NUMERICAL MODELLING AND MONITORING OF SLOPE MOVEMENTS VIS-À-VIS DEVELOPEMNT OF TRIGGER ACTION RESPONSE PLAN FOR OPENCAST COAL MINES

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ABSTRACT

This paper presents the application of recent guidelines of Directorate general of Mine safety in January 2020 for a typical coal Opencast mine. TARP suggested for the opencast coal mine is demonstrated with reference to the typical geo-mining conditions and recent data during this typical COVID19 period from opencast coal mine on monitoring the movements and numerical model studies for design of stable dump slopes and high wall slopes along with sensitivity analysis on effect of ground water. Development of proper TARP suitable for the geo-mining conditions of any opencast mine with observational approaches and meticulous monitoring and online interpretation and communication to the grass root level. Indian mining industry has recently witnessed the biggest slope stability disaster involving 23 persons under slope failure in the year 2017. Adopting a suitable TRAP will lead to self-reliant and sustainable practices with improved safety and stability of slopes.

The analyses of factor of safety of slopes for existing slopes are found to be within prescribed safety limits. The monitoring results up to 20 June 2020, revealed the overall stability of dump slopes with practically considerable vertical displacement within 12 mm on the dump-A. However, these local movements observed from the Total Station reading is due to high moisture content of materials and deployment of HEMM near to the monitoring stations for the formation of benches in dump. The maximum horizontal movement at any station is within 14.5 mm across 19 days indicating a daily movement of 0.76 mm which is far below the critical limit proposed by various researchers, and hence the slope is considered stable. Further analysis may be carried out in future for the Mine A with a large scale monitoring data to obtain an insight of slope movements.

1. INTRODUCTION

All geotechnical investigations aimed at collecting input design parameters, however complete, involve an inherent risk of inaccuracy. Hence, any attempt of slope stability analyses and evaluation need to be supported by a sound slope monitoring programme in order to ensure the safe and smooth mining operations.

The slope monitoring method allows failures to be predicted and safe working conditions. Slope monitoring can be used to confirm failure mechanisms. The review of monitoring results, visual inspection and regular briefing of field people help to detect the onset of failure. The slope monitoring is also advisable for three consecutive wet seasons to detect any failure well in advance for the dumps, which are more than 60 m high. Initially, the monitoring can be done twice (before and after the monsoon) in a year till any movement is detected. Then the frequency can be increased to monthly basis. The interval between the monitoring stations should be decreased (5m to 10 m) in the movement zone. The monitoring should be done weekly and then daily, in this situation, to predict the date of failure in advance for the safety of men and equipment.

The main objective of slope monitoring study is to detect any instability well in advance so that any damage to men and machineries can be avoided. If the failure is unavoidable then it can be brought down in a predictable manner. The early identification of movement zones allows steps to be taken to minimize the impact of mining on stability by the implementation of correct remedial measures and at the same time provides for optimum coal extraction. The system contrasts strongly with more common `passive' systems that frequently only record the occurrence of an event for subsequent post-mortem examination. The active monitoring system permits early and confident decision making by management for safety purposes.

The first sign of instability is a tension crack. So, it is important to carry out regular inspection to detect the development of tension cracks on the crest of the slope as well as on benches and to carry out prompt remedial measure. They may develop as a function of high stresses in the slopes. The opening of cracks will tell whether any deep - seated failure can occur or not. Tension cracks should be filled with sandstone and sealed with clay to prevent the entry of water, which may cause failure. The rate and scale of movement in the form of velocity or what can also be termed as average velocity is another key parameter for the identification of pit slope instability. The average velocity is a derivative of the accumulated displacement based on a reference time and an assigned time window.

Prior to failure of slopes progressive, regressive and steady movement are observed. Zavodni and Broadbent (1980) have studied these movements based on empirical formula with data obtained from multiple opencast mines. Progressive stage refers to the accelerated movement till failure whereas in regressive stage means decelerating movement towards stabilization. Displacement with no acceleration or deceleration is referred as Steady displacement (Fig 1).

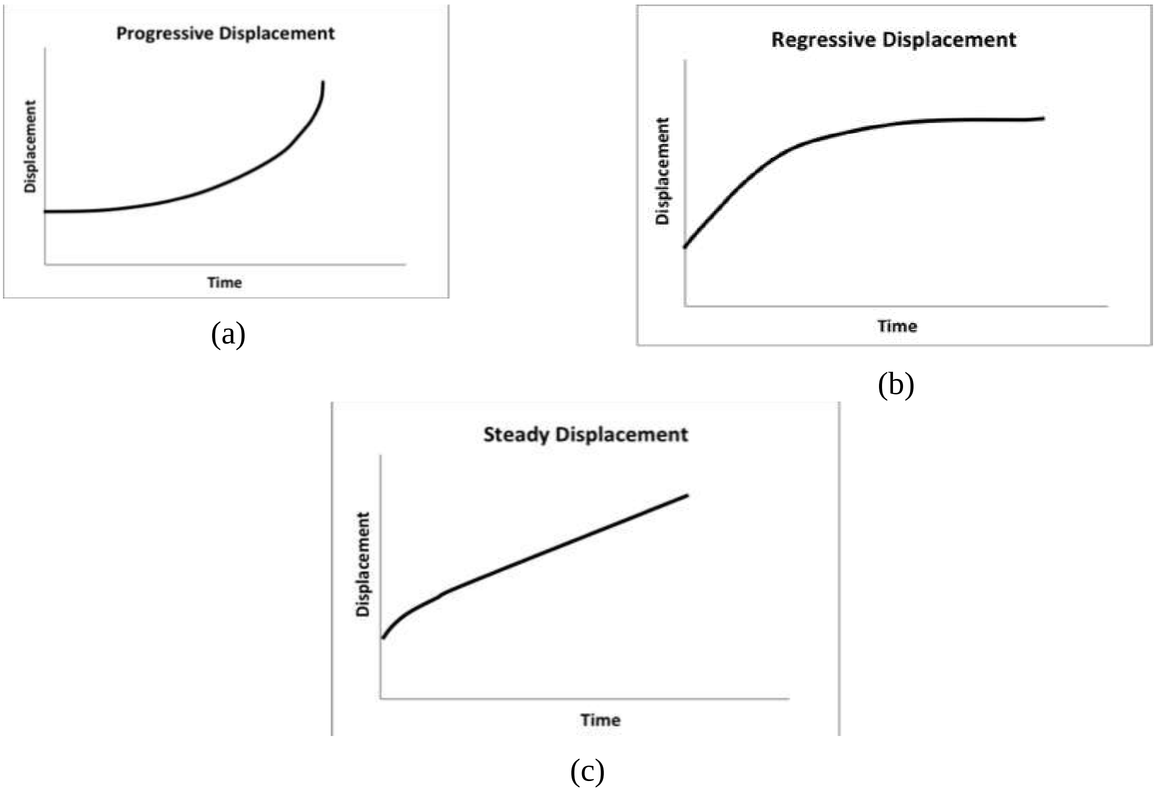


Fig 1 Progressive Displacement, b-Regressive Displacement, C- Steady Displacement

(Zavodni, Z.M., and Broadbent, C.D. 1980)

Recently DGMS vide its tech circular no 02 of Dt 09.01.2020 has laid down comprehensive guidelines towards slope monitoring methodology. I

2. GEOMINING DETAILS

The study site(Mine A) is an opencast coalmine project situated in IB valley coalfields in Odisha. The method of mining adopted is shovel dumper combination. Drilling and blasting is done to extract the overburden material. Surface miner is engaged for extraction of coal. The top ten seams namely Parkhani, Lajkura Top III, Lajkura (I+II), Lajkura Middle, LajkuraBott II, LajkuraBott I, Rampur IIIB , Rampur IIIA, Rampur II & Rampur I seams are considered for quarrying considering Rampur I seam as base seam. The seams Rampur IAII &IAI are assessed separately without C: OB ratio lines. Locally these 2 seams are not developed, however in the area of their development they can be mined by deepening the quarry further and the parting between Rampur I and these 2 seams is around 5 to 10m only.

Opencast mining method has been adopted due to incropping of the coal seams at a shallow depth, OB: Coal ratio is favourable (2.59: 1) for opencast mining, and the mining by opencast method will be economical against underground method.

For the above geomining conditions, CSM was recommended due to its precision cuttings, thereby improving the quality of mined coal especially in seams having dirt bands. There will be more than 25 benches in the mine having 255 m depth (max) in which these machines cannot be deployed exclusively due to limitation of mobility /flexibility. Hence only two seams in Rampur horizons were chosen for deployment. These machines also require wider benches which will require comparatively higher volumes of OB to be removed in the initial stages leading to higher cost of production and imbalance in equipment utilisation due to subsequently decreasing OB: coal ratio. Therefore only top benches requiring lesser volume of OB handling was chosen as the place of deployment of CSM. In view of 15 seams and equal nos. of inter burden layers to be tackled, an equipment system which is capable of dealing many layers at a time (flexibility) of operations with the help of smaller units was also recommended as shovel dumper combination.

2.1 Overburden Dumps

The major constraint for this FY 2020-21 is OB dump as the temporary option of the internal dumping in the previous FY 2019-2020 shall remain the major dumping site. The actual OB dump is occupied by a nearby Village which was expected to shift. But as there is much delay in acquiring the land it shall majorly effect the mine scheduling.

Hence, the OB quantity which is around 84.6 Lakh cum is proposed to be dumped internally as well as in the external OB dump area. The Internally dumped quantity shall be re-handled to the de-coaled area later. Upto 20 June 2020, the mine excavation has gone upto about 28 m depth with four OB benches including three benches of 6 m height, and about 2 m high Top soil bench. Coal bench of about 8 m thickness is being exploited by Surface miner while the OB is removed by Shovel dumper combination. The present status of OB dump is shown in figure 2.

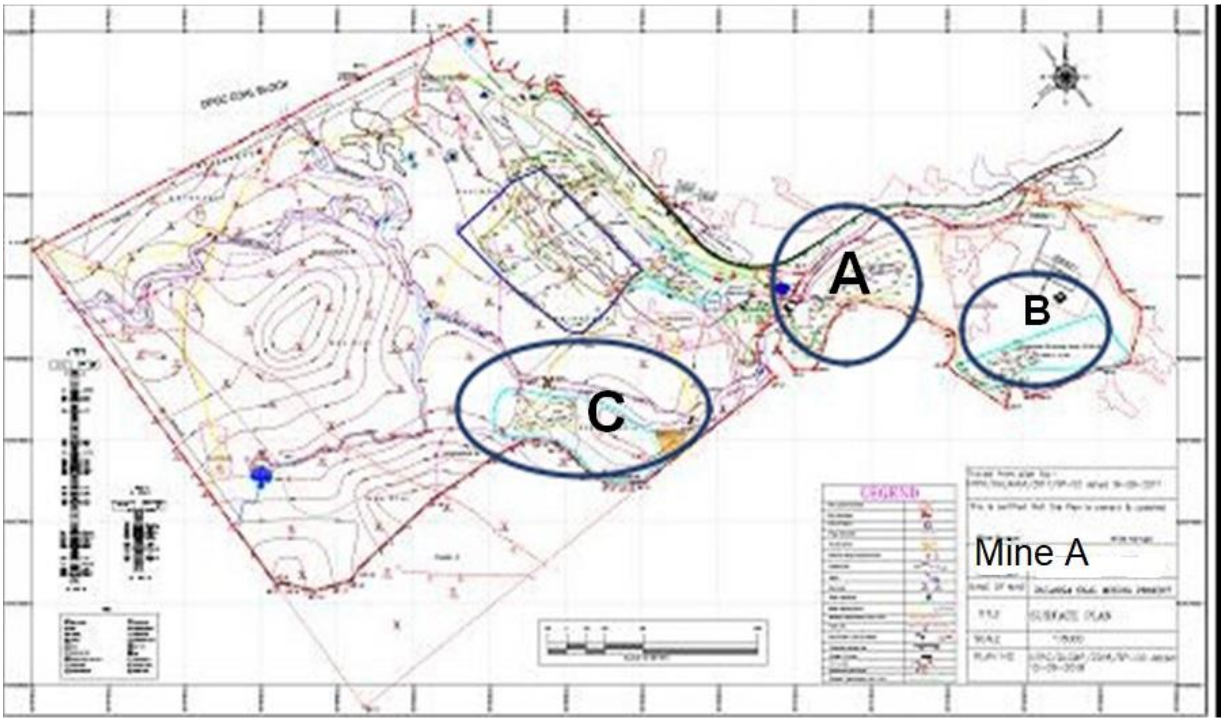


Fig 2. Mine Plan showing three number of exisiting dump at mine A

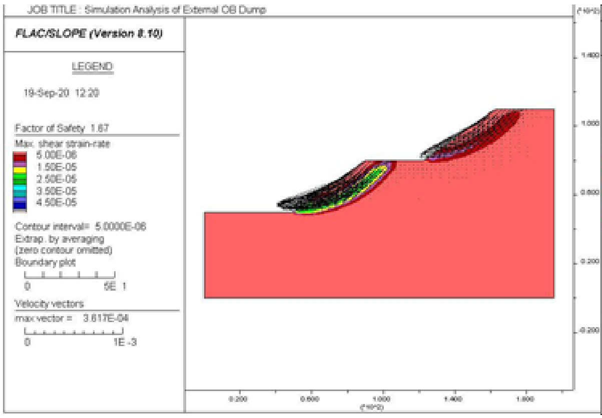
3.NUMERICAL MODELLING

It is prudent to know the lithological units in which the slope is to be cut. Engineering properties of these litho units will influence the analysis for slope stability. The rock mass strength of lithology was appropriately reduced from laboratory test results of various samples and previous experiences of conducting simulation studies, along with data of geo-mechanical of Mine A. Properties of Overburden (OB) and rehandled Overburden (ROB) were also considered in the model. Cohesion, Friction angle, and density of OB material are 36 kPa, 310, and 1.80 gm/cc respectively. Cohesion, Friction angle, and density of coal are 300 kPa, 440, and 1.549 gm/cc, respectively. Cohesion, Friction angle, and density of sandstone are 350 kPa, 420, and 2.25 gm/cc, respectively. FLAC/SLOPE software is used for stability analysis for dump and quarry slopes. FLAC SLOPE determines the factor of safety of the slope by Shear Strength Reduction Technique. The “strength reduction technique” is typically applied in factor-of-safety calculations by progressively reducing the shear strength of the material to bring the slope to a state of limiting equilibrium. FlAC/SLOPE performs the bracketing function between the stable and unstable solutions for a given set of material properties. For a user defined strength properties FLAC/SLOPE determines the stable and unstable solutions. Then it sequentially decreases the limit between the two performing iterations till a certain level of tolerance.

3.1- Stability of Dump Slopes

The stability analysis was done considering typical vertical cross sections of the proposed pit and dump. The proposed external dump consists of two decks of 30 m each with total height of 60 m. The condition of two benches with bench angle of 37º and 30 m height of individual decks was simulated. The factor of safety estimated for the above sections is 1.67 indicating stability of dumps

Internal dump with total height of the internal dump as 290 m was simulated with 9 benches of 30 m height and one upper bench of 20 m height comprising of 50 m high crown dump. The factor of safety estimated for the above sections indicated stability of dumps. Resultant Factor of safety of 1.34 indicates stability of internal dump. FLAC/Slope models simulated for the external and internal dumps are illustrated in figure 3, and 4 , respectively.



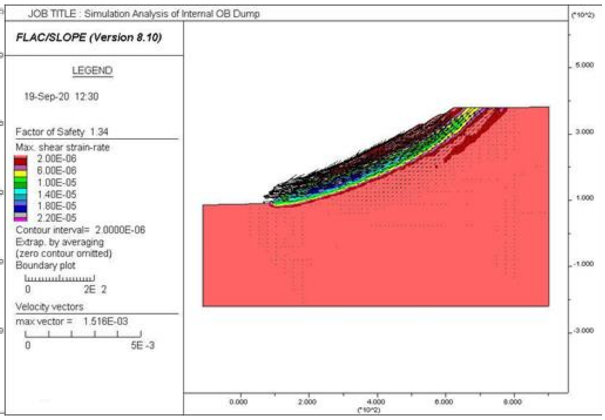


Figure 3. Simulation of External Dump   Fig 4. Simulation of Internal Dump

3.2. Stability of Bench Slopes

As per the approved mining plan Mine A project quarry cross sections in 5th year, 10th year, 20 th year and final stage were analysed in FLAC/SLOPE software. The Factor of safety output in drained and undrained conditions are are tabulated in Table 1. At this stage the working pit will be encountering fault plane. The effect of fault plane was also considered for deriving factor of safety

Table 1: Details of stability analysis through simulation of slopes at various stages of mining at Mine A as per approved Mining Plan

Stage/Year	Depth (m)	FOS with Dry condition of slope	FOS with Undrained condition of slope
5	50	2.4	
10	123	4.48	2.92
20	160	4.22	2.77
Final Stage	235	2.19	1.3

3.2.1 Sensitivity Analysis

The sensitivity analysis was done with an aim to know the influence of water on the factor of safety. This study is highly beneficial to choose the best method of remedial measure for any critical slope. The influence of groundwater on factor of safety is remarkable. The stability analyses of highwall slope have been conducted in undrained geo-mining condition also. It is evident that the highwall slopes which may stable in drained condition with cut-off safety factor of 1.3 . The factor of safety is reduced to less than 1.3 when thes lopes are subjected to undrainedcondition . As mentioned in Table no.1 the varying factor of safety can be seen in drained and undrained condition. However, it may be recalled that the most likely condition of the slope was already adjudged to be drained condition. The slopes are likely to be stable with available shear strength of highwall slope material in this condition. In order to avoid undrained condition, attention must be paid to avoidentry of rain/ surface water in the slope by providing suitable drainage in and around thequarry, failing which the slope can become unstable. It should be taken up well beforethe onset of monsoon.

Numerical analysis was performed with varying water level of 20m, 15m, 10m and 5m for a 235 deep pit. This analysis shows the effect of change in factor of safety due to change in ground water level. Evidently lowest factor of safety was obtained with 5m water level from original ground level. Hence care must be taken to arrest accumulation of water inside high wall. Depressurization and dewatering methods may be adopted to achieve the same. Sensitivity Analysis for FoS of 235 m final stage pit with varying water level for 20 m indicated Fos as 1.42, for 15 m is 1.34, for 10 m is 1.29 and for 5 m water it is 1.2. It is evident that with increase in water level there in decrease in factor of safety. Figure 5 shows a FLAC/SLOPE model with highest water level (i.e 5m from OGL) displaying lowest FOS of 1.23. Even if the factor of safety of 1.23 considerably safe, with adoption of proper dewatering arrangement it will tend to increase.

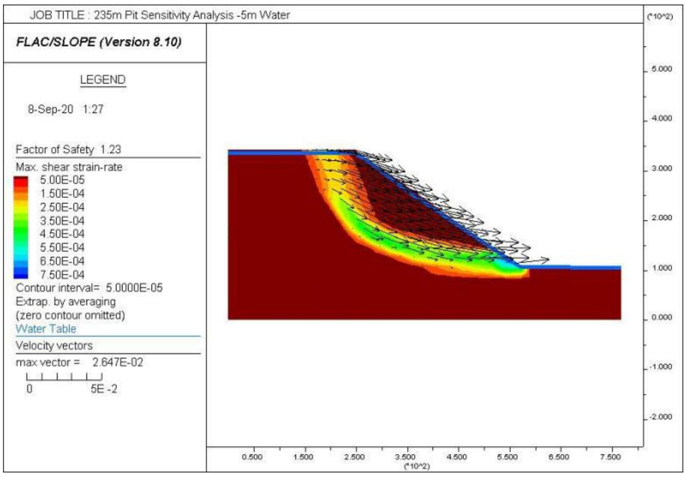


Fig 5. Simulation of 235m deep Pit with 5m Water Level from OGL (Original ground level).

4. FIELD MONIOTIRNG OF SLOPE MOVEMENTS

The main objective of slope monitoring study is to detect any instability well in advance so that any damage to men and machineries can be avoided. If the failure is unavoidable then it can be brought down in a predictable manner. The early identification of movement zones allows steps to be taken to minimize the impact of mining on stability by the implementation of correct remedial measures and at the same time provides for optimum coal extraction. The system contrasts strongly with more common `passive' systems that frequently only record the occurrence of an event for subsequent post-mortem examination. The active monitoring system permits early and confident decision making by management for safety purposes.

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The rate and scale of movement in the form of velocity or what can also be termed as average velocity is another key parameter for the identification of pit slope instability. The average velocity is a derivative of the accumulated displacement based on a reference time and an assigned time window. On filed the most common form of monitoring is by continuous measurement of Reduced Level by Total stations. The change in RL w.r.t to a time window provides a broader idea about the velocity of slopes if any.

Another common method of monitoring is monitoring widening of cracks by crack meter. It is a localized form of monitoring which provide micro level observations to estimate any impending failure. One recent development in countries such as Australia and USA is the development of Slope Stability Radar (SSR). Radar technology, used widely in a variety of fields for several. SSR is now being widely used in several countries to provide real time monitoring and advance warning signals before any slope or dump failure in opencast mines. SSR system can detect and alert movements of a wall with sub-millimetre precision, with continuity, and broad area coverage. This monitoring occurs without the need of mounted reflectors on benches or walls and the radar wave adequately penetrate through rain, dust, or smoke continuously. The SSR system produces data for interpretation quickly. The radar is moved around the mine in a repeatable manner to compare movements at each site and determine problematic areas. Several case studies of SSR providing improved operational risk management of slope have been reported from different places of world during last about 20 years, and in case of any necessity with trigger levels as in Table 2, this system may be adopted. The experiences of this mine regarding suitability of the system considering the technical and financial aspects is yet to be seen with reference to regular monitoring results of slope movements.

5. Observation of Slope Movements and TARP

Multi monitoring stations are installed on Dump A for recording the reduced level in continuous mode in a fixed interval. Observation of the monitoring stations was conducted with Total station on 16 March, 15 Apr, 4 May, 18 May, and 10 June 2020. Maximum variation observed in the vertical movement was not perceptible and hovering about 1 to 6 mm in majority of the stations indicating stability of the slope. Maximum vertical movement observed was about 12 mm at the station SM-3, which may be practically attributed to settlement of the ground in the initial stages of the monitoring. Vertical movement at various monitoring stations on the OB dump. From March2020 to First week of May 2020, accelerated movement was observed on almost all the stations; however the stability was indicated after May 2020 without any ostensible variation.

5.1 TARP (Trigger Action Response Plan)

Pit slope failures generally pass through several stages of movement, such as (Sullivan, 2007): 1. Viscoelastic response 2. Primary Creep, which may eventually stabilise, or progress to 3. Secondary Creep 4. Tertiary Creep (cracking and dislocation) 5.Collapse 6. Post collapse deformation The first two stages or “initial response” include elastic rebound, relaxation and/or dilation of the rock mass (Zavodni, 2001). Secondary creep and pre-collapse deformation is associated with yielding, softening, strength loss, localised failure and slip on structures within the rock mass. The exact part of the curve in Figure.1 described by FOS = 1.0 is controversial, although generally accepted to be somewhere between Secondary Creep and Collapse. Work conducted by Sullivan (2007) summarizes the development of pit slope movement phases and provides a holistic view of the possible stages of pit slope movement from the perspective of velocity. Sullivan (2007) proposed the classification of pit slope velocities for planning as well as for the determination of critical velocities when imminent failure is expected, as shown in Table 2.

Table 2: Classification of pit slope velocities for the detection of critical velocities (Sullivan 2007)

Author	Velocity (mm/day)	Period over which velocity applies (days)
Ryan and Call (1992)	12	2
	50	2
Zavodni (2001)	17	2
Zavodni (2001)	15	
Martin (1993)	10-100	
Zavodni and Broadbent (1982)	50	2
Zavodni (2001) Borax Mine	150	
Call and Nicholas (from Zavodni 2001)	300	
Savely (1993)	30-10000	
Sullivan (1993)*	1000*	<hours

Note: * Minimum instantaneous velocity immediately prior to collapse.

The author suggests adopting a monitoring protocol able to monitor the slope deformation in real time or near real time at mm level accuracy to better understand the slope behavior. Table 3 & 4 suggests the trigger level and monitoring plan to be adopted by mine management.

Table 3: Trigger level and monitoring plan for slopes

Average slope Movements (mm/day)	**Suggested method of monitoring**	**Suggested Monitoring period**	**Response and Control measure**
< 0.1	Conventional Total Station monitoring (CSTM)	Monthly	Normal condition of slope -No appreciable response required
> 0.1	Conventional Total Station monitoring	Monthly	Initial response should start
0.1 to 15	Conventional Total Station monitoring	Fortnightly	Indicates no failure expected within 48 hours
15-50	CTSM + Crack meters/Extensometers	Weekly	Indicates no failure expected within 24 hours
50-100	CTSM + Crack meters/Extensometers/Other instruments	Once in two days	Indicates progressive failure

>100	Slope Stability Radar or other systems of monitoring	Daily	Clear the vicinity
>150	Slope Stability Radar or other systems of monitoring	Hourly	Stop further working and Clear the Area

Table 4: Frequency of monitoring plan for dump movements

Average slope Movements (mm/day)	Suggested method of monitoring	Suggested Monitoring period	Condition of slope -Response and Control measure
< 2	Conventional Total Station monitoring	Monthly	Normal condition of slope - No appreciable response required
2-5	Conventional Total Station monitoring	Weekly	Initial response should start
5 to 10	Conventional Total Station monitoring (CTSM)	Once in two days	Indicates no failure expected within 48 hours
10-50	CTSM + Crack meters/Extensometers/Other instruments	Daily	Indicates no failure expected within 24 hours
>50 mm	Slope Stability Radar or other systems of monitoring	Continuous observation	Indicates progressive-failure Clear the vicinity

6. CONCLUSIONS

The analyses of factor of safety of slopes for existing slopes are found to be within prescribed safety limits. The monitoring results up to 20 June 2020, revealed the overall stability of dump slopes with practically considerable vertical displacement within 12 mm on the dump-A. However, these local movements observed from the Total Station reading is due to high moisture content of materials and deployment of HEMM near to the monitoring stations for the formation of benches in dump. The maximum horizontal movement at any station is within 14.5 mm across 19 days indicating a daily movement of 0.76 mm which is far below the critical limit proposed by various researchers, and hence the slope is considered stable. Further analysis may be carried out in future for the Mine A with a large scale monitoring data to obtain an insight of slope movements. Table 3 and 4 are suggested as Trigger level and monitoring plan for bench slopes; and Frequency of monitoring plan for dump movements, respectively.

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