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Stability Assessment and Optimal Excavated Design of a Rock Slope in an Opencast Limestone Mine

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Abstract

The stability of rock slopes in an opencast limestone mine throughout the mining process was investigated using the limit equilibrium approach (SlopeW). The optimal excavation method with a substantially steeper slope angle of 45^0 rather than 35^0 was successfully accomplished at the critical geological section of the pit slope under numerous geologically disturbed area such as joints, faults and folds on a geotechnical basis in order to ensure adequate stability against any failure while working in the mine. The primary objective of this paper is to use the limit equilibrium approach in the SlopeW programme to predict the slope's safety factor and critical failure surface geometry due to the imposed of a surcharge loading of dump on top of the open pit slope for a 110m deep rock cut in the limestone mine. Geotechnical studies covering field geological mapping, laboratory experiments on rock samples cored from exploration drilling and different rock blocks retrieved straight from the mine were used to determine the physico-mechanical characteristics of the rock components, and numerical analysis using limit equilibrium technique (SlopeW) was carried out. 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 old scheme and shifting dump 25m away from the top of pit slope for future safe workings in the mine.

Keywords: *Opencast mine, Limestone, Slope stability, Limit equilibrium method (LEM), Safety factor, Dump load.*

1.0 Introduction

The current study used the limit equilibrium approach (SlopeW) to explore the rock slope stability of an opencast limestone mine located 200 kilometers northeast of Hyderabad in Telangana State (Fig.1). The effect of surcharge loading and the deeper excavation procedure from 90m to 110m depth has received special attention. Much of this investigation has been inspired by design optimization requirements that rely on understanding of nonlinear continuum mechanics in addition to the underlying geological data in the slope, such as faults, joints and bedding pattern, and surcharge load.

Prior to the numerical analysis, the excavated existing slope for a depth of 90m (old scheme) was originally planned on the key geological section using the usual limit equilibrium approach. However, a substantial amount of limestone could not be mined from the open pit near the section, and slope collapses on top benches near the dump area were seen if this old technique was applied. As a consequence, it is of considerable relevance that the slope stability boosted by a relatively steeper angle of excavated slope may be justified as a result of crucial dealing with thorough geotechnical analyses of slopes throughout the mining process.

There is now a well-developed framework for estimating slope stability[2-7, 10-18, 20-24]. These researchers evaluated recent advances in the characterisation of complicated rock slope deformation and collapse using numerical modelling approaches. Furthermore, the process impact generated by excavation with surcharge loading owing to dumps, which is intimately related to the building sequence and step, must be

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strongly simulated by a kind of numerical software with sophisticated geomaterial constitutive models.

It should be noted, however, that a nonlinear dynamical reaction of the quarried slope is highly dependent on rockmass properties, excavation pattern of rockmass, rock joint structure and fissured geometry, in situ stress distribution, dump loading, and hydrogeology, as well as their mutual interaction. In reality, numerical limit equilibrium approaches may be utilised to recognise these synthesized aspects on the nature of complicated rock slope deformation. The application of the limit equilibrium approach is advised herein to optimise the development of an ideal excavation slope design scheme for the key portion of the mine.

2.0 Study Area

The limestone mine is located 200 kilometers (km) northeast of Hyderabad city in Telangana State,India (Fig. 1).The lease area lies between latitude N 18º42'57.60" to 18º 44'44.6" and longitude E 79º 23'7.6" to 79º 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 mean sea level in height. Due to the growing demand for limestone material, the present mine development is taking place on plains and hillsides. Site investigation and exploratory holes indicate the sequence that this area has the cement-grade limestone deposits that form part of a sequence of sandstone, shale and various types of limestone (i.e., lower grey limestone, middle purple limestone and upper purple limestone). Limestone ore from this mine is mined by a fully mechanized opencast 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.

Presently, the limestone mine is working at a maximum depth of 90m with eight benches with an inclination of about 70 degrees (Fig.2). 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 opencast mines reach greater depths due to land availability limits. The deposit is faced with numerous geological discontinuities,

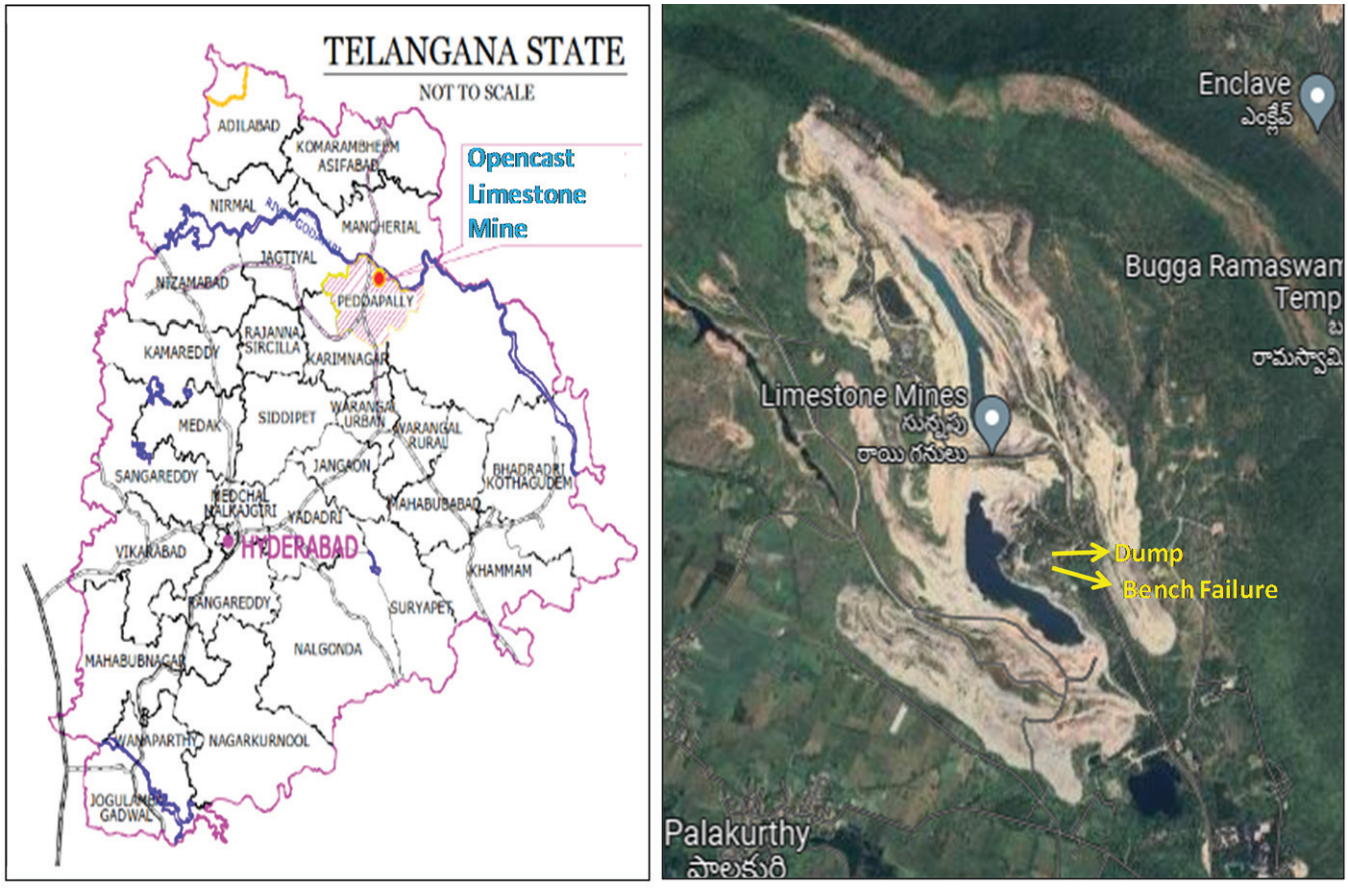


Figure 1: A location plan of an opencast limestone mine



Figure 2: A view of the opencast limestone mine

such as 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, rockmass condition, the existence of major and minor faults, rainwater infiltration into the slope, and the existence of external loads on cut slopes.

3.0 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 granites form basement to a sequence of Proterozoic sedimentary formations belonging to the Pakhal Super group, which in turn are overlain by the rocks of Sullavai Group. Close to the area towards the north, the well-known coal-bearing sequences of the Gondwana Supergroup occur within the NW-SE trending Pranahitha-Godavary valley. The basement granites and the overlying Pakhals and Sullavais have been affected by regional faults from NW-SE to WNW-ESE. 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.

Table 1: The lithological succession at limestone mine

Formations	Lithologies	Thickness 'm'
Precambrian	Sullavai Sandstone	10
	Upper Shale	15
	Flaggy Limestone	15-110
	Grey Limestone	
	Purple Limestone	
	Pranhita Sandstone	
	Lower Shale	120
Archean	Granite	Not ascertained

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. The order of superposition of the different limestone horizons and the associated shale and sandstone beds is given in (Table 1).

There are three limestone bands in the mine, namely, lower grey limestone, middle purple limestone and upper purple limestone. The limestone mine comprising these three limestone bands has been divided into the Palakurthi area, the Takkalapalli area and the Lower Vindhyan area. 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 70º in hills to 30º 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.3 and 4). The geological sectional view of the open cut slope is given in Fig.5.

The area experiences tropical climatic conditions, with the temperatures dipping from as low as 8ºC in winter to as high as 48ºC in summer. Groundwater will be met in the developing quarry excavation, according to extensive drilling investigations at the limestone mine. Furthermore, while mining, constrained bedrock aquifers will be discovered



Figure 3: Two sets of joints in the benches of the mine



Figure 4: Joint filled with ferruginous material in the benches of the mine

throughout the developing quarry.The average rainfall of the area is around 1100 mm per year.

Kinematic analysis was used to show the potential for different modes of rock/soil slope failures, such as planar, wedge, and toppling failures caused by the presence of unfavourably oriented discontinuities[8,9]. 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 slopes. The results of the field mapping and core logging (Figs.6a and b)were tabulated in Table 2.

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 2. 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 programme named

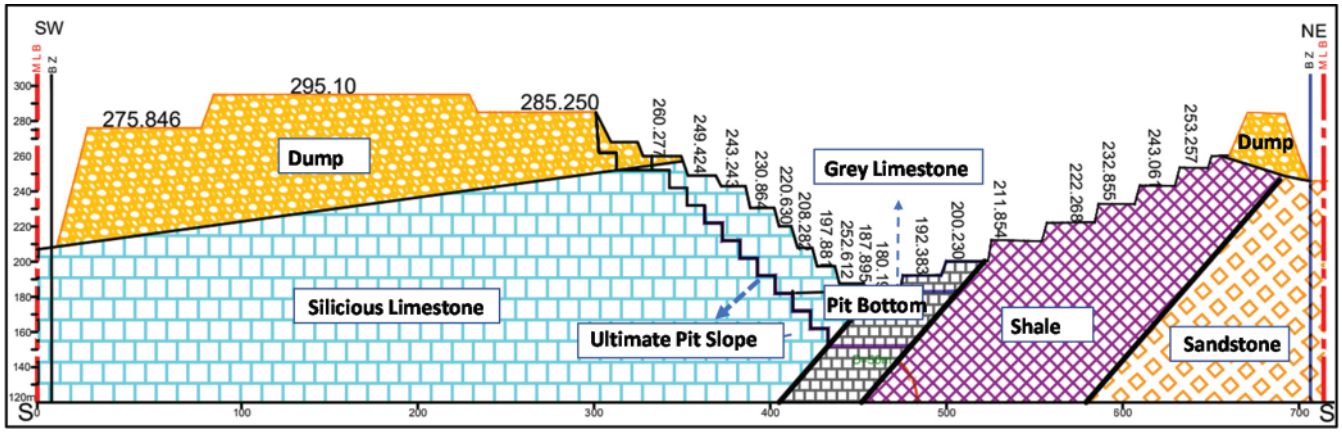


Figure 5: A View of the geological critical section in the mine

Table 2: Joint features observed in different sections of the limestone mine[19]

Section	Feature	Strike	Dip amount	Dip direction
Critical section (Fig.5)	Bedding planes	140° – 320°	22°	N 230°
	Joint-1	N – S	90°	-
	Joint-2	E – W	90°	-
	Random	140° – 320°	80°	N 050°
	Bedding planes	130° – 310°	17°	N 220°
	Joint-1	N – S	90°	-
	Joint-2	E – W	90°	-
	Joint-3	65° - 245°	90°	-



Figure 6: (a & b): Field mapping in the mine

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.7).

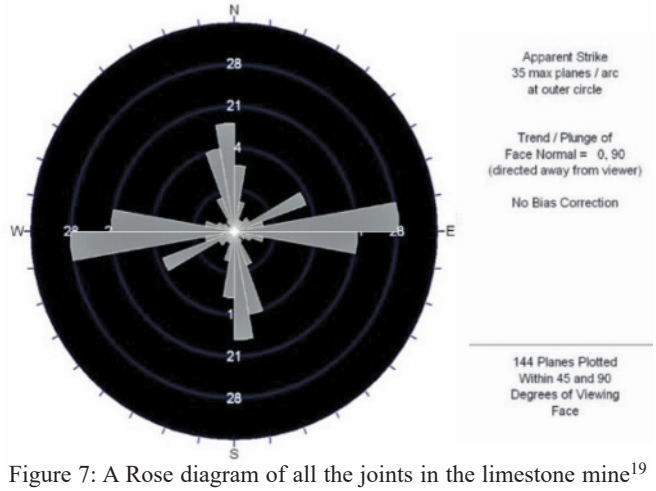


Figure 7: A Rose diagram of all the joints in the limestone mine[19]

4.0 Physico-Mechanical Properties

The geomechanical rockmass 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 rockmass.

The system is based on six parameters: (i) Intact core's uniaxial compression strength, (ii) Rock quality designation (RQD), (iii) Joint or fracture spacing, (iv) Joint or fracture orientation, (v) Joint or fracture 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. Borehole RMR ranges from 60% to 68% of the core categorised as a fair rock (class III).

Table 3 summarizes the physicomechanical characteristics employed in the simulations. In the current simulations, a nonlinear material Mohr-Coulomb model with a tension cut-off was applied.

Table 3: Strength parameters of different materials[19]

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

5.0 Two-Dimensional (2D) LEM Analysis

The geology, physico-mechanical characteristics of the rock in the slope, groundwater hydrology, and dump loading are the primary elements impacting the stability of the development slope. The slope stability on the current critical section 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° is either 1.98 for dry conditions (Fig.8), 1.96 for saturated conditions in circular failure (Fig.9), 1.72 for dry conditions (Fig.10), or 1.68 for saturated conditions in noncircular failure (Fig.11)[19]. However, even with such a old

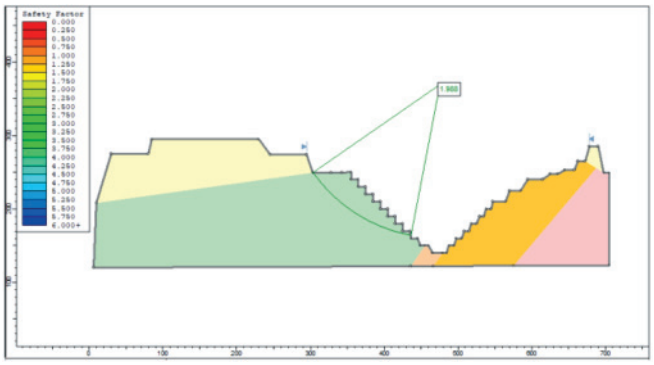


Figure 8: Numerical analysis of critical section in the dry condition in circular failure

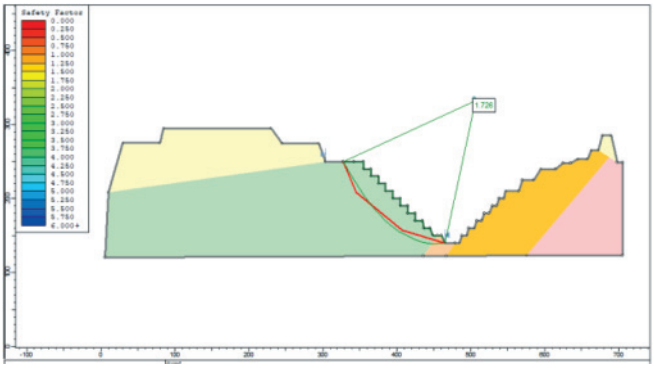


Figure 9: Numerical analysis of critical section in the dry condition in non-circular failure

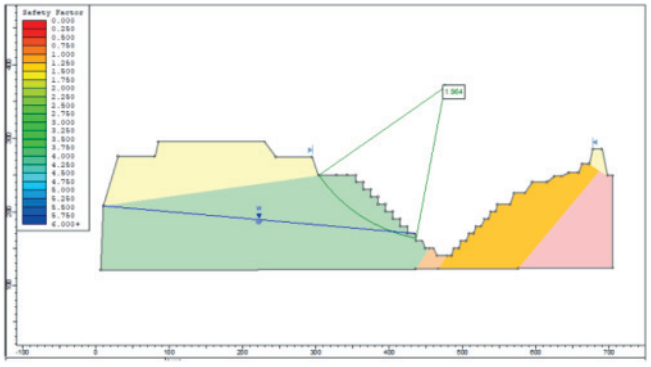


Figure 10: Numerical analysis of critical section in the saturated condition in circular failure

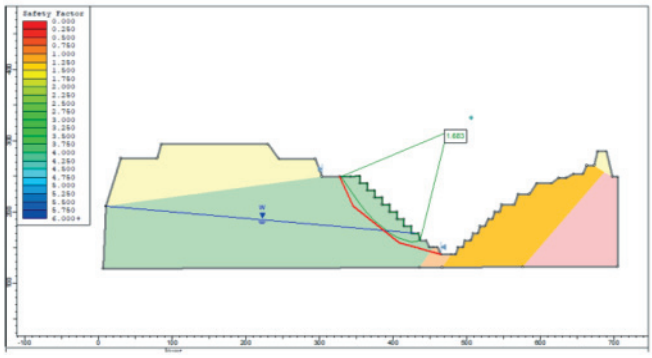


Figure 11: Numerical analysis of critical section in the saturated condition in non-circular failure

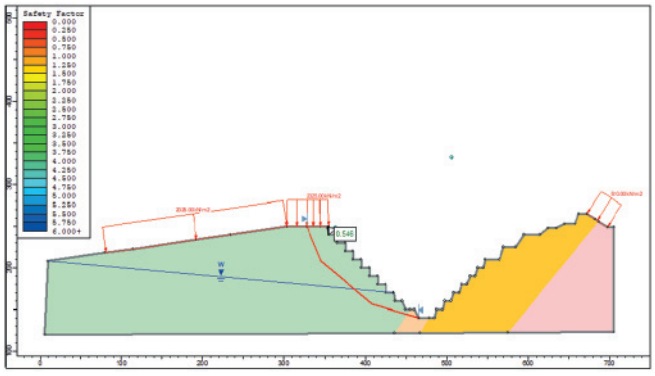


Figure 12: Formation of a critical failure surface at a surcharge loading due to dump from a distance of 0m from the top of pit slope

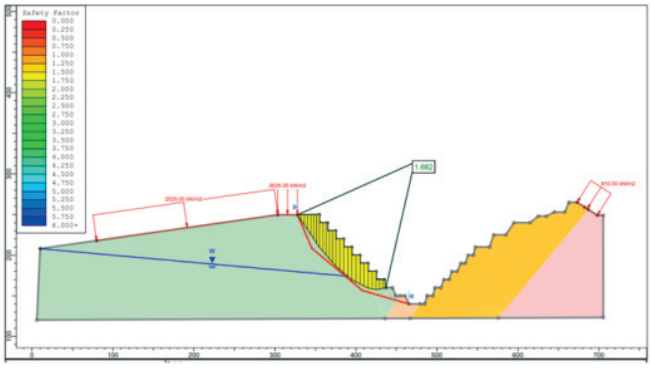


Figure 13: Formation of a critical failure surface at a surcharge loading due to dump from a distance of 25m from the top of pit slope

scheme plan with a comparatively soft angle of 35º, the slope would become unstable (FOS=0.546) due to the dump load effect (Fig.12) and new scheme dump 25m away from top of the slope FOS is 1.68.

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 above-mentioned deformation analysis will yield an ideal slope design scheme in key portions.

6.0 Results and Discussion

The analytical results of two-dimensional LEM approaches were compared to 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 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.

Fig.12 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[19]. Fig.13 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.

7.0 Conclusions

A timely correct design for a mine under surcharge loading owing to excavated waste might improve 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 hazardous slope deformation.

SlopeW was used to analyse the stability of an opencast limestone slope, and a moderately steep excavation strategy was provided, which was successfully implemented on the important geological part of the limestone mine, allowing the mine to extract locked-up limestone mineral reserves. The excavated rock slope schemes were optimised utilising matured geotechnical investigations, such as field geological mapping, laboratory analysis, and numerical analysis with SlopeW, to provide an ideal choice for mine engineers and researchers.

The results show that 45^o is the best final slope angle design for a 110m deep opencast pit slope compared to the present slope angle of 35^o for a 90m deep open cut slope with bench dimensions of 8m height by 8m width. 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 and dump need to shift 25m away from the existing position in new scheme. According to the findings of this study, the optimal slope ensures the long-term stability, productivity, and safety of mines with increased limestone mineral extraction. The above-discussed studies describe the application of a sophisticated stability analysis model that requires extensive calibration and mature engineering judgment. For comparable geo-mining settings, the technique for optimal slope design employing proper geotechnical assessments may be applied.

8.0 Acknowledgments

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