Geotechnical Modeling of Optimal Pit: West Limb of the Tarkwaian of Ghana*

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Abstract

Tarkwa Gold Mine is depleting its reserves to the east of the mine, on the Tarkwaian paleo placer deposit. It has, as a result embarked on vigorous near mine exploratory works to the west of the concession for reserve generation. Results indicate gold mineralisation of economic interest. The Mine seeks to provide optimal slope design that would satisfy shareholders and employees in the context of safety, ore recovery, and financial returns. Rock Mass Rating (RMR) and subsequent adjustment to obtain the Mining Rock Mass Rating (MRMR) was done for rock characterisation. The ratings for the various geotechnical zones ranged from 40.91 to 67.72 and rated from *fair* to *very good*. Kinematic stability analyses were performed for all the three design sectors using stereographic techniques to determine the failure modes kinematically possible in bench and/or multi-bench scale slopes. Multi-bench scale planar and wedge failures were kinematically possible in all sectors. Limit equilibrium analysis gave factors of safety that exceeded the minimum acceptable factor of safety of 1.05 for completely weathered material and 1.20 for fresh rock. The probability of failure was however less than 5%. Pit wall architecture for the geotechnical domains were 8 meters, 18 meters, 75 degrees for the berm width, bench height, and bench face angle respectively. Indicative overall slope angles fell between 50.02 to 59.21 degrees and rated from fair to very good.

Keywords: Tarkwaian**,** Depleting Reserves, Pit, Rock Mass Rating, Stability Analysis

1 Introduction

Tarkwa Gold Mine (TGM) is a global leader in sustainable gold mining in Africa. TGM has two operations in Ghaana, Tar and the Damang Mines. The Tarkwa operation has embarked on vibrant near mine exploratory work to the west of the Tarkwa concession for reserve generation. This is because over the past eighteen (18) years, it has been mining extensively from the eastern flank of its concession, thereby depleting the reserve to this part of the reserve (Anon., 2006). Some of its existing active open pits have been mined to a high depth leading to an increase in the stripping ratio. The western flank of the Tarkwaian placer deposit has since not been exploited. It is against this background that the design of a new open pit otherwise called Kobeda Pit, has been proposed for consideration. Hence, it is worth designing optimal slope parameters for this urgent pit to obtain slope architecture required for it operations.

Geologically, the Tarkwaian conglomerates which host the gold mineralisation at the Tarkwa mine overlies the Birimian greenstone belts uncomformably. This gold mineralisation is concentrated in conglomerate reefs, similar to that of the Witwatersrand system (Kesse, 1985). The gold deposits are composed of a succession of flat dipping stacked tabular palaeoplacer units, consisting of quartz pebble conglomerates within Tarkwaian sedimentary rocks (Kesse, 1985). The Tarkwa basin is filled with coarse-upward sequence of clastic sedimentary rocks (Griffis *et. al*., 2002)., The Tarkwaian Group of Proterozoic age (2132 to 2095Ma), comprise of the Kawere, Banket, Tarkwa phyllite and Huni 'series' (Fig. 1), and the rest forms part of the Birimian. The Kawere 'Series' consists of between 250 and 700 meters of repeated upward sequence of erosively-based, polymictic, poorly sorted, often matrix supported conglomerates grading up through immature pebbly quartzite to parallel-laminated or cross-bedded feldspathic quartzites. Again intrusives of clasts origin which comprise mainly of basic lavas with subordinate felsic lavas, quartz and doleritic units are uncommon (Griffiths *et al.,* 2002) The meta-sedimentary rocks comprise of turbiditic wackes and argillites including Tarkwa phyllites and siltstones, with similar chemistry to that of the volcanic rocks. No quartz-rich, craton-derived, border sediments are found except in the west of Cote d'Ivoire, suggesting an intra-oceanic plate origin (Kesse, 1985).
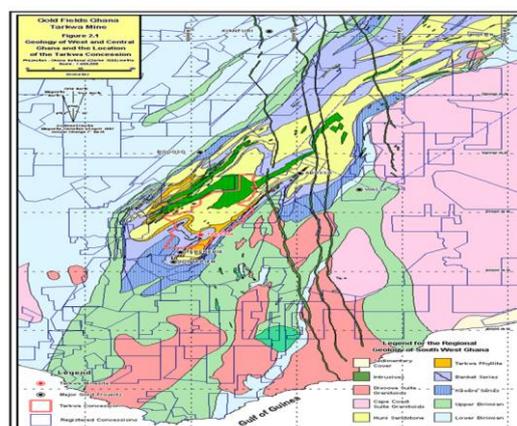

Fig.1 Geology of West and Central Ghana Hosting the Deposit (Modified after Anon., 2006)

Mining is undertaken by conventional open pit methods using hydraulic excavators and haul trucks. Bulldozers are used for clearing vegetation; topsoil stripping, waste dump construction and general pit/road maintenance. Topsoil is either stockpiled for use in future, for reclamation or hauled directly to areas that are being rehabilitated for placement. Waste from open pits is hauled to waste dumps or to in-pit backfill dumps. Wherever practicable, waste dumps are constructed in 15 m lifts at an overall slope of 22° to ensure long-term stability.

Evaluation from earlier work indicate some gold mineralisation of economic interest towards the west of the concession (Karpeta, 2002). This intervention is anticipated to increase reserve, to reduce the high stripping ratio, increase and consolidate its expectation with stakeholder and communities, as the Life-of-Mine improves.

2 Resources and Methods Used

In-debt geotechnical considerations are critical in the choice of any conceptual pit shell modeling and design. Hence, a number of methods and levels of analysis were assessed in the process of the open pit slope matrix. First, there was surface mapping of relevant structural features, drill holes logging, and follow up verification of lithological logs and as well as collar coordinates of all drilled points. Then the case by case modeling ranging from local bench design to overall stability of the walls was looked at to ascertain the domain design. Realistic design performance and calibration of parameters through back-analysis were done. The process required the use of a variety of methods of analysis and software applications, ranging from limit equilibrium to more involving numerical analysis such as distinct element, which could capture detailed geology and handle mix failure modes (Anon, 2008).

Before the design and analysis stage, a considerable amount of field work was carried out to provide the required data. The data gathering and interpretation process was extremely important and its quality and thoroughness was responsible for the success of the design.

The aspects of preliminary data collection required prior to design are as follows:

(i) Regional geology, regional faulting and emplacement of the ore are important factors worthy of consideration. These usually define the lithological and structural domains in the pit.

(ii) Hydrogeology and understanding of the groundwater regime impact overall stability.

(iii) Structural mapping of the different domains and rock types control both bench design and overall stability. This includes both joint sets, dykes, faults and lithological contacts among others.

(iv) Identification of alteration zones within the pit is important. Alteration affects rock strength; therefore, different alterations within the same rock should be grouped separately.

(v) Laboratory testing of the different rock types with the results grouped per the degree of alteration.

Stability analyses are routinely performed in order to assess the safety and functional design of an excavated slope and equilibrium conditions. The analysis technique chosen depends on both site conditions and the potential mode of failure, with careful consideration being given to the varying strengths, weaknesses and limitations inherent in each methodology.

The difficulty in predicting failure velocity also necessitates an accompanying development of a design methodology for cases in which precise prognosis cannot be made (Sjoberg, 1999). Slope design is categorised into deterministic and probabilistic approach.

The methods considered under deterministic approach are;
(i) Borehole
(ii) Laboratory testworks
(iii) Hydrogeological data
(iv) Empirical and classification methods.
(v) Limit analysis and limit equilibrium analysis.
(vi) Kinematic analysis using stereonet.
(vii) Numerical methods

In the deterministic approach, a point estimate of each variable is assumed to represent the variable with certainty (Coates, 1977). The analysis is based on the concept of factor of safety where a single hypothetical value for each input parameter is used without considering the extent of uncertainty. However, uncertainty is not formally recognized since in conventional analysis, one is not much concerned with reliability associated with this unique value.

2.1 Classification of Empirical Methods

Numerous design methods were considered on the basis of past slope performance and were adopted based on known slope failures. Due to the complexity of rock mass, a number of studies were conducted to correlate rock slope design with rock

mass parameters. Many of these methods have been modified over the years and are now being used in practice for preliminary and sometimes final design (Laubscher, 1990).

Rock mass classification has been developed as a useful tool for preliminary assessment of slope stability which gives some simple rules about modes of instability and the required support systems. In recent times, rock mass classification has been providing systematic design aid in an otherwise haphazard 'trial-and-error' procedure (Bieniawski, 1989).

These classification system considered aimed at (Duran and Douglas (2000):

(a) Identifying the most significant parameters influencing the behaviour of rock mass
(b) Dividing a particular rock mass formation into groups of similar behaviour, thus rock mass classes of varying quality.
(c) Providing a basis for understanding the characteristics of each rock mass class
(d) Relating the experience of rock conditions at one site to the conditions and experience encountered at others.
(e) Providing common basis for communication between engineers and geologists.
(f) Deriving quantitative data and guidelines for slope engineering design.

According to Duran and Douglas (2000), the empirical rock mass rating techniques that can be utilised in the design of slopes include the following:

(i) RMR – Rock Mass Rating (Bieniawski, 1989).

(ii) MRMR – Mining Rock Mass Rating (Laubscher, 1990).

(iii) SMR – Slope Mass Rating (Romana, 1985).

(iv) SRMR – Slope Rock Mass Rating (Robertson, 1988).

(v) RMS – Rock Mass Strength (Selby, 1980).

It is worth noting that the rating values for each method vary slightly depending on their intended usage since a number of these methods were developed for the design of support in underground excavations. The parameters and or weighting used have been modified to aid application of the stability of large pit slopes.

The *in-situ* RMR was adjusted to take account of the expected mining environment factors, namely:

(a) the influence of weathering

(b) structural orientation

(c) induced stresses

(d) blasting effect

The RMR rating summed up to 100. The various RMRs were calculated from the averages of these parameters. The adjusted RMR is the Mining Rock Mass Rating, (MRMR). The MRMR's were calculated based on the following percentage ratings: Summaries of the MRMR's and the Indicative overall slope angles (IOSA) for each pit sector are tabulated in Table 3.

Adjustment factor to the basic rock mass rating were applied to most empirical rating methods, which account for such factors as defect orientation, excavation method, weathering, induced stresses and major planes of weakness.

The RMR captured summation of rating assessment for intact rock block strength, rock mass block size, defect condition and ground water. The block size was assessed using Defect Spacing and Rock Quality Designation.

Precisely, uniaxial compressive strength test and point load test were performed on the samples to establish the strength magnitudes, in accordance with International Society for rock Mechanics, Anon, (1985) standards. The cylindrical cored specimen for uniaxial compression strength test were prepared with length to diameter ratio 2.0.

Tilt test or direct shear test on rock cores was also conducted to determine the basic friction angle on discontinuity surfaces.

3 Results and Discussion

3.1 Results of Data Input

In all, fourteen (14) oriented boreholes from the north wall, east wall, and south wall were geotechnically logged (see Section from Table 1). From the logging exercise, the oriented boreholes at the east wall dipped at 75° to the west orienting at 270^0. Oriented boreholes at the north wall were found dipping to the south at 75° orienting at 180°, while those to the south wall dipped at 75° to the north orienting at 0 ° (Fig. 2).

Table 1 A Section Collar Data of Holes Drilled

| Hole ID	Y	X	Z	Depth	Dip	Azimuth
GDKD002	7395.185	8127.482	108.02	74.1	-51.16	357.02
GDKD003	7244.061	8139.389	94.54	69.02	-50.4	357.18
GDKD004	7207.669	8218.438	84.272	79.7	-50.86	215.92
GDKD005	7398.761	8055.667	78.273	79.8	-51.08	177.76
GDKD006	7250.536	8140.427	94.88	122.15	-54.28	314.07
GDKD019	7602.297	7884.635	100.801	100.98	-54.72	180.2
GDKD020	7515.763	8017.63	61.88	79.83	-53.94	180.3
GDKD021	7681.11	7884.661	87.336	118.6	-54.44	181.16
GDKD069	7559.2	7933.596	80.157	102	-65.2	340.2333
GDKD070	7436.501	8092.992	99.658	83.34	-55.05	40.475
GDKD072	7552.269	7912.444	81.141	80.13	-64.4	222.925
GDKD075	7492.373	8008.082	62.241	80.28	-64.86	219.32
GDKD076	7520.533	8031.831	62.12	85.7	-63.025	43.2
GDKD077	7423.11	8078.746	96.538	100	-63.85	218.725
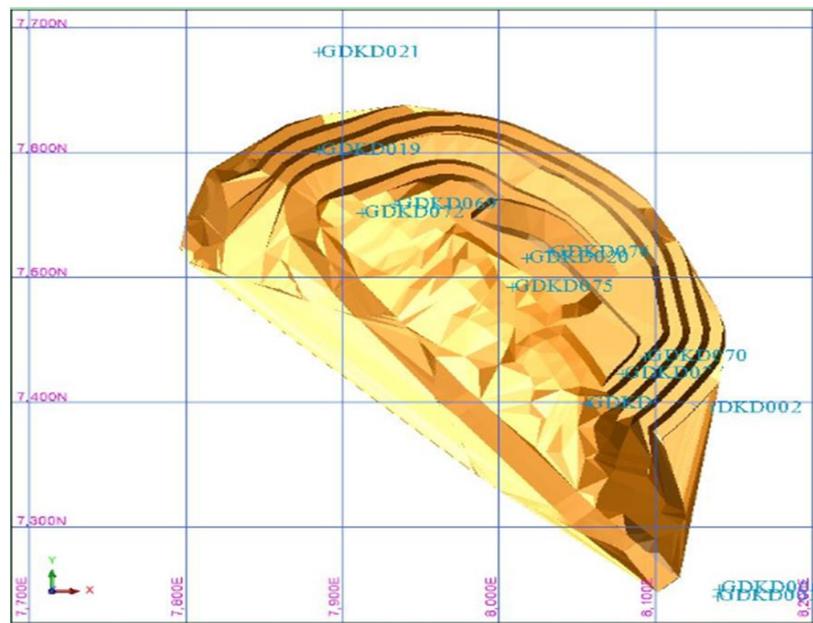
Fig. 2 Spatial Distributions of Geotechnical Holes

Table 2 Strength Test Results of Core Samples including Lithologies

Hole ID	Depth		Lithology	Weathering	UCS
	From	**To**			**MPa**
GDKD069	22.78	23.22	SSSL	MW	5.93
GDKD069	23.22	23.46			
GDKD069	47.05	47.56	SSSS	SW	65.25
GDKD069	50.1	50.42	SSSS	SW	62.60
GDKD069	52.81	53.19			
GDKD069	53.19	53.59	IFDL	UW	90.83
GDKD069	53.91	54.18			
GDKD069	66.02	66.35	SSSS	UW	97.72
GDKD069	68.37	68.64	SSSS	UW	92.69
GDKD069	99.15	99.96	SSSS	UW	95.22

The empirical evaluation is based on the mining adjusted Mining Rock Mass Rating (MRMR) classification system (Laubscher, 1990). This is an extremely useful and robust method of utilising all the relevant rock mass parameters to assist with mine design. It has been used in open pit mining from initial scoping studies through to full mine production.

Table 3 RMR, MRMR and IOSA values for the Geotechnical Domains

Domain	RMR	MRMR	IOSA
OXIDE			
North Wall	42.73	31.43	45.12
East Wall	42.50	31.30	45.20
South Wall	43.82	32.70	46.10
TRANSITION ZONE			
North Wall	57.05	41.03	50.51
East Wall	56.89	40.91	50.45
South Wall	57.32	41.22	51.11
FRESH ROCK			
North Wall	64.05	50.85	55.51
East Wall	63.23	50.07	55.03
South Wall	67.72	53.58	56.79

3.2 Hydrogeological Model

Ten Casagrande standpipe piezometers were installed in the boreholes to record piezometric pressures within the monitored horizons. The provided groundwater profile data was input into slope stability analysis and was also used in generating the phreatic water surface. The groundwater level was estimated to be some 56 meters from the surface (Fig. 3).
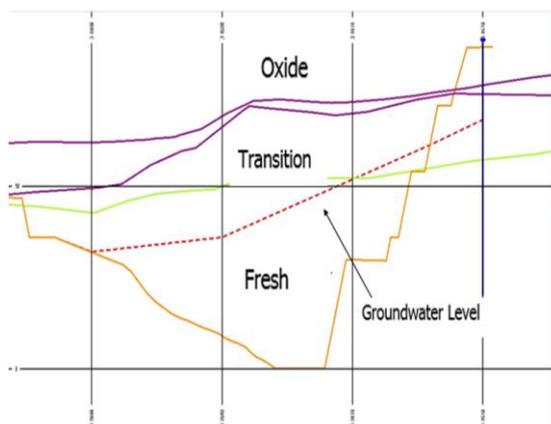

Fig. 3 Schematic Hydrogeological Model showing the Phreatic Water Surface

3.3 Rock Mass Stability Analysis

Two-dimensional limit equilibrium slope stability analysis was carried out on the pit slope sectors using the "SLIDE 6.0 software". The "Spencer and Bishop Method of slices" was used in the analysis for the various slope sectors. The SLIDE analysis was conducted to determine the Factor of Safety (FoS) for each pit sector. The minimum factor of safety for which failure occurred was obtained depending on the stabilising forces against the destabilising forces. For increased overall accuracy, the analysis was done for both circular and non-circular modes of failure (Table 4).

The pore water pressure was also factored into the analysis. The stability of each model was analysed under dry and saturated ground water conditions. The minimum acceptable factor of safety was 1.05 for completely weathered material and 1.20 for fresh rock throughout the analysis in keeping with acceptance criteria.

Table 4 Summary Input Parameter for Analysis

Material type	Bulk Unit Weight (KN/m^3)	Cohesion (KN/m^2)	Friction Angle (Degrees)	Strength type
Oxide	18.00	20.00	25.30	Mohr-Coulomb
Transition	22.00	14.00	29.40	Mohr-Coulomb
Fresh Rock	27.00	0.07	35.50	Hoek-Brown

Limit Equilibrium Analysis

Slope design models were formulated from each sector and tested using limit equilibrium analysis. The proposed pit area was divided into four sectors in the optimization of the slope design. The sectors are; North, East, South, and West walls. The ore body was emplaced on the west wall at an angle of 23^0. Model for the North Wall under saturated condition is as indicated in Fig. 4. The rest of the sections were individually captured.
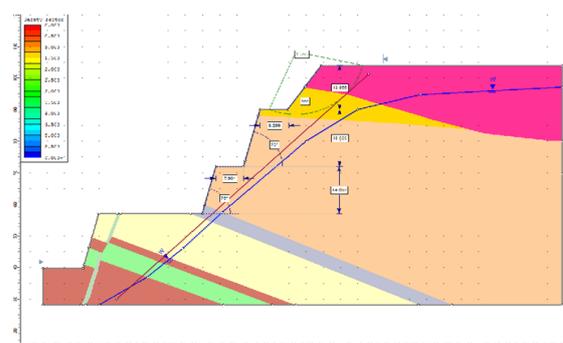

Fig. 4 Wet Stability Analysis for North Wall

Kinematic Analysis

Kinematic analysis was carried out to evaluate the various potential modes of failures. The stability assessment was performed for the following failure modes using the mean discontinuity orientations and the proposed bench face angles for:

(i) Toppling
(ii) Wedge and
(iii) Planar

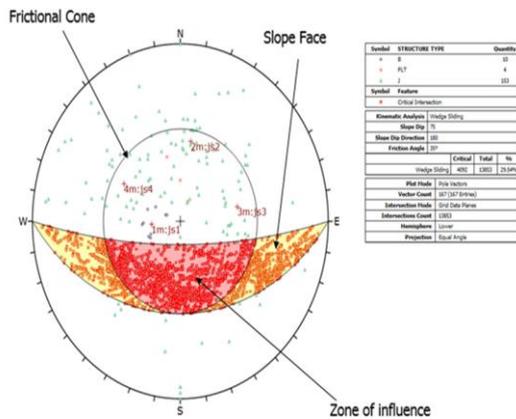Fig. 5 presents wedge failure mode at the East wall which appeared critical.

Fig. 5 Wedges Sliding Potential Analysis for the East Wall

Spill Berm Width Determination

The width of the berm required to contain any block of failed wedge from the wall was determined by means of "SWEDGE" (Fig. 6). The width of the catch berm was determined from the volume of failed wedge material using the relationship.
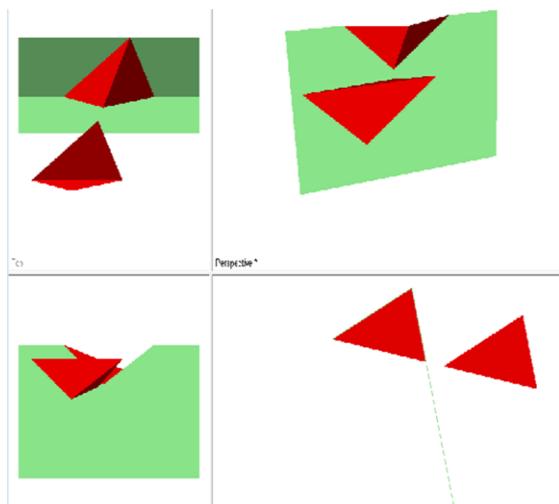
$$SBW(m) = \sqrt[3]{Vol * 1.5}$$

Fig. 6 Determination of Volume of Wedges using "SWEDGE"

Structural Modeling of Pit Shell

The various data gathered including structural mapping carried out aided to identify structures that are inclined sub-vertically and generally found to be unfavorable to stability of the pit (Fig.). These could potentially cause major planar instability if found frictionally unstable.
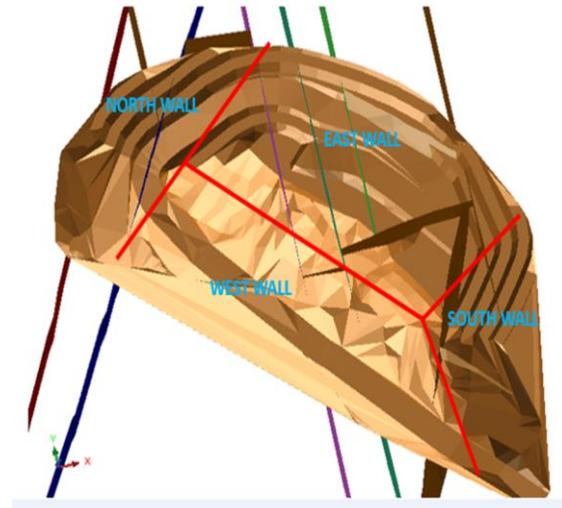

Fig. Structural Model of the Kobeda Pit

3.5 Discussion

Probability of failure analysis which was conducted using a numeric tool referred to as fair to good rating. Results generated were very close to zero percent. A check was conducted by comparing the results with empirically generated data as proposed by Haines *et al.*, (2002) at an earlier work done from same deposit (Table 5). Probability of failure was assessed once the Factor of Safety has been determined by limit equilibrium analysis and this gave Pit Slope architecture as soon in Table 5.

Table 5 FoS and Pf for Pit Slope Architecture

Slope Profile Element	Factor of Safety (FoS)	Probability of Failure (Pf)
Individual Bench	1.05 – 1.10	< 35%
Bench Stack	1.20 – 1.25	10 % – 15%
Overall Slope	1.35 – 1.50	<5%

From the limit equilibrium analysis, the minimum factor of safety for overall slope for the Kobeda Pit was 1.59 for the north wall. The corresponding Pf is less than 5%. It can therefore computed that, generally, the Probability of failure for all sectors of the proposed pit was less than five percent again

indicating rating. Pit Wall Architecture for the various geotechnical domains gave values as shown in Table 6.

Table 6 Summary of Design Domains for the Pit Architecture

Domain	Parameter	North	East	South
Oxide	Bench Face Angle	55	55	55
	Bench Width	6	6	6
	Bench Height	12	12	12
	Overall Slope Angle	45.0	45.2	46.1
Transition	Bench Face Angle	70	70	70
	Bench Width	8	8	8
	Bench Height	18	18	18
	Overall Slope Angle	51.0	50.4	51.0
Fresh	Bench Face Angle	75	75	75
	Bench Width	8	8	8
	Bench Height	18	18	18
	Overall Slope Angle	54.5	54.5	56.7

4 Conclusions and Recommendations

4.1 Conclusions

From the Bieniawski's approach, the Rock Mass Rating (RMR) for the various lithologies were; 49.31 for sandstone, 40.03 for lithic sandstone, 58.41 for conglomerate and 55.34 for mafic intrusive.

The RMR for Oxide material for the three geotechnical sectors were 42.73 for the North Wall, 42.50 for the East Wall and 43.82 for the South Wall. The Transition gave RMR values of 57.05, 56.89, and 57.32 for the north, east and west walls respectively. The Fresh Rock MRM values estimated for the North, East and South Walls were respectively 64.05, 63.23, and 67.72.

The MRMR for the North, East and South Walls were 31.43, 31.30 and 32.70 respectively for Oxide material. Transition rock indicated MRMR values of 41.03, 40.91 and 41.22 for the north, east, and south walls respectively. The values for the Fresh Rock in the North, East and South Walls were 50.85, 50.07, and 53.58 respectively.

The average values for the Indicative Overall Slope Angles (IOSA) corresponding to the MRMR for the Oxide, Transition and the Fresh Rock were 45.43^0, 50.69^0, and 55.78^0 respectively.

From the kinematic analysis conducted, the result indicated higher potential for both planar and wedge failure in the north and east walls. The potential for planar sliding is higher in the north wall than in the east. Also, the east wall was more susceptible to wedge failure than the north wall. The north and east walls have low potential to toppling instabilities. The south wall gave indications of planar, wedge as well as toppling modes of failure. The optimum slope parameters generated for the proposed Kobeda pit are shown in Table 6.

From the simulation carried out to determine the volume of failed wedge material using "SWEDGE", the maximum volume of failed rock was 157.42 m^3. This could conveniently be contained on one berm. This informs the choice of support systems for open pit slopes. The volume of failed material from the walls suggest either increasing the shear strength or normal loading as the most effective and cost efficient support systems for the proposed pit. Slope monitoring to measure rock mass displacement was considered by a combination of visual monitoring of tension cracks, wire extensometers, and the use of survey prisms to aid early detection.

4.2 Recommendations

It is recommended that:
(i) Vigorous groundwater monitoring programmes should be designed and implemented to mitigate the effect of groundwater on slope instability.

(ii) Diversion ditches should be constructed to divert storm water from entering the pit. Particularly, horizontal drains will be required for pit wall depressurisation as mining progresses

(iii) Rock face mapping programs should also be implemented to determine the presence of adverse structures that were possibly not captured during the geotechnical core logging. It also has the added advantage of optimising the overall slope angle and decreasing the stripping ratio.

(iv) Blasting, excavation and surcharging will result in redistribution of stresses within the pit wall. Hence numerical analysis should be conducted to ascertain the amount of deformation within the pit wall.

(v) As probability of failure approaches 10%, a more comprehensive slope monitoring will be required. As survey prims and berms become inaccessible, a real time slope monitoring system will have to be procured for use.

Acknowledgement

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