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Using a 3D Limiting Equilibrium Modelling Tool for Slope Stability in Weathered Rocks: A Case Study

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Abstract. Using three-dimensional limit equilibrium analysis to evaluate open pit slope stability has become popular in the mining industry. These tools allow geotechnical engineers to accurately input actual rock slope conditions and material strengths and obtain results that reflect slope behaviour and stability. The Lima Kwasi Gap Pit is one of Abosso Goldfields Limited's Paleoplacer satellite pits south of the Damang Pit Cut-Back (DPCB). It lies between the Kwesi and Lima North Pits. Deterministic and probabilistic analyses were conducted for slopes in weak rock materials using 3D Limiting Equilibrium Analysis. The Particle Swarm search method identified failure surfaces with low failure potential on both the east and west walls. The Factor of Safety (FoS) of 1.75 and Probability of Failure (PoF) of 9.2% from the analyses satisfy the design acceptance criteria for the mine. The study showed that 3D modelling tools could assist geotechnical engineers in accurately modelling ground conditions and material properties.

Keywords: Lima Kwesi Gap Pit · 3D Limiting equilibrium · Weak rock

1 Introduction

Slope stability analysis methods have been introduced and thoroughly discussed for several decades. One of these methodologies is limiting equilibrium analysis. It has been applied in different forms to various cases for almost a hundred years [1]. In recent years, geotechnical engineers are increasingly using 3D Limiting equilibrium analysis tools to solve stability issues. 3D stability analysis more accurately represents slope behaviour and stability, especially where discontinuities strike more than 20° - 30° from excavated faces [2]. McQuillan et al. [3] argued that 3D modelling tools should be used instead of 2D approaches because 3D tools will adequately model the proper mechanics of rock slope conditions and material strengths.

The term weak rocks in the International Society for Rock Mechanics (ISRM) Classification [4] describes rock strength ranging from extremely weak (R0) to weak (R2). These rocks have uniaxial compressive strengths ranging from 250 kPa to 25 MPa [5]. Figure 1 shows the range of uniaxial compressive strength values for weak rocks as suggested by ISRM Suggested Methods [4]. The weak rocks encountered in the Lima Kwesi Pit are weathered materials with estimated UCS values between 7 MPa and 20 MPa.

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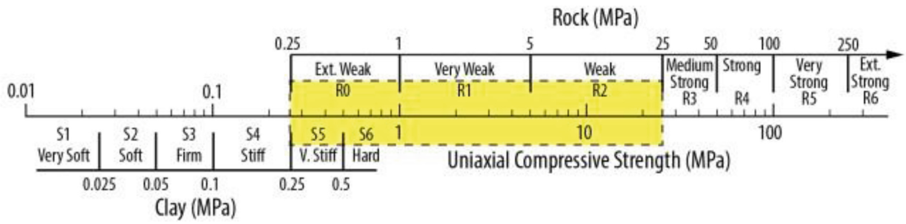


Fig. 1. Shows the range of uniaxial compressive strength typically associated with 'weak rock' geology [4]

The Lima Kwesi Gap Pit was part of a Reinvestment Plan, which Damang Mine commenced in 2017. The pit was scheduled to be mined in 2018. However, further optimizations of the life of mine plan rescheduled the pit extraction to 2023. The open pit has a mine life of one year with a total pit size of 1.7 Mt. This paper discusses the findings of 3D Limiting Equilibrium (3D LE) stability analyses conducted for the pit.

2 Project Area

The Lima Kwasi Gap Pit is one of Abosso Goldfields Limited's Paleoplacer satellite pits located south of the Damang Pit Cut-Back (DPCB), between the Kwesi and Lima North Pits. The current pit is generally hosted within weathered- to transition material. Three east-west faults intersect the walls. Bedding planes observed in the rock mass are predominantly planar-rough and slightly undulating with chloride, carbonate, and iron oxide coating (Fig. 2).

3 Material Characterization

The weak rocks in the pit are derived from weathering of the parent paleoplacer rocks. The rock mass is highly weathered and has moderately weak uniaxial compressive strength (about 25 MPa). Generally, the Lima Kwesi Pit is characterized by medium-to-coarse grained footwall Banket sandstone, cross-bedded sandstone with closely packed bedding spacing of approximately 0.02 m and a high persistence of +6 m along both dip/strikes. The beds generally dip towards the east at angles varying from 42° to 62°. The weathering process for the Lima Kwesi Gap produced a vertical profile of materials with different chemical, mineralogical and physical characteristics. (Although the rock mass had bedding planes, it was thought they had similar strength to the intact material and would, therefore, not need to be modelled with anisotropic strength.)

4 Stability Analysis

Stability analysis was conducted in line with the provisions of regulations 82 and 83 of Ghana's Minerals and Mining Regulations, 2012 (LI 2182) [6]. The inputs used for the 3D LE modelling were structural, geological, groundwater information and the pit design. The material properties of the various rock units were also used in the model.

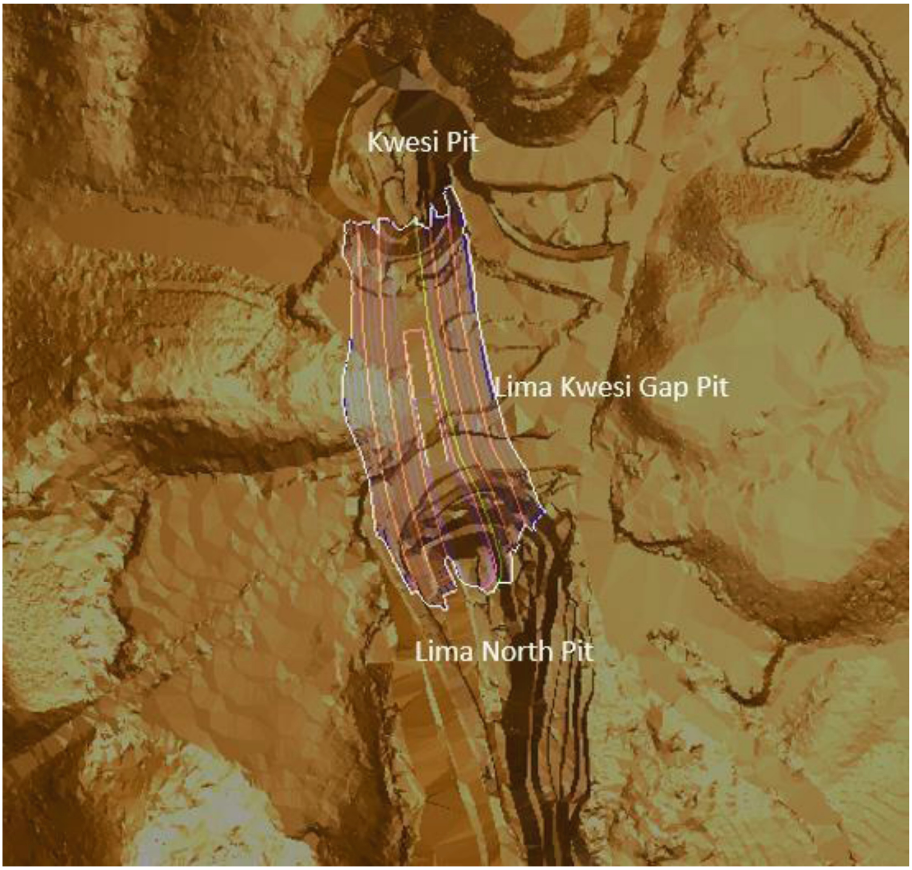


Fig. 2. Location of the Lima Kwesi Gap Pit

A review of the historical performance of the pits in the Kwesi and Lima areas suggests that previous mined-out pits performed satisfactorily with minor bench scale failures, which were observed periodically during heavy downpours. These failures were appropriately managed to ensure the safety of men and mining machinery. The proposed Lima Kwesi gap pit design was engineered using the geotechnical design parameters shown in Table 1.

4.1 Limiting Equilibrium Analysis

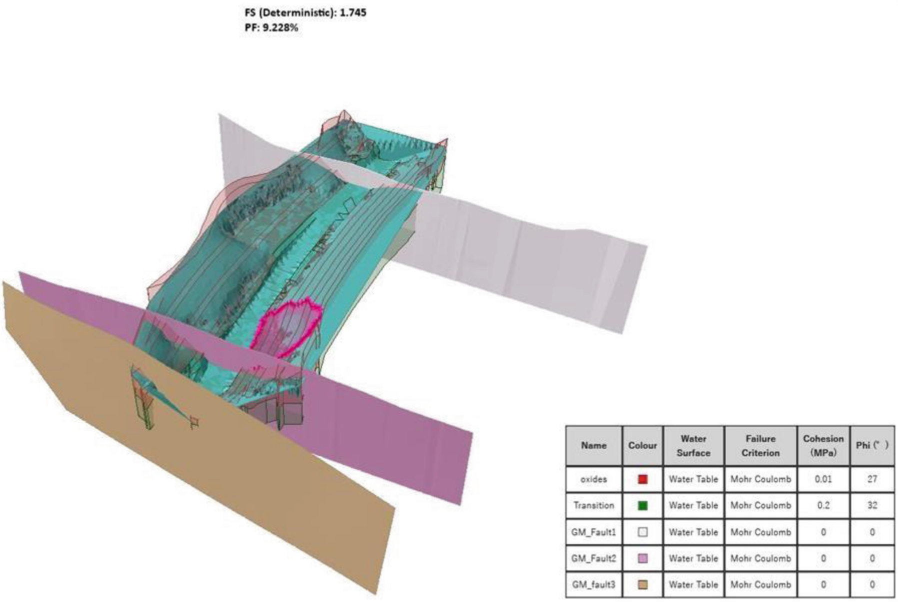
The 3D LE analysis tool, Slide3, was employed to analyze the overall slope stability of the Lima Kwesi Pit (Fig. 3). Safety factors were calculated, and probabilities of failure were also determined. The LE analysis methods selected for the modelling were the Bishop, Janbu, and Spencer methods. Particle Swarm Analysis (PSA) was used to search for the critical failure surfaces, as shown in Fig. 4. This metaheuristic approach can accommodate weak layers (large-scale discontinuities) by considering them an additional variable in the optimization problem.

Table 1. Design parameters for the Lima Kwesi Gap Pit

Above 948 mRL (metres relative level, which is a measure of elevation)		
Bench Height		12 m
Bench Face angle		45°
Spill berm Width		6 m
Below 948 mRL		
Bench Height		12 m
Bench Face angle		65°
Spill berm Width		6 m

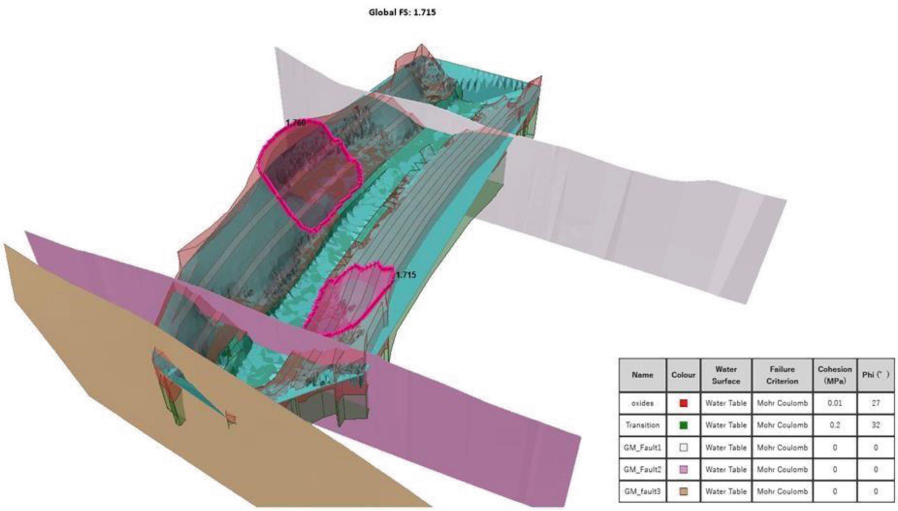
Groundwater was also incorporated using an elevated groundwater level of 966 mRL, and the effect of the three (3) east-west striking structures was also factored into the analysis.

A section was taken along the critical failure surface for the initial overall slope stability result and analyzed in Slide2 and RS2 software. The outcomes of the 2D analysis results are shown in Figs. 5 and 6.



Name	Colour	Water Surface	Failure Criterion	Cohesion (MPa)	Phi (°)
oxides		Water Table	Mohr Coulomb	0.01	27
Transition		Water Table	Mohr Coulomb	0.2	32
GM_Fault1		Water Table	Mohr Coulomb	0	0
GM_Fault2		Water Table	Mohr Coulomb	0	0
GM_fault3		Water Table	Mohr Coulomb	0	0

Fig. 3. Results of overall slope stability



Name	Colour	Water Surface	Failure Criterion	Cohesion (MPa)	Phi (°)
oxides	■	Water Table	Mohr Coulomb	0.01	27
Transition	■	Water Table	Mohr Coulomb	0.2	32
GM_Fault1	□	Water Table	Mohr Coulomb	0	0
GM_Fault2	■	Water Table	Mohr Coulomb	0	0
GM_fault3	■	Water Table	Mohr Coulomb	0	0

Fig. 4. Results of particle swarm analysis

5 Results and Discussions

The 3D Limiting Equilibrium Analysis outcome produced a Factor of Safety (FoS) of 1.75 and a Probability of Failure (PoF) of 9.2%. Furthermore, the 3D LE analysis identified other failure surfaces on the east and west walls with low failure potential. The analyses of 2D cross-sections taken through the critical failure surface produced safety factors of 1.79 and 1.77 for Slide 2 and RS2, respectively. (These 2D results were very close to the 3D answer.) (The authors plan to investigate why the 2D results were higher than the 3D safety factor in a future study.)

Finally, it was observed that the critical failure surfaces obtained were all in the pit's completely weathered (oxide) zones (Table 2).

6 Conclusions

Based on the results obtained from the analyses conducted on the available data (PoF of 9.2% and FoS 1.75), it is evident that the Lima Kwesi Gap pit satisfies design acceptance criteria of FoS of 1.3 and PoF of less than 12% for overall slope stability.

3D modelling tools can also assist geotechnical engineers in appropriately modelling ground conditions and material properties.

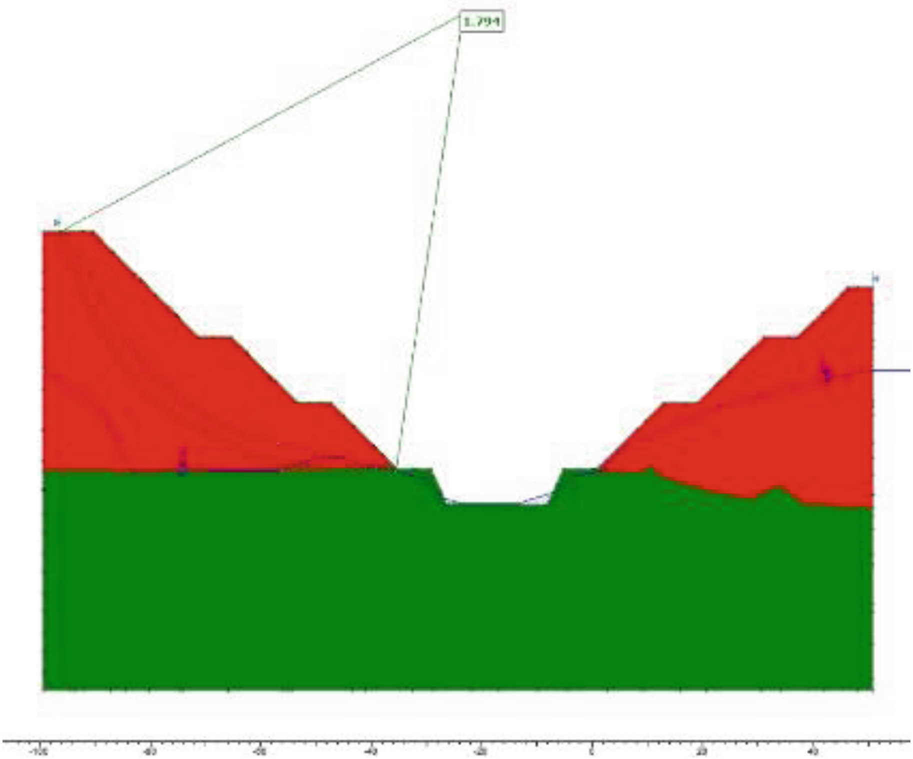


Fig. 5. Slide 2 results of the section taken along the critical failure surface

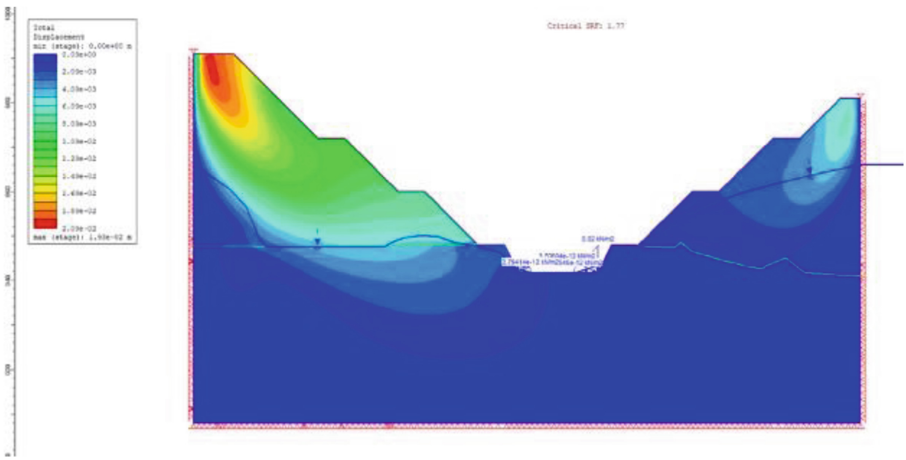


Fig. 6. RS2 results of the section taken along the critical failure surface

Table 2. Summary of stability analysis results

	Slide 3 Analysis Result	
Probability of failure		9.2%
FoS		1.75
	Slide 2 Analysis Result	
FoS		1.79
	RS2 Analysis Result	
FoS		1.77

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