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Monitoring and Prediction of Slope Failure Instability in a Limestone Mine

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Abstract

In a mining operation, maintaining safe and cost-effective slope geometries is critical. Monitoring has often proven to be a valuable method in dealing with potential slope instability when design analysis and engineering judgment have dictated conservative and usually more expensive problem solutions. Unexpected pit wall collapses could have a significant impact on the safety and profitability of an openpit operation. As a result, a well-planned and executed monitoring programme can permit operation with a lower theoretical margin of safety. Monitoring provides an important check on design parameters and can measure the effects of corrective actions, which lead to increased significant production and reduced economic losses. Often, early warning of impending failure can be established.

In this paper, a slope failure of a pit wall stability on the north side of a limestone mine which leads to stopping the workings by the regulatory body was studied. A comprehensive slope monitoring strategy has been implemented to improve safety and mine more economically using different slope monitoring techniques like visual inspection, prism monitoring, piezometer and wireline extensometers are also used to predict the instability of the failure area of a limestone mine. All of these monitoring tools offer primary monitoring, which is used to determine the riskiness of a failure area or zone. It gives early warning of further failure or instability if the slope is detected in challenging conditions. Today's mining regulations place a strong emphasis on the proactive identification and mitigation of risks to employees and the operation. This paper focuses on reducing operational and safety risks through an approved monitoring programme. Based on slope monitoring results of the failure area, remedial measures to improve the stability of the workings are presented for a limestone mine.

Keywords: *Slope Failure, Slope monitoring, Risk, Limestone mine.*

1.0 Introduction

Slope instability can be expected in any open pit, ranging from bench sloughing to large-scale slope deformation. Because of the inherent variability of rock strength and geologic structure, the uncertainties associated with sampling and measuring rock characteristics, and the mathematical and geometric approximations of the stability analysis, even a "safe" slope, designed to some customary safety factor, has a finite probability of instability.

The current tendency in slope design is to quantify the variability of the stability analysis input parameters in order to assess the chance of failure and then use this probability of failure in a cost-benefit analysis to establish the economically best slope angles. Analyses of this type, which compare the cost of stripping to the cost of slope instability, indicate that the economic optimum slope angle may, in some cases, have probabilities of instability as high as 30 per cent.

Acknowledging that slope instability can occur leads to commitment to a monitoring programme to ensure safe working conditions. The objectives of any slope monitoring programme are:

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(a) to maintain safe operating procedures in order to protect personnel and equipment;
(b) to provide advance notice of instability, allowing mine plans to be modified to minimise the impact of slope deformation; and
(c) to provide geotechnical information useful for analysing slope failure mechanisms, designing appropriate remedial measures, and redesigning the slope.

The monitoring programme is determined by operational requirements as well as factors such as costs, system capabilities, mining methods, and environmental concerns. The programme's skilled responsible person must have a thorough understanding of the mining method, planning schedules, and surrounding geology. The maturity of the programme in managing potential failures should range from regular visual inspections to systematic automated face measuring. Mining operations, on the other hand, do not have to be hampered by slope movement if the failure mechanisms are understood and the slopes are properly monitored and evaluated. This significantly reduces risk, and installing appropriate monitoring systems in an open pit mine makes economic sense. This allows for more sensitive slope designs while still ensuring mine personnel's safety. The expense of the monitoring system is often offset by the increased revenue from steeper slopes and the cost savings from tiny, controlled failures, allowing mining to proceed under hazardous situations safely and profitably.

A strong monitoring programme is necessary for slope monitoring, the goal is to find movement that could cause a structure to collapse and to give people enough time to properly evacuate the region or structure. The intensity of the programme is proportional to the impact of the activity, and the emphasis can shift on a regular basis.

This paper describes common methods for monitoring rock slope failure or movement and how the results are interpreted. For actively mined slopes, like those in open pit mines and quarries, where deformation monitoring systems may be carefully set up, monitoring programmes are seen to be most suited. The slope's accelerating movement will be detected by stability monitoring techniques. The effectiveness of such monitoring is determined by the amount of advanced warning provided by slopes before failure, as well as the monitoring system's ability to detect such warning. There is substantial evidence that slopes provide adequate warning, implying that it is well worth the effort to investigate and implement appropriate monitoring systems. Failures in today's hard rock open pit mines, on the other hand, frequently occur after very small deformations. Such failures can be very localised, and they can happen seemingly without warning unless such a localised area is closely and accurately monitored. Correct design, legal compliance, monitoring requirements, and system design that accommodates both geotechnical and survey monitoring instrumentation are the most important considerations for effective monitoring. Monitoring programmes provide risk-reduction measures such as relocating operations away from the active slide and redesign the unstable workings to stable condition.

2.0 Importance of Monitoring

Deformations in the rockmass caused by rock excavation must be closely monitored to avoid accidents, loss of ore reserves and equipment, mine closure, and, in some cases, loss of life (Zhang, et al., 2016). When designing a safe and efficient mining operation, rock properties, geological structures, and hydrologic conditions must all be taken into account. A safety factor that has been engineered is used to control equipment damage as well as the risk of damage from rock fall and slope failure. When it comes to safety, there is a need to keep costs under control. By reducing waste removal, weakened pit walls can help to reduce and control operational costs. However, steeper walls increase the possibility of slope stability issues. Benches and berms are used in mine workings to catch falling material, blasting techniques to prevent needless fracturing, and groundwater management to help stabilise slopes. Unknown geological structures, unanticipated weather patterns, or seismic activity, on the other hand, can cause proper designed slopes to fail. To offer early warning indications of failures in light of this uncertainty, routine visual inspections and systematic monitoring should be carried out.

Despite all of the dangers connected to high walls and slope failures, Girrard (2017) states that there are a number of strategies to lessen these dangers:

(a) safe geotechnical design of overall workings;
(b) adequate bench dimensions;
(c) monitoring equipment that can alert users about impending failures; and
(d) scaling of loose material from high walls successfully.

To reduce the risks associated with slope failure due to geologic uncertainty, precautionary measures are required. Slopes and pit walls must be monitored for early warning signs of failure or rapid displacement to protect workers and equipment. Even if geotechnical considerations with a higher factor of safety are made to make the working environment safer, unexpected and/or unknown geologic structures, abnormal weather patterns, hydrological condition, or seismic shocks can all cause a sudden failure. Monitoring systems, when used correctly, can reduce uncertainty and aid in the development of appropriate action plans.

Using monitoring systems for risk assessment analysis has several advantages. Monitoring can help validate the overall mine plan and design. Slope monitoring equipment measurements help determine whether to maintain, steepen, or reduce slope angles while maintaining safety and financial benefits. As a result, slope angle analysis results may have an impact on future mine planning and design. Monitoring ensures the safety of mining equipment, production, and, most importantly, mine personnel by providing visual proof of slope stability and safety management. Most monitoring systems can also trigger warning alarms when they detect unstable areas, ensuring that precautionary measures are taken as soon as possible. Furthermore, the monitoring system easily provides rates of movement of the unstable zones, providing an estimate of the time required to clear the area in the event of a major failure. Mines can save a significant amount of resources if they receive adequate warning time before a failure.

According to Girrard (2017), common warning signs of slope instability are tension cracks, scarps, abnormal water flows and bulges or creep. It should be noted that each mine is distinct, and monitoring techniques for a single mine may be chosen based on varying rock types and other mine-specific criteria. It is helpful to understand the type of movement that is occurring when setting up a movement monitoring programme. This data can be used to select appropriate equipment for the site and to aid in the interpretation of the results.

Zavodni (2000) demonstrated the rock's response to rock excavation. When a slope is excavated or exposed for the first time, there is a period of initial response due to elastic rebound, relaxation, and/or dilation of the rockmass caused by stress changes caused by the excavation. The presence of tension cracks at or near the slope's crest indicates that the slope will fail after a period of initial response and possible stability. The formation of such cracks indicates that the slope's movement has exceeded the rockmass's elastic limit. However, with the implementation of a monitoring system, mining may be possible under these conditions. An operational slope failure, defined as a condition in which the rate of deformation exceeds the rate at which the slide material can be mined safely, may occur at some point (Call, 1982).

The difference between regressive and progressive time-displacement curves can be used to calculate either rockmass plastic strain or operational failure (Figure 1). When disturbing events like blasting or water pressure are removed from the slope, a regressive failure (curve A) occurs with short-term decelerating displacement cycles. When displacement grows at a rising rate – often algebraically – to the point of collapse unless stabilisation measures are taken, this is known as a progressive failure (curve B). Correct curve interpretation aids in understanding the slope failure mechanism and predicting future slope performance. A regressive failure can quickly transform into a progressive failure, resulting in collapse (curve C). Figure 1 also depicts geological conditions associated with this type of time-displacement curve. When the slope has discontinuities that dip out of the face at a shallow angle that are flatter than the friction angle of these surfaces (Type I) or discontinuities that dip out at a steep angle that are steeper than the friction angle of these surfaces (Type II), these geological conditions may be related to progressive failure (Broadbent et al., 1982).

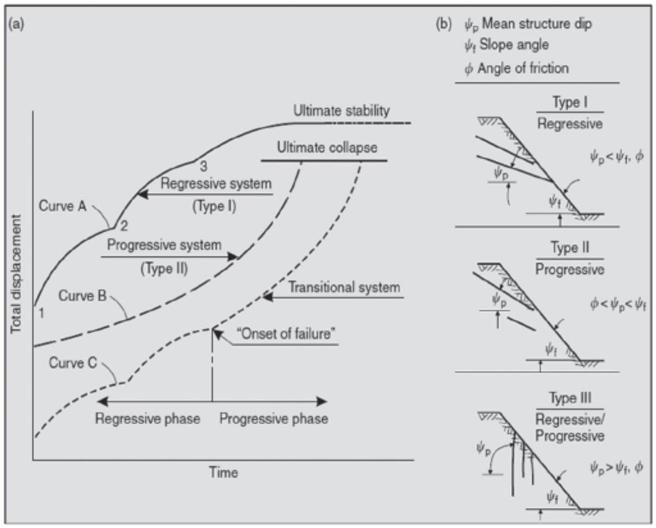

Figure 1: Slope movement types: (a) typical repressive and progressive displacement curves; (b) structural geological conditions associated with slope movement types (Broadbent and Zavodni, 1982).

3.0 Types of Monitoring

Mining companies frequently utilise deformation monitoring to control geotechnical concerns. Deformation monitoring identifies a progressive failure's distinct escalating pattern and gives time to make a plan. Geotechnical hazards can be removed from a danger region with enough time if they are discovered early enough. By guaranteeing that deformations occur at a constant rate, deformation monitoring also enables engineers to ensure that geotechnical structures work as intended. If measured deformation is consistent with design assumptions, deformation may not be speeding to progressive failure. To achieve the mining design, engineers might decide whether more research and analysis are required or whether the deformation can be controlled without additional mitigation.

In general, two types of slope monitoring methods are available for the measurement of slope movement (Hoek et al., 1981, 1989 & 1991; Kliche 1999):

(i) Surface measurements (ii) Sub-surface measurements

Surface monitoring methods:

a. Crack Width Monitors,
b. Surveying,
c. Tiltmeters,

d. Laser Imaging,
e. Synthetic Aperture Radar,
f. Global Positioning System,

Sub-surface monitoring methods:

a. Time–Domain Reflectometry,
b. Borehole Probes,
c. Inclinometers.

Only when the surface movement accurately represents the overall slope movement are surface measurements useful. Measurement of subsurface slope movement is frequently used as part of a monitoring programme to provide a more complete picture of slope behaviour. The primary goal of these measurements is to determine which slide surfaces are being measured. When selecting a monitoring system, other factors to consider include the amount of time available to set up the equipment, the rate of deformation, and safe passage to the site.

The interpretation of deformation data is an important part of monitoring operations because it allows for the rapid identification of slope acceleration or deceleration, which indicates whether stability conditions are deteriorating or improving. This allows for appropriate action in terms of the operation's safety and economics (Stacey, 1996).

Total station surveying, crack width meters, global positioning system, satellite scans, and inclino-meters will be used in the monitoring programme to provide data of deformation against time. Plots of this data are essential for understanding the mechanism of slope deformation and, potentially, predicting failure time.

4.0 Case Study

This case study is based on an open pit limestone mine located in Tirunelveli district, Tamilnadu state, India. This mine is one of the major producers of limestone in Tamilnadu 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. The estimated production capacity of these leases is 3.96 lakhs metric tonnes per annum. The geometries of the mine are 150m in width and 600m in length. The pit is working at a depth of 100m from the surface, thus leaving nine benches each 10m in height. The existing pit had an overall slope angle of up to 27º (Figures 2 and 3). On both sides of Krishna mines lease area, i.e. East and West sides, the mines belonging to India Cements Ltd., are in operation. The waste from Krishna mines is dumped on both the South and North side of the lease area. For limestone extraction and overburden removal, modern technology such as mechanised drilling and blasting, shovel dumper combinations, and so on are used.

Presently, there is a slope failure towards the north side of the pit and there is concern regarding the stability of the slopes which leads to stoppage of workings in the area by the regulatory body. So, geotechnical investigations were conducted to determine the possible causes of failure, and tensile cracks were discovered on the north side of the limestone mine.

Geology

The limestone deposit belongs to the Archaean Era and represents the metamorphosed sediments of the Dharwarian Age and forms part of the major Ramayanpatti limestone band, which traverses in the East-West direction for a distance of about 3 kilometers. This is one of the most important limestone formations of Tamilnadu. Limestone is seen occurring as a linear body in the mining lease area up to a depth of over 120m. The width of the limestone band varies from 40-50m in Western part whereas it is 20-40m in the Eastern part of the mine. Limestone band is striking in the East-West direction. The angle of dip is 80º due south. The limestone is flanked by kankar followed by quartzite with

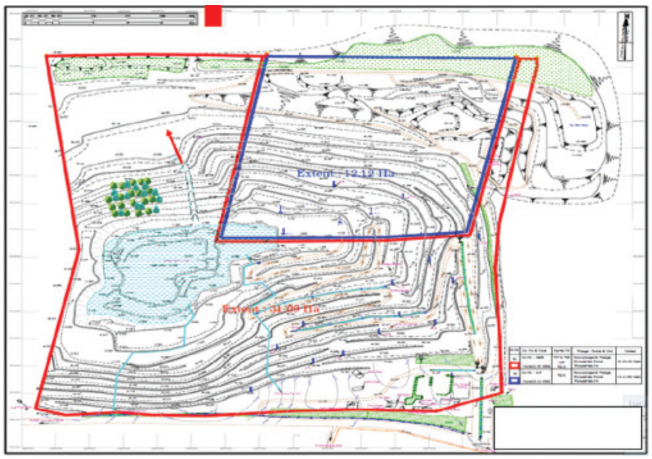

Figure 2: A plan view of the limestone mine

Figure 3: A photograph showing slope failure area in the limestone mine

kankar patches and magnesium limestone. Intermittent charnockite patches could be observed if the contact rocks are also dipping in the same direction. The limestone occurs as fine-grained, medium-grained to nearly coarse-grained crystals. The colour also varies from white, yellow, honey yellow, blue and pink with varying gradation in physical and chemical characteristics.

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 rockmass 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 rockmass 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 rockmass 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.

5.0 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 accumulation of rock and/or soil on a bench, a visual inspection is required. Visual inspection should be an important part of any pit wall monitoring programme. In addition to visual monitoring, instrumentation is commonly used (Samuel et al., 2015; Kumar et al., 2017 & 2018).

Visual examinations are done to look for material ravelling from 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 rockmass 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 rockmass and the likelihood of slope instability dictate the frequency of visual inspection (Samuel et al., 2015).

On a daily basis, the mines perform a formal visual inspection. However, all personnel working in the open pit perform continuous informal monitoring. During 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 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 downslope 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 in 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. As a result, an extensometer can be scanned frequently during the day, daily, or weekly, depending on the risk associated with the instability. Extensometer data are useful for tracking adjustments in deformation rates and making operational choices regarding tension crack mining activities (Samuel et al., 2015).

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 150mm deformations were noticed at the topmost benches of the failure area only (Figure 4).

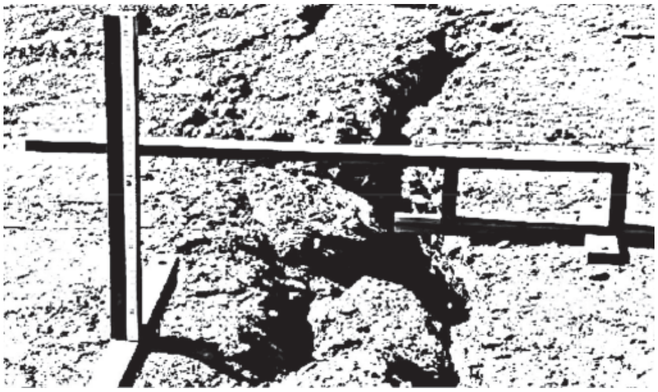

Figure 4: Wireline extensometer installation in tensile cracks developed area near to slope failure zone

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 (Afeni et al., 2013).

(a) a network of reference beacons on stable ground that can be seen from the transfer station is required.

(b) a number of transfer stations are built on stable ground at locations where the slope surface can be seen. If the monitoring point positions are to be measured, the transfer stations should be configured in such a way that they form a suitable survey network for line-of-sight network.

(c) the installation of monitoring prisms at the suspected likely unstable slope zone of interest is the third component.

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. The monitoring sites on the slope can be reflectors or survey prisms depending on the distance and precision necessary (Wyllie and Mah, 2004). The frequency of monitoring is influenced by the type of rock present, nearby activities, and the monitoring programme's goals. Measurements may be performed every few weeks or even months 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 (Figure 5). 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 as shown in Figures 6 and 7 and no deformation was observed in the prism stations outside 5m to failure zone as shown in Figure 8. Therefore it indicates that within 5m of the failure zone stabilized within seven days of the failure, and strata outside 5m from the failure area is not influenced by failure which is in stable condition.

Figure 5: Prism network and monitoring setup in the limestone mine (NITK Report, 2019)

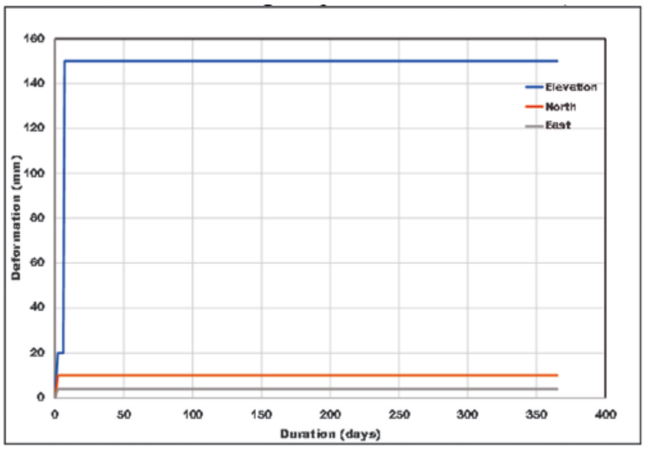

Figure 6: Deformation monitoring prism station graph results within 5m (East Side) of the failure zone

As a result, at the limestone mine, the 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.

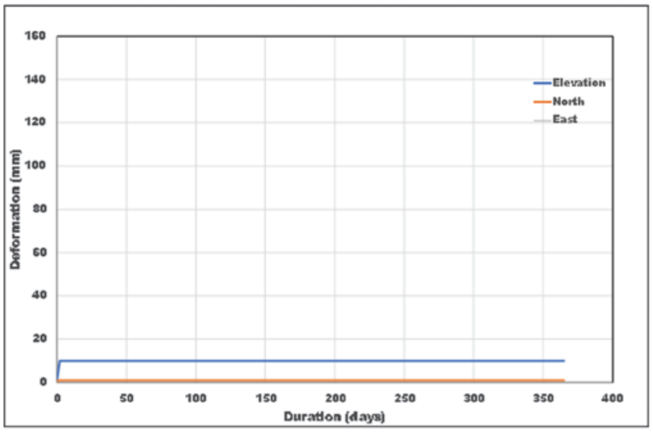

Figure 7: Deformation monitoring prism station graph results within 5m (West Side) of the failure zone

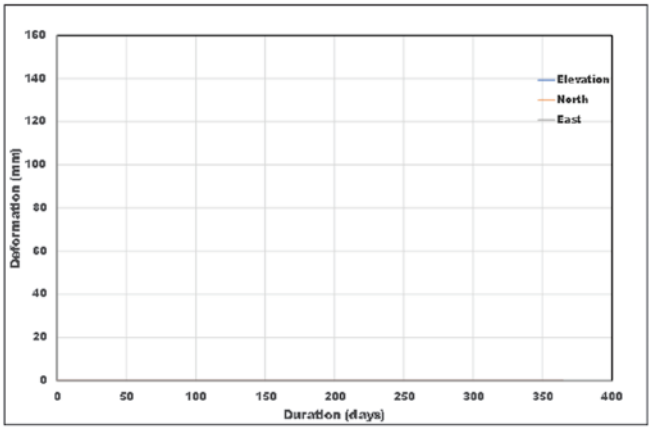

Figure 8: Deformation monitoring prism station graph results outside 5m of the failure area

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 studied also check their pit walls for fresh indications of seepage or adjustments in flow rates, which usually signal the beginnings of unstable rock slopes (Samuel et al., 2015).

Limestone mine locality receives about 350mm of rainfall a year. It's a dry locality other than monsoon period. No water seepage was observed in the failure area.

Stability Performance of Failure Zone

A pit wall failure towards the North side of the pit, where passage to the slope is hazardous and/or there is a need to make frequent and accurate measurements using visual inspection, wireline extensometer, piezometer and total station prism monitoring is 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 5m from the failure zone is not influenced by the failure which is in stable condition.

The monitoring is made 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 with an overall slope angle of 30^{o}.

6.0 Conclusion and Recommendations

Slope monitoring has allowed for a fundamental shift in risk management in open pit mining operations, 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 open pit mines.

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 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 recommendations made are 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, future workings of the failure zone are redesigned with an overall slope angle of 30^{0}.

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