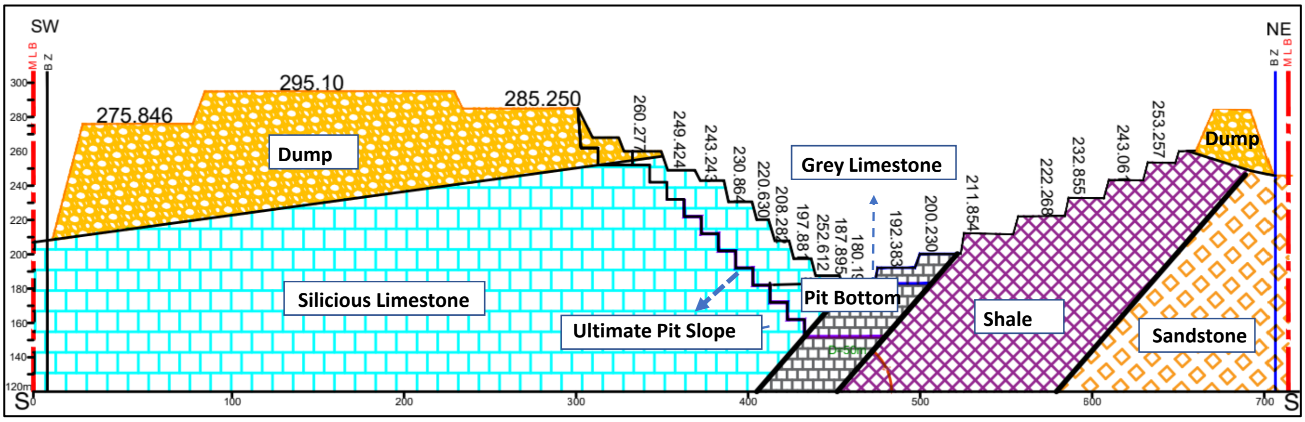

Figure 4. A View of the geological critical section in the mine [28].

TABLE I. JOINT FEATURES OBSERVED IN DIFFERENT SECTIONS OF THE LIMESTONE MINE [28]

Section	Feature	Strike	Dip amount	Dip direction
Critical section (Fig. 4)	Bedding planes	140º – 320º	22º	N 230º
	Joint-1	N – S	90º	–
	Joint-2	E – W	90º	–
	Random	140º – 320º	80º	N 050º
	Bedding planes	130º – 310º	17º	N 220º
	Joint-1	N – S	90º	–
	Joint-2	E – W	90º	–
	Joint-3	65º – 245º	90º	–

Figure 5. Field mapping in the mine.

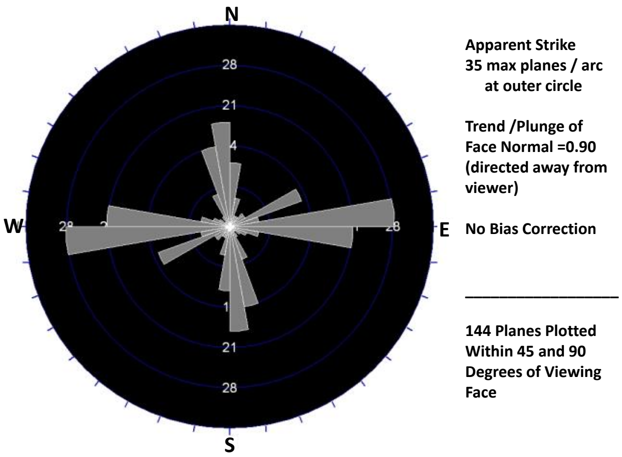

Figure 6. A Rose diagram of all the joints in the limestone mine [28.]

Detailed joint mapping was carried out in different sections of the mine. Two distinct sets of joints were identified in the mine, mostly vertical joints trending E-W and N-S. A summary of the joint features observed in the mine is given in Table 1. The joints are close-spaced at 5 to 10cm. They are mostly tight, but occasionally ferruginous/calcareous and clayey material filling was also present. The joints are smooth with planar discontinuities. The rocks are dry, and no water seepage was observed anywhere within the mine. Minor (small-sized) limestone cavities are present in some places.

The trends of the joints and bedding planes were plotted on stereographic projects, and the contour plots were obtained using the computer software program named DIPS (of RocScience Inc.). Based on the kinematic analysis of the major planes of the different discontinuities, it was seen that there is no possibility of any wedge failure in the benches at the mine (Fig. 6).

B. Physico-Mechanical Properties

The geo-mechanical rock mass rating (RMR) technique devised by Bieniawski[1] was used to classify cores from boreholes and samples collected from the crucial section in situ. Based on core drilling information, this rating system gives a quantitative technique for identifying the engineering feature of a rock mass. Table II summarizes the physico-mechanical characteristics employed in the simulations. In the current simulations, a nonlinear material Mohr-Coulomb model with a tension cut-off was applied.

The system is based on six parameters: (i) Intact core's uniaxial compression strength, (ii) Rock quality designation, (iii) Joint spacing, (iv) Joint orientation, (v) Joint condition, and (vi) Groundwater conditions. Each of the six criteria is assigned a relative weighting factor, which is then added together to get an RMR in a range of 0-100. Mine borehole RMR ranges from 60% to 68% of the core categorised as a fair rock (class-III)

TABLE II. STRENGTH PARAMETERS OF DIFFERENT MATERIALS [28]

Litho-Type	Density (kN)	Cohesion (kN/m^2)	Angle of Friction, ø (Degrees)
Sullavai Sandstone	27.2	160	40
Upper Shale	27.2	170	40
Flaggy Limestone	27.8	180	40
Grey Limestone	27.8	165	40
Purple Limestone	27.8	190	40
Pranhita Sandstone	27.2	170	40
Lower Shale	27	160	40
Dump Material	25	100	25

C. Two-Dimensional (2D) LEM Analysis

The geology, physicomechanical characteristics of the rock in the slope, groundwater hydrology, and dump loading are the primary elements impacting the stability of the rock cut slope. The slope stability on the current critical section of the pit slope moving dump surcharge loading 25m away from the crest of the pit slope was first investigated as a planar issue using the traditional limit equilibrium approach. The safety factor of the slope around this new scheme with a slope angle of 45^0 is either 1.98 for dry conditions, 1.96 for saturated conditions in circular failure (Fig.7), 1.72 for dry conditions, or 1.68 for saturated conditions in noncircular failure (Fig.8) [28]. However, even with such an old scheme plan with a comparatively soft angle of 35^0, the slope would become unstable with a safety factor of 0.54 due to the dump load effect (Fig. 9) and the new scheme dump 25m away from the top of the slope FOS is 1.68 (Fig. 10).

Furthermore, the most significant drawback of this excavation method is that a large volume of limestone, particularly up to 110m deep, cannot be mined out. Is there a stable excavation design for the slope that requires less expenditure and has a sharper slope angle? Designers think that by carefully considering the deformation impact of the entire slope structure, it is conceivable to conduct an excavation procedure for the slope with a considerably sharper slope angle compared to its former design. Such a surcharge impact can only be verified by a series of numerical experiments. To justify such loading impact, a simple hypothesis is that excavation and dump loading distance increases when the pit slope is alternatively run during open slope mining. The recommended results show that 45^0 is the optimal final slope angle design for a 110m deep open cut slope with dump surcharge loading 25m away compared to present slope angle of 35^0 for 90m deep slope with dump surcharge loading 0m away from the pit slope.

D. Results and Discussions

The geological mapping of the study area of joints and bedding planes using the DIPS software provided vital information of stability of rock cut slopes in the mine. Based on the kinematic analysis of the major planes of the different discontinuities, it was seen that there is no possibility of any wedge failure in the benches at the mine.

The analytical results of two-dimensional LEM approaches were compared with field observations in the old scheme. The non-circular slip surface mode using Bishop's method produced a comparably less safety factor, which may be ascribed to satisfying movement equilibrium and total force equilibrium to varying degrees.

The noncircular type of failures were noticed during field observations in the mine. The factor of safety levels was reduced in the old scheme compared to the new scheme due to the surcharge load of the dump located on top of the pit slope. The pit cut slope was made up of sandstones, shale, and limestone. The results show that 45^0 is the best final slope angle design for a 110m deep open cut slope compared to the present slope angle of 35^0 for a 90m deep open cut slope with bench dimensions of 8m height by 8m width.

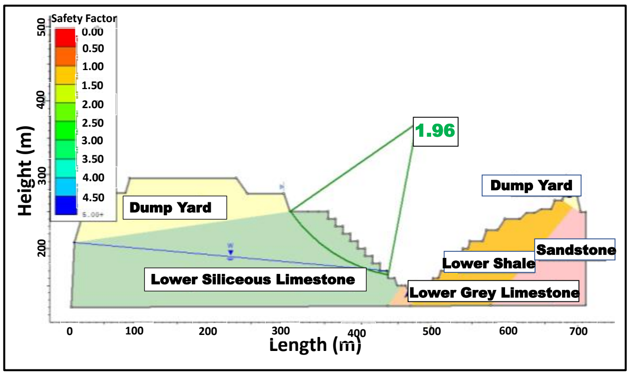

Figure 7. Numerical analysis of critical section in the saturated condition in circular failure.

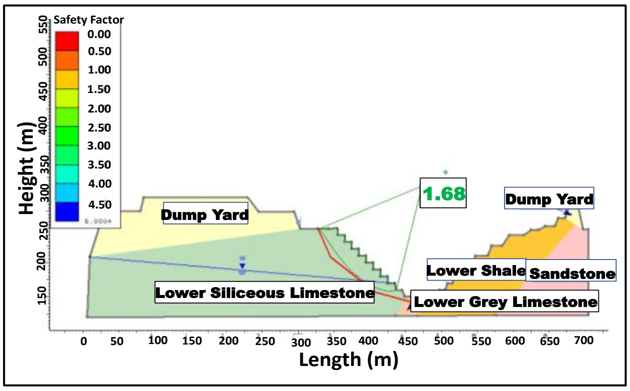

Figure 8. Numerical analysis of critical section in the saturated condition in non-circular failure.

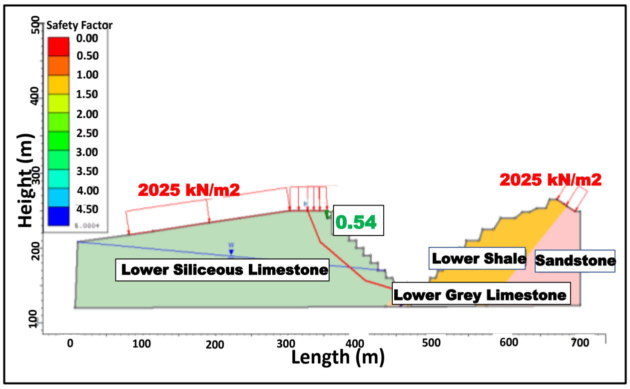

Figure 9. Formation of a critical failure surface at a surcharge dump loading from a distance of 0m from the top of the pit slope [28].

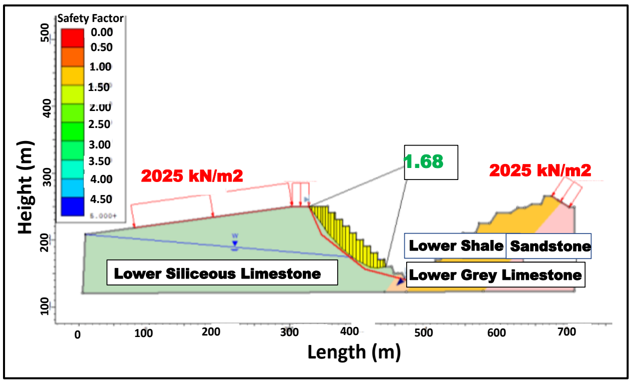

Figure 10. Formation of a critical failure surface at a surcharge dump loading from a distance of 25m from the top of the pit slope [28].

Fig. 9 depicts the slip surface as it passes through the crest and intersects the toe of the first bench for dump loading with a distance of 0m, and is classified as a bench failure [28]. Fig. 10 depicts the failure surface travelling through the top of the slope and crossing the toe of the bottom most bench for dump loading with a distance of 25m, and is classified as a toe failure. This was also demonstrated by the simulation of this old scheme using SlopeW. It is also recommended that no activity or construction take place on the top of the pit slope crest in order to prevent further slope failures in the old scheme.

A timely correct design for a mine under surcharge loading owing to excavated waste improved the mine's stability. By using advanced numerical techniques and putting excavation and shifting dump 25m away from the crest of the pit slope, It is feasible to perform an excavation scheme with a steep slope angle by taking the deformation effect into account at particular rock slopes with complicated geometries and geomaterials. As a result, in rock engineering practice, such developed geotechnical analyses should be used to prevent dangerous slope deformation. The recommended optimal final slope angle design as shown in Fig. 10, ensures the long-term stability, productivity, and safety of mines with increased limestone mineral extraction.

III. Case Study-2

This case study is based on an open-pit limestone mine located in Tamilnadu state, India. This mine is one of the major producers of limestone in the state. The lease area contains high-grade crystalline limestone and magnesia limestone. The proved mineable reserve in the lease area is around 20 million tonnes with a production capacity of 3.96 lakhs metric tonnes per annum. The geometries of the mine are 150m in width and 600m in length. The open pit is working at a depth of 100m from the surface, thus leaving nine benches each 10m in height with a final slope angle of 27^0 (Fig. 11). On both sides of the limestone mines lease area, i.e., East and West sides, the other limestone mines are in operation. The waste from limestone mines is dumped on both the South and North side of the lease area. For limestone extraction and overburden removal, drilling and blasting, shovel-dumper machine combinations are used.

There is a slope failure and tensile cracks were discovered towards the north side of the pit which is a concern regarding the stability of the slopes in the mine. So, geotechnical investigations were conducted to determine the possible causes of failure on the north side of the limestone mine.

A. Geotechnical Site Characterization

The limestone formation is part of the significant Ramayanpatti limestone band, which extends in an E-W orientation for a distance of 3km, and dates back to the Archaean Era. It is made up of metamorphosed sediments from the Dharwarian Age. One of the most significant limestone structures in the state of Tamilnadu is this one. In the mining lease region, limestone is visible appearing as a linear mass at depths of more than 120m. In the western section of the mine, the limestone band's width ranges from 40 to 50m, while in the eastern half, it is 20 to 40m wide. In an east-west path, the limestone band is remarkable. The drop is 80 degrees straight south. Kankar surrounds the limestone on either side, then quartzite with areas of kankar, and finally magnesium limestone. If the contact rocks also slope in the same direction, intermittent charnockite areas may be seen. The grains of limestone are fine-, medium-, or virtually coarse-grained. Additionally, the color can be white, yellow, honey golden, blue, or pink and can differ in gradation in terms of its physical and chemical properties.

Figure 11. A photograph showing slope failure area in the limestone mine [29].

In the northern face of the pit, two suspected faults have been observed with strikes 150-230, 090-270 (filled with clay) and varying thickness. About 40m from the surface level, the rock mass observed is very poor. The rock is converted into the soil and exhibits grey to greenish colours. Quartz veins have been observed with a highly fractured nature and coated with ferruginous material. A cavity in the soil with poor rock mass is present in the slope failure area. The host rock (Charnokite) was evaluated for stability.

The structural geology was studied in the pit up to a depth of 120m on the North side. The studies included mapping the highwall to characterise the orientation and distribution of the discontinuities, as well as drilling a number of drill holes with the oriented core. The mapping revealed that four persistent joint sets dominated the geologic structure, which was supported by core orientation measurements.

The rock type is poor to fair up to 60m depth from the surface, according to strength estimates conducted during pit wall mapping, with a uni-axial compressive strength of 50MPa. The various parts of the rock mass were classified using empirical systems. All of the rocks on the pit's North side were deemed to be of poor to fair quality, with an RMR value of 46, and South and East sides RMR value of 71 has been classified as good [29].

B. Stability Monitoring of the Failure Area

The pit stability monitoring on the Northern side of the limestone mine is carried out using Visual measurements, A Wireline Extensometer for tension crack mapping, Prism monitoring and Groundwater monitoring to ascertain the instability of the area/slope.

Visual inspection: Visual inspections are performed on a regular basis in all mines. Visual inspection of pit walls can be used to reduce the risk to mine workers. According to the Metalliferous Mines Regulations (MMR), 2017 (Sections 115 & 116), no work shall be performed on/ at/or below a face or pit wall of a surface mine until the shift boss has examined and declared the face or wall safe. This statement implies that the pit walls are being visually monitored. It also states that loose rock and/or soil shall not be allowed to accumulate on a bench or catchment berms in such a way that anyone working on a lower bench is endangered. To assess the deformation of rock and/or soil on a bench, a visual examination is required. Visual inspection should be an important part of any pit slope monitoring programme. In addition to visual monitoring, instrumentation is commonly used [29-30].

Visual examinations are done to look for material ravelling from the pit or bench walls and tension cracks. Workers in mines are taught to watch for any unexpected or potentially hazardous pit wall or bench behaviour. Mine engineers, geotechnical officers, and technicians are normally in charge of formal inspections. As part of the visual inspection record-keeping procedure, pictures are frequently taken. Visitation logs and observations of any evolution in the behaviour of the rock mass over time are maintained. The majority of the time, the occurrence of fresh fissures or rockfalls requires more formal and regular visual inspections, which frequently results in the adoption of additional monitoring systems. The condition of the rock mass and the likelihood of slope instability dictate the frequency of visual inspection [29].

On a daily basis, the mines perform a formal visual inspection. However, all personnel working in the open pit perform continuous informal monitoring. During the inspection, the slope failure area observed tensile cracks behind the failure area topmost bench only. The failure in the North side pit wall is observed due to, steeper slopes, weak and worn lithology, inadequate drainage, and routine production blast close to the area some potential causes of the fractures and vertical sinking on the north side pit wall slopes.

Wire-line Extensometer: Wire-line extensometers are used to evaluate changes in tension crack width deformation in active zones of instability. To make a straightforward extensometer, a steel peg is frequently hammered into the ground on the down slope side of an apparent crack. A thin steel wire that is attached to the peg and extended across the crack connects the tripod and hanging weight to the pulley. Visual measurements of changes in crack width are made by comparing where the hanging weight is placed with respect to a ruler that is mounted to the tripod. The mine makes use of both low-tech internal wire-line extensometers with alarm-trigger capabilities. Extensometers are implanted when a tension crack is visible. According to the danger posed by the instability, an extensometer can be checked regularly throughout the day, daily, or weekly. Extensometer data are useful for tracking adjustments in deformation rates and making operational choices regarding tension crack mining activities [30].

In the limestone mine, Wire-line extensometers are installed to detect the tensile cracks developed at top most benches of the failure area. The deformations in the cracks are measured on a daily basis. The observations of results found that a maximum of 150mm deformations were noticed at the topmost benches of the failure area only (Fig. 12).

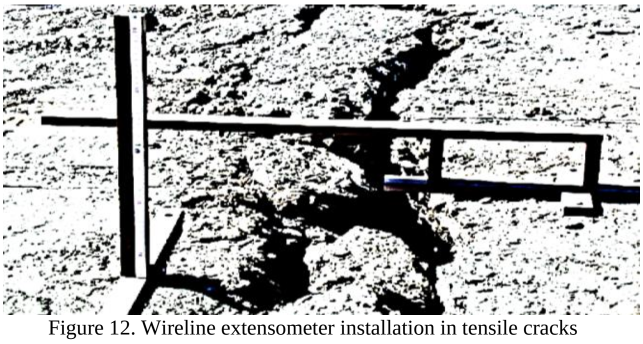

Figure 12. Wireline extensometer installation in tensile cracks developed area near to slope failure zone [29]

Total station and prisms monitoring: The use of a total station and prisms is the most commonly used monitoring technique for pit wall monitoring. Slope monitoring with a total station typically consists of three components [31].

- A network of reference beacons that can be seen from the transition point and are located on stable ground is necessary.

- Several transition sites are constructed on solid ground near places where the slope surface can be seen. The transfer points should be set up in such a manner that they make an appropriate survey network for the line-of-sight network if the monitoring point locations are to be measured.
- The third component is the placement of tracking prisms at the presumed unstable slope zone of interest.

In order for the distance readings to closely match the actual slope deformation, the observation direction should point in the direction of deformation that is most likely to occur. Depending on the distance and level of accuracy required, the tracking locations on the incline may be reflectors or survey prisms [32]. The frequency of monitoring is influenced by the type of rock present, nearby activities, and the monitoring program's goals. Measurements may be performed every day or weekly or monthly on slopes that move slowly. An automated system should be set up to take more frequent readings at predefined intervals for a slope that could move quickly, as decided by the geotechnical engineer.

In total 36 points were identified as critical locations towards the North side of the pit. The monitoring was carried out after failure on the North wall for a period of one year on a daily basis (Fig. 13). A maximum of 150mm deformations recorded in the prism stations within 5m of the failure zone on the North wall have occurred within 7 days of failure and later strata is stabilized and no deformation was observed in the prism stations outside the 5m to failure zone. Therefore, it indicates that within 5m of the failure zone stabilized within seven days of the failure, and strata outside the 5m from the failure area is not influenced by failure which is in stable condition.

As a result, at the limestone mine, the in-house prism deformation system is used to identify long-term slope deformation trends and predict where future slope failure or instability is likely to occur. A special area is declared in response to slope movement, detailed inspections are performed, and other monitoring devices are installed.

Groundwater Monitoring: The stability of a rock slope is influenced by the presence of groundwater within a mass of rocks. Piezometers are commonly used to evaluate the effectiveness of mine dewatering programmes and pore pressure. The piezometers normally require manual water level readings every week to every month inside the standpipe. The miners also check their pit walls for fresh indications of seepage or adjustments in flow rates, which usually signal the beginnings of unstable rock slopes [30].

In the failure area of the limestone mine, the field observations indicated that occasional small seepage of water was noticed. No major aquifer was noticed in the failure zone.

C. Stability Performance of Failure Zone

A pit wall failure towards the north side of the pit, where the passage to the slope is dangerous and/or there is a need to make frequent and accurate measurements using visual examination, wireline extensometer, piezometer and total station prism monitoring are carried out to rapidly analyze the results.

The monitoring studies provided useful information in the stability assessment of the failure zone. The monitoring observations indicated that after the failure of slopes, instability in the area is restricted within 5m of the failure area up to a period of seven days only, and outside the 5m from the failure zone is not influenced by the failure which is in stable condition.

The monitoring is made of indigenous available equipment and it provides valuable information about stability of the failure zone. Based on monitoring results, future workings of the failure zone are redesigned using GALENA Software [33] with an overall slope angle of 30^0 (Figs. 14–15).

Figure 13. Prism network and monitoring setup in the limestone mine [29]

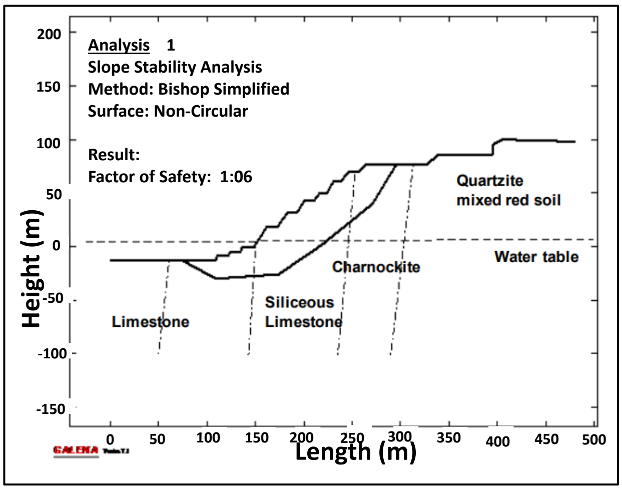

Figure 14. Pit slope stability analysis along failure section [29]

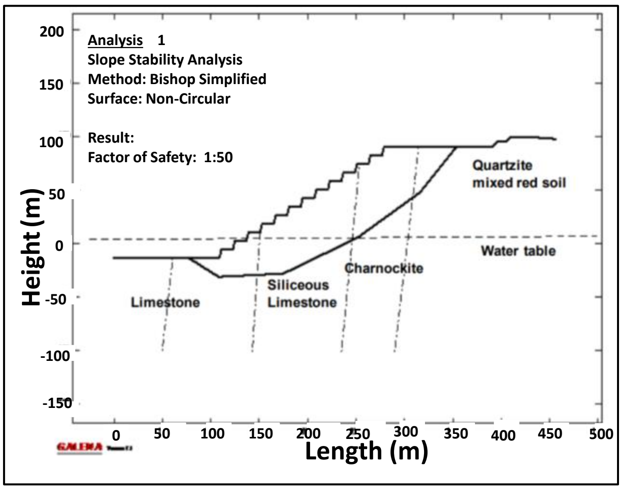

Figure 15. Planned pit slope stability analysis along failure section [29]

D. Results and Discussions

Slope monitoring has allowed for a fundamental shift in risk management in open-pit mining operations in this mine, which will significantly improve slope design and safety by supplying accurate, dependable deformation data that can later be reviewed to further our understanding and analysis of failure mechanisms in the mines.

The monitoring studies conducted by the author provided useful information in the stability assessment of the failure zone. The monitoring observations indicated that after the failure of slopes, instability in the area is restricted within 5m of the failure area up to a period of seven days only, and outside the 5m from the failure zone is not influenced by the failure which is in stable condition. The slope failure in the mine occurred due to steeper slopes, weak and worn lithology, inadequate drainage, and routine production blast close to the area, some potential causes of the fractures and vertical sinking on key highwall slopes. The relatively steeper slope failed due to permeability differences between soft and hard lithology.

The recommended design as given in Fig. 15 by the author made that failed bench slopes should be pushed back in order to create new benches. The proposed bench redesign should be carried out from top to bottom. The failed zone should be reformed by repositioning the benches. The pushback should be enough to form the final benches in place. Based on monitoring results, the future workings of the failure zone are redesigned with an overall slope angle of 30^0.

IV. Conclusion

The above-discussed studies carried out by the author was successfully implemented in both open pit limestone mines in different geo-mining conditions in India, which allowed the mines to extract locked-up limestone mineral reserves and conserve the safety of personal and mining equipment. The excavated rock slope schemes were optimised utilising matured geotechnical investigations, such as field geological mapping, laboratory analysis, and numerical analysis to provide an ideal choice for mine engineers and researchers. The applied methodology of sophisticated geotechnical studies with extensive calibration using field studies and mature engineering judgment provided long-term stability of slopes, increased production and safety for the extraction of locked-up reserves in the limestone mines. For comparable geo-mining settings, the technique for optimal slope design employing proper geotechnical assessments may be applied.

Conflict Of Interest

The author declares no conflict of interest.

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