

Integrated analysis method for rock slope stability of the deep open pits

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ABSTRACT

Due to increasing demands of mineral commodities, modern pits are faced with the challenges of deepening and widening the existing pits. As the pit deepens, the perimeter of the pit and the quantity of the material to be hauled rises, practically exponentially. Excessively steep slopes induce failures, which is counter intuitive to the economic benefits that may have initially been planned for. In open pit mining, several rock slope stability analysis methods are routinely performed to predict the safe and functional design and excavation of slopes based on varying external loads. Current literature indicates that all the existing rock slope stability analysis methods have got limitations in the accurate stability assessments as the pit deepens. To address the limitations introduced by modern slope stability methods, integration of these stability methods was applied on a real deep slope. The study results shows that integrating the stability methods improves the understanding of the slope behavior, and contributes to more accurate stability assessments as the pit deepens beyond the anticipations. This enhances the accuracy and reliability of stability assessments, addressing the complexities introduced by modern technologies and geological factors.

Keywords: *Modern pits; Deepening; Failure, slope stability analysis methods, Integration, Accuracy.*

1. Introduction

In open pit mining, a major challenge of a rock engineer is to design the steepest possible slope angle to achieve the lowest stripping ratio while ensuring maximum ore recovery considering the safety of the personnel and equipment (Ali and Morteza 2014; Obregon and Mitri, 2019). Excessively steep slopes induce failures which is counter intuitive to the economic benefits that may have initially been planned for. Consequently, the sloughed material lead to re-handling costs, may damage equipment, and may potentially cause fatalities. The deeper the mine gets, the more the volume of waste required to be removed becomes. As a result, the depth of the open pit mines is excavated in proportional to the production costs, the price of the commodity, and geological as well as geotechnical conditions permit (Kiria et al., 2024). The permanent overall pit slope angle is hence ruled by geological conditions, production costs and the characteristics of the rock mass where the slope will be excavated (Gong and Bowa 2021; Chen and Guo 2022). Generally, open pit mining depths vary from plus/ minus 50 m to about 500 m world over (Zyryanov et al., 2021). There are some few exceptions that are as deep as 1.2 - 1.4 kilometers (Youchen and Sijing, 2011). The depth of an open pit is highly dependent on the strength of the rock formation in and around the pit itself and worthiness of the minerals accessible within the overall volume of the pit created. As the pit deepens, the perimeter of the pit and the quantity of the material to be hauled rises, practically exponentially. Eventually, climax is reached when the cost of deepening the pit is higher than the value of what is being extracted by deepening. The depth and width of open pits is proportional to cost of material handling and likelihood of slope instabilities. (Reshetnyaket al., 2008).

Due to greater demands for minerals and stable pits, modern pits are faced with the challenge of deepening the pits greater than 500 m through varying geological environments, stress conditions, ground

water, pit geometry and rock mass strength. In this article, real modern pit faced with the challenge of expanding and deepening the pit to 680 m through diverse stratigraphy, weathered rock, heavily jointed rock and regions of high pore water pressure has been studied using integrated stability analyses system. Results obtained in this study indicate that, all the stability analyses methods have got shortfalls. To alleviate the shortfalls, integrated stability analyses method was applied. The study results shows that integrating the stability methods improves the understanding of the slope behavior and contributes to more accurate stability assessments as the pit deepens beyond the anticipations.

2. Literature review

Before any slope stability analysis commences, a detailed site investigation is conducted to ascertain one or several factors that may cause open pit slope instability. These may include one or a combination of these; gravity, mining method, geometry of the slope, geotechnical properties of material (soilmass/rockmass), surface and groundwater, geological discontinuities, geology, dynamic forces, presence of unknown underground workings (Wyllie and Mah 2004, Khosravi et al., 2017; Sarfaraz et al., 2021a; Sarfaraz et al., 2021b).

Gravity is the force that acts everywhere on the earth's surface, pulling everything in a direction toward the center of the earth. On benches nearly parallel to the horizontal surface the force of gravity performs downhill. In situations where the rockmass remains on the horizontal surface, there is no movement under the force of gravity. Indeed, if the rock mass on the horizontal surface develops weak or fails, this leads to the unsupported mass to slide downhill. Nelson (2013) indicated that the influences of gravity on stability of the object is determined into two

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components: a constituent performing perpendicular to the slope and component performing tangential to the slope as shown in Figure 1.

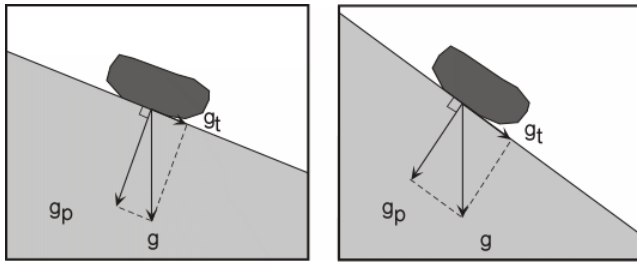


Figure 1: Stability of an object on a slope (Nelson, 2013).

A constituent performing perpendicular to the slope of gravity, g_p , aids to grip the rock mass in place on the slope. The component performing tangential to the slope of gravity, g_t , originates a shear stress parallel to the slope that jerks the rock mass in the down-slope direction parallel to the slope. Consequently, down-slope sliding is favored by steeper slope angles which increase the shear stress, and anything that reduces the shear strength, such as lowering the cohesion among the particles or lowering the frictional resistance (Nelson, 2013).

In open pit mining, the mining method (type of equipment used to excavate the rockmass) have the influence on the geometry of the slope. The use of shovels in mining brings about erroneous slope angles unlike the excavators (Swedge, 2006). One of the important parameters of slope geometry affecting its stability is the slope angle. Slope stability generally decreases with increase in slope angle. With increasing slope angle, the tangential stress increases which result in an increase in shear stress thus reducing its stability (Bowa, 2020).

The rock mass strength is a very important factor that affects the stability of the slopes. It consists of cohesion and friction angle of material. Cohesion is a property of a rock or soil that determines how effectively it resists deformation or breaking due to forces such as gravity. Slopes consisting of rocks or with poor cohesiveness are less stable (Shukla et al., 2011). Cohesion is aided by a variety of factors, some of which strengthen it while others undermine it (Sarfraz et al., 2021). The ability of a unit of rock or soil to endure a shear force is measured by its angle of internal friction.

Although Surface water is not always directly involved as the transporting medium in mass movement processes, it does play an important role. Once adsorption takes place consequently the surface frictional interaction between mineral grains could be lost resulting in a loss of cohesion, thus reducing the strength of the soil (Lancine et al., 2020). Besides, infiltrations of rainfall or snow melt enhance weight to the slope, seepage of water into the soil or rock and substitute the air in the pore space or fractures thereby increasing the weight. The increased weight leads to slope instability (Zhang, et al., 2011).

Beneath the surface of the earth, groundwater exists nearly everywhere. The water that fills the pore spaces amid grains in rock or soil, leads to the slope instability in the rock (Muhammad et al. 2014, Zhanga et al., 2025). The water table is the boundary that divides the saturated region below, wherein all pore space is filled with water from the unsaturated region above. Variations in the level of the water table occur due to variations in rainfall. The water table has a tendency to rise during wet seasons when more water penetrates into the system, and drops during dry seasons when less water penetrates (Lancine et al., 2020). Another aspect of water that distresses slope stability is fluid pressure. The deeper the soil and rock gets buried in the earth, the more the grains rearranges themselves to form a more compact assembly. However, the pore water is constrained to occupy the same space. Thus, increasing the fluid pressure to an extent where the water begins supporting the weight of the overlying rock mass. When this situation occurs, friction is condensed. Consequently, the shear strength holding the material on the slope is also reduced, leading to slope failure (Muhammad et al., 2014).

A discontinuity is a plane or surface that marks a change in the

physical or chemical characteristics in a soil or rock mass. A discontinuity can be in the form of a bedding plane, schistosity, foliation, joint, cleavage, fracture, fissure, crack, or fault plane. The stability of rock slopes is significantly influenced by the structural discontinuity in the rock in which the slope is excavated (Bowa and Kasanda, 2020). The discontinuity controls the type of failure which may occur in a rock slope (Bowa et al., 2018). The properties of discontinuities such as orientation, spacing of discontinuities, persistence, roughness and infilling would play important role in the stability of the jointed rock slope. Discontinuities may occur multiple times with broadly the same mechanical characteristics in a discontinuity set, or may be a single discontinuity. It makes a soil or rock mass anisotropic. The mutual orientation of discontinuities determines the shape of the individual potential failure blocks. The orientation of a major geological discontinuity relative to an engineering structure also controls the possibility of unstable conditions (Shukla and Hossain, 2011).

Dynamic forces have adverse effects on the stability of the open pit slope. These dynamic forces are grouped into two in surface mining namely; earthquake and blasting forces. In seismically active areas of the world for open pit mining slopes excavated into a flat ground surface, topographic influences can cause ground vibrations at the crest of the slope. When compared to the spectral features of the earthquake motion, the amount of amplification or reduction relies on the dynamic properties of the pit slope (rock mass stiffness, slope geometry, natural periods of resonance) (Basha and Moghal, 2013).

Surcharge loads from adjacent trash dumps, in-pit dumps, service erections, excavation and hauling equipment are the most prevalent destabilizing forces onto the slope susceptible to slope failure in open pit mines (Gong and Bowa, 2021). The results obtained by some researchers (Chen and Guo, 2022) indicate that the pit bottom subsidence/slope failure increases when moving from underground openings located near the pit bottom unlike mining openings located far from the pit bottom.

3. Slope stability analysis methods

In open pit mining, slope stability analysis is routinely performed to assess the safe and functional design and excavation of the slopes. The analysis technique chosen is largely dependent on the most probable mode of failure, with careful consideration being given to the variances in strengths, weaknesses, and limitations inherent in each analysis method. As a result, several analysis methods or techniques may be integrated and applied to get to the most accurate predictions on the stability of the slope. The common analysis methods for slope stability include; kinematic, limit equilibrium, and numerical analyses (Chen et al., 2017; Firincioglu and Ercanoglu, 2021). Kinematic analyses involve analyzing the geological structures, considering the discontinuities. Kinematic analyses indicators lead to early determinations of the potential failure mechanisms of the created rock slopes and potential slope stability (Pham & Nguyen, 2024). Nevertheless, kinematic analyses indicators presents limitations including highly dependence on the quality and preservation of the discontinuity surface, uncertainties in the discontinuities' dip and directions, and the possibility of multiple generations of indicators due to changing stress conditions. To address the limitations of kinematic analyses indicators Limit Equilibrium Method (LEM) are a good hand-pick to attain the factor of safety in the rock slopes where the failure mechanism grants limit equilibrium in all blocks (Deng et al., 2020). Yet, LEM cannot be applied to determine the displacements and model the progressive slope failure mechanisms in complex rock slope geometry and combination of rock mass with different properties. LEM's inadequacy in investigating the slope failure mechanisms is supplemented by simulating the rock slope using numerical modeling (Firincioglu and Ercanoglu, 2021). Numerical models are computer programs that endeavor to characterize the mechanical response of a rock mass subjected to a set of existing conditions and induced external load due to the slope excavation. Numerical analysis can incorporate key geologic features like discontinuities providing more realistic projections of the behavior of

the real slopes than analytical models. Unlike, non-numerical analysis methods such as analytical, kinematical and limit equilibrium, these tend to over simplify the conditions, possibly leading to overly conservative solutions. Besides, numerical analysis can help to explain observed physical behavior (Barla et al., 2012). Nonetheless, the assumed information used on joint properties may lead to unrealistic prediction (Li et al., 2020). In the interim, numerical modelling require a super user to obtain accurate predictions. Moreover, numerical modelling technique requires an ongoing calibration, constraints, the need to be aware of scale as more information unfolds when the pit deepens (Li et al., 2020). Therefore, integration of the stability methods enhances the accuracy and reliability of stability assessments, addressing the complexities introduced by modern technologies and geological factors (Raza et al., 2025).

4. Integration of the stability analyses methods on a case study of Lumwana super pit

The stability of the Super Pit was conducted by integrating three methods namely; Kinematic analysis using DIPS software method, Limit Equilibrium Method (LEM) using SLIDE Software and numerical method using RS2 software on the case study of Lumwana Super Pit. Integration of the stability methods (Kinematic analysis method, Limit Equilibrium Method (LEM) and Numerical Method) was conducted to enhance the accuracy and reliability of stability assessments, addressing the complexities introduced by modern technologies and geological

factors. Figure 2 below shows the detailed methodology that was used for field data collection, integrated slope stability analysis at Lumwana pit slopes. Barrick Lumwana Mine has up to date been mining their Chimiungo pits with maximum depth of 160 m which is just above their maximum allowable bench stack height of 144 m in fresh rock (their shallowest pit – Chimiungo East being just 100 m and their deepest pit – Chimiungo Main being 240 m). Due to high demand for copper, Barricks Lumwana Mine is in the process of joining the 3 existing pits (Chimiungo Main, Eastand South) to become one pit known as Chimiungo super pit shown in Figure 3. Thereafter, deepen the super pit to the depth greater than 600 m through diverse strata containing oxides (weathered saprolite) and Saprock (transitional material) as well as fresh rock (grey gneiss, ores schist and pink gneiss). The critical sections of the Chimiungo superpit are shown in Figure 4.

4.1. Kinematic analyses

Kinematic analysis using DIPS software was conducted on the mapped geological structures for the Super Pit shown in Table 1 for sections SP 01-04. This was conducted to predict the failure modes and probabilities of failure. DIPS software is predominantly used to examine the orientation data of physical structures, mainly discontinuities in rock masses. It employs stereographic projection to picture and examine the orientation data, assisting in identifying potential failure modes such as toppling, planar or wedge sliding failure mechanisms. The analysis results for the potential failure mechanism and probabilities of failure are provided in Table 2.

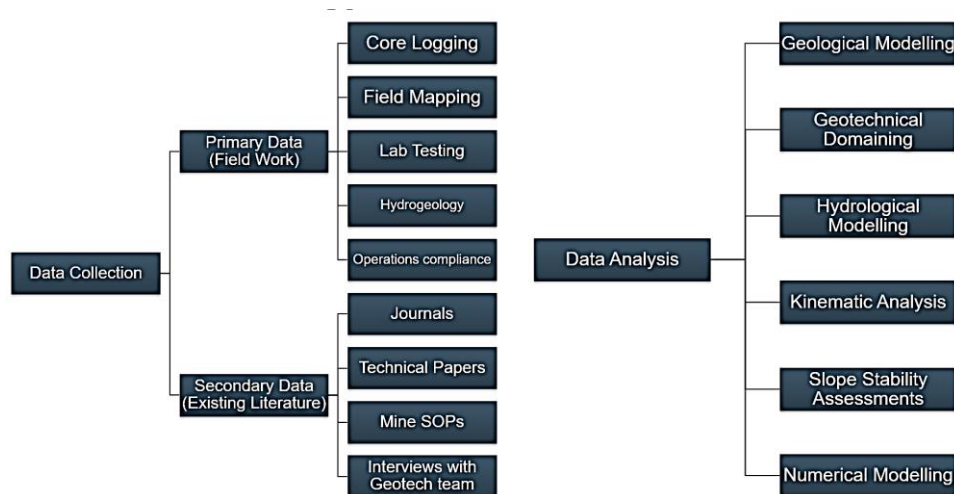


Figure 2: Methodology chart.

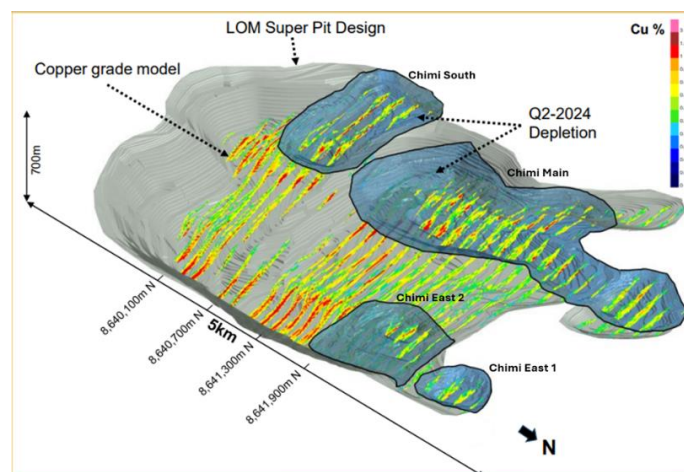


Figure 3: planned chimiungo super pit.

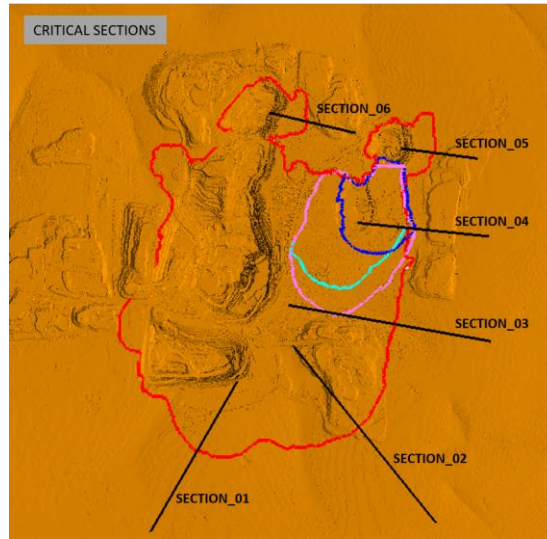


Figure 4: Critical Sections of the Chimiwungo Super Pit.

Table 1: Slope and discontinuities orientations.

| Section | Structural Properties | | Structure Orientations | | Slope: Dip/Dip Direction (Degrees) |
|---------|-----------------------|----------------|------------------------|-----------|------------------------------------|
| | Group | Friction Angle | Dip | Direction | |
| 1 | Joints | 28 | 64 | 31 | 55/15 |
| | Shears | 22 | | | |
| | Fabrics + shears | 31 | | | |
| | Average | 27 | | | |
| | | | | | |
| 2 | Joints | 28 | 75 | 125 | 55/320 |
| | Shears | 22 | | | |
| | Fabrics + shears | 31 | | | |
| | Average | 27 | | | |
| | | | | | |
| 3 | Joints | 28 | 75 | 213 | 50/285 |
| | Shears | 22 | | | |
| | Fabrics + shears | 31 | | | |
| | Average | 27 | | | |
| | | | | | |
| 4 | Joints | 28 | 20 | 161 | 50/268 |
| | Shears | 22 | | | |
| | Fabrics + shears | 31 | | | |
| | Average | 27 | | | |
| | | | | | |

Table 2: Kinematic analyses results.

| Failure Mode | Section 1 (POF) | Section 2 (POF) | Section 3 (POF) | Section 4 (POF) |
|-------------------|-----------------|-----------------|-----------------|-----------------|
| Planar sliding | 1.26 | 0.44 | 3.37 | 2.29 |
| Wedge sliding | 1.87 | 0 | 0 | 0 |
| Direct toppling | 0.90 | 1.26 | 0.57 | 1.58 |
| Flexural toppling | 0.34 | 0.87 | 0.79 | 0.15 |

4.2. Limit equilibrium method

In areas with rock mass stacks where the discontinuities with external loads like ground water and layered soil masses are not well defined, the use of Dips software to predict the failure modes and probabilities of failure leads to unrealistic results. To resolve this, Slide 2 Software was applied to conduct stability analyses of the slope for sections SP 01- SP4. Slide 2 Software applies limit equilibrium principles to investigate the stability (obtain the factor of safety) of the rock slopes. The analysis in this article utilizes the existing slope design parameters shown in Tables 3 and 4 for the Super Pit. The existing parameters are split into two

design categories into domains based on potential instability caused by a combination of groundwater and unfavorable rock structure presented in Tables 3 and 4 and material properties shown in Table 5. Sensitivity analyses to investigate how much the stability of a slope is affected by changes in the ground water levels was also conducted for sections SP01, SP03 and SP04. Figures 5, 7, 8 and 10 shows the slope stability analysis results while the water table sensitivity analyses results are presented in Figures 6, 9 and 11.

4.3. Numerical analyses using RS2 software

Slides software's inadequacy in investigating the progressive behavior and determination of displacements of the slope is supplemented by numerical modelling. For this research, RS² numerical modelling software was applied to provide comprehensive rock behavior in terms of displacements, and failure modes as the pit deepens. RS² uses Finite Element Analysis (FEA) to deliver comprehensive analysis of the slope's conduct. The analysis in this article utilized the existing slope design parameters shown in Tables 3 and 4 for the Super Pit and material properties shown in Table 5. The set ups for the Super Pit was modelled with the slope height of 680 m for sections SP01 to SP04 shown in Figures 11, 13, 15 and 17. The analysis involves determination of Strength Reduction Factor (SRF) and progressive displacement as presented in Figures 12, 14, 16 and 18 for each section, respectively.

5. Discussions

The kinematic analyses results provide the failure modes and probabilities of failure for each section. The obtained results were further analyzed using slope design acceptability criteria by Stacey and Stacey (2009). It is noticed that the obtained probabilities of failure associated with acceptability slope design criteria by Read and Stacey (2009) for the Super Pit in sections SP 01-04 are all less than 5%. This

entails that the obtained results are compliant to the acceptability slope stability failure criterion by Read and Stacey (2009). However, where rock mass have discontinuities with external loads like ground water, the use of Dips software to predict the failure modes and probabilities of failure lead to unrealistic results. To resolve this, Limit Equilibrium Method (LEM) was applied to obtain factor of safety of the slope for sections SP 01- SP04. The obtained factors of safety are all above 1.3 for all sections SP 01-04 as shown in figures 4, 6, 7 and 9. This entails that obtained factor of safety for all sections of the Super Pit are compliant to the acceptability slope stability failure criterion by Read and Stacey (2009). Conversely, sensitivity analyses for the ground water table revealed that, the factor of safety was sensitive to the changes in the levels of water table. As lowering the groundwater levels led to improved factor of safety as shown in Figures 5, 8 and 10. Nonetheless, LEM could not provide predications of displacement behavior of the slope and indications of where failure could possibly take place. To resolve this, numerical modelling was applied. Results obtained for numerical models shown in Figures 12, 14, 16 and 18 indicate maximum shear strain providing a good indication of where the failure is occurring. The displacement contour clearly highlights the zone of failure. A Post-Benching SRF indicates that the slope is stable in terms of Rock Mass. However, as ground water levels rises, SRF reduces exponentially towards the toe of the slope.

Table 3: Favorable rock domain design parameters.

| Geological Domain | Bench Face Angle | Bench Height | Berm Width | Inter-Ramp Angle | Maximum stack height | Geotechnical berm width (at base of stack) | Comments |
|-------------------|------------------|--------------|---------------------|------------------|----------------------|--|---|
| Oxides | 55° | 4 m | 7 m | 22° | 76 m | 20 m | Geotechnical berm required at base of oxide stack, always. |
| Transitional Rock | 70° | 12 m | 7.5 m | 43° | 88 m | 20 m | Geotechnical berm at base of stack only if stack height reaches 48m, otherwise add benches to fresh rock stack. |
| Hanging wall | 90° | 12 m | 8.5 m | 55° | 272 m | 30 m | |
| Ore-Body | 90° | 12 m | 8.5 m | 55° | 244 m | 30 m | |
| Footwall | 90° | 12 m | As per footwall dip | | | Not applicable | Follow footwall down dip |

Table 4: Un-favorable rock domain design parameters.

| Geological Domain | Bench Face Angle | Bench Height | Berm Width | Inter-Ramp Angle | Maximum stack height | Geotechnical berm width (at base of stack) | Comments |
|-------------------|------------------|--------------|------------|------------------|----------------------|--|---|
| Oxides | 55° | 4 m | 7 m | 22° | 76 m | 20 m | Geotechnical berm required at base of oxide stack, always. |
| Transitional Rock | 70° | 12 m | 7.5 m | 43° | 88 m | 20 m | Geotechnical berm at base of stack only if stack height reaches 48m, otherwise add benches to fresh rock stack. |
| Hanging wall | 90° | 12 m | 10 m | 50° | 272 m | 30 m | As per unfavourable structural zones |
| Ore-Body | 90° | 12 m | 10 m | 50° | 244 m | 30 m | Use where slope design cuts across the orebody creating condition for rock fabric to dip out of the slope. |

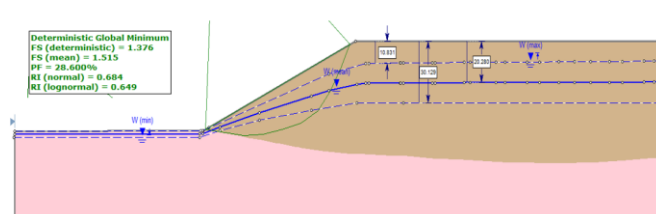


Figure 5: Stability analysis results for Section SP01.

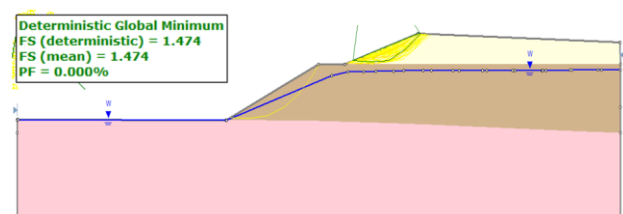


Figure 7: Slope stability results for section SP02.

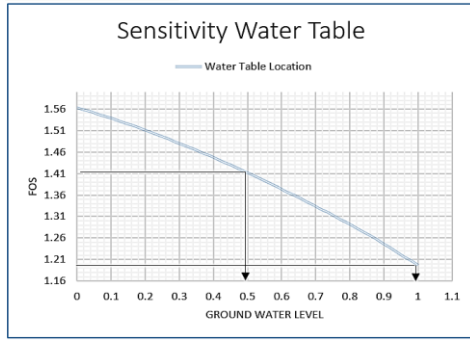


Figure 6: Water Table Sensitivity for Section SP01.

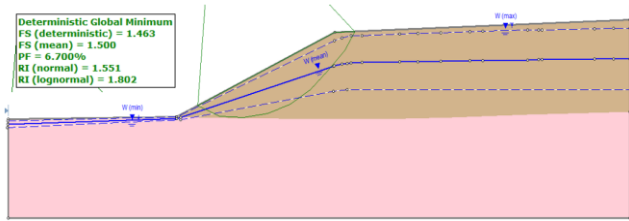


Figure 8: Slope stability results for Section SP03 post-mining.

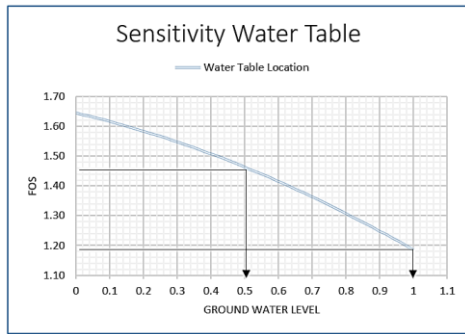


Figure 9: Water table sensitivity for section SP03.

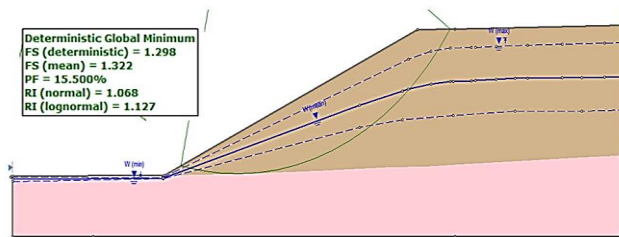


Figure 10: Slope stability results for section SP04.

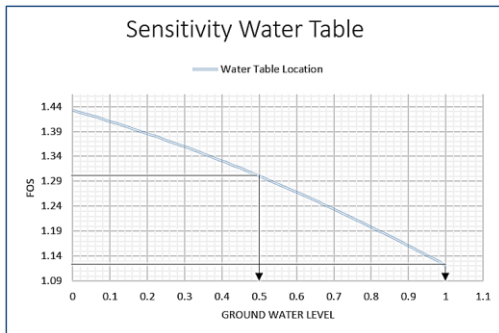


Figure 11: water table sensitivity for SP04.

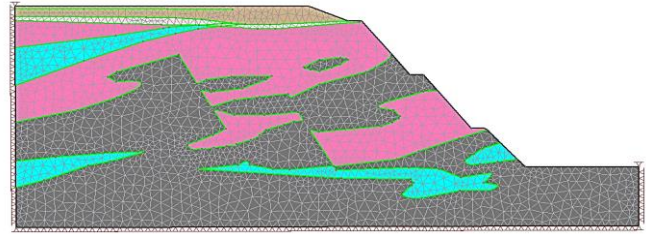


Figure 11: Section SP01 pre-benching slope model at 680m height.

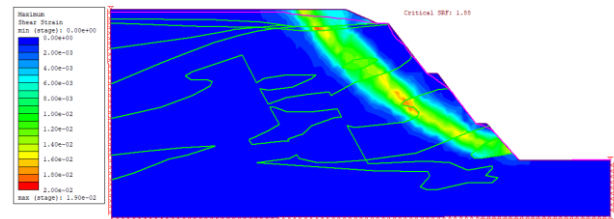


Figure 12: SP01 critical strength reduction factor (SRF) = 1.88 post benching.

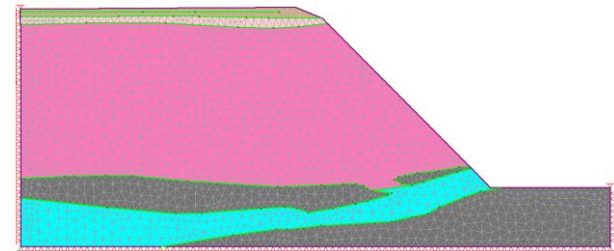


Figure 13: Section SP02 pre-benching slope model at 680 m height.

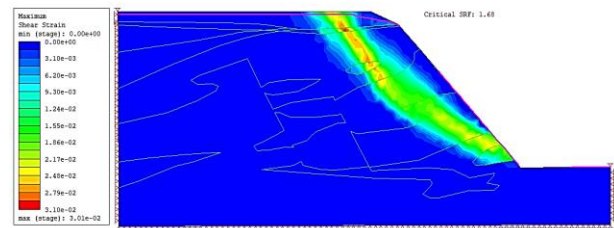


Figure 14: SP02 critical strength reduction factor (SRF) = 1.68 pre-benching.

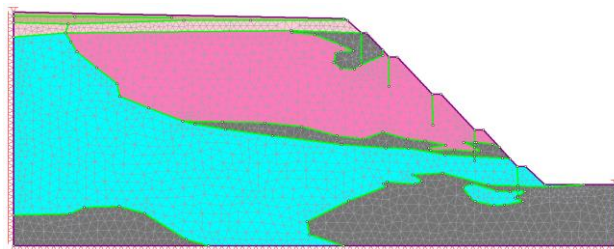


Figure 15: Section SP03 pre-benching slope model at 680 m height.

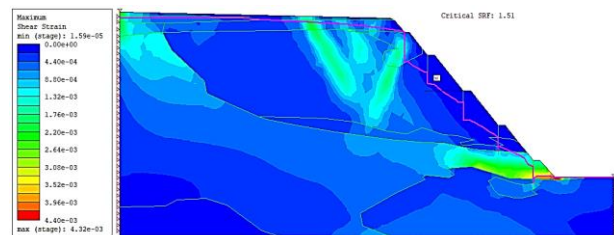







Figure 16: SP03 critical strength reduction factor (SRF) = 1.51 post benching.

Table 5: Modelling material properties.

| Material Name | Color | Unit Weight(kN/m ³) | Strength Type | Cohesion (kPa) | Phi (deg) | UCS (kPa) | GSI | Hydraulic Properties (m/s) |
|---------------|---|---------------------------------|------------------------|----------------|-----------|-----------|-----|----------------------------|
| SAP |  | 21 | Mor-Coulomb | 21 | 28.2 | | | 3.05E-06 |
| SRK D=0.7 |  | 24 | Generalized Hoek-Brown | | | 38000 | 41 | 5.01E-05 |
| FR GNG D=0.7 |  | 27 | Generalized Hoek-Brown | | | 152000 | 58 | 4.35E-08 |
| FR SCH D=0.7 |  | 28 | Generalized Hoek-Brown | | | 60000 | 52 | 4.35E-08 |
| FR GNP D=0.7 |  | 26 | Generalized Hoek-Brown | | | 145000 | 57 | 4.35E-08 |

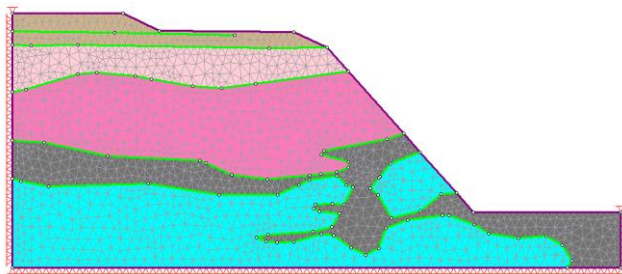


Figure 17: Section SP04 pre-benching slope model at 680 m height.

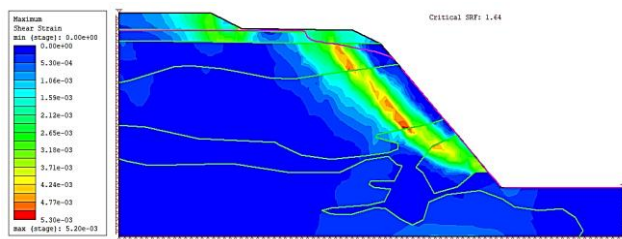


Figure 18: SP04 critical strength reduction factor (SRF) = 1.64 pre-benching.

6. Conclusions

Based on this study, the following conclusions are made;

- Kinematic analyses provided estimates on the probabilities of failure and potential failure mechanism based on the mapped information, ignoring the influence of groundwater as the pit deepens.
- LEM provided a comprehensive slope stability prediction considering the influence of groundwater levels, without providing the indications of where failure may occur.
- Numerical modeling mimicked the Super Pit in terms of physical behavior in varying ground water level.

However, the solutions obtained are only estimates based on estimated inputs and may struggle with extreme nonlinearities. Therefore, integrating the above stability methods improves the understanding of the slope behavior and contributes to more accurate stability assessments as the pit deepens beyond anticipations.

References

- [1]. Ali MA and Morteza O (2014) Determination and stability analysis of ultimate open-pit slope under geomechanical uncertainty. *International Journal of Mining Science and Technology*, 24 (1): 105-110.
- [2]. Barla M, Piovano G and Grasselli G (2012) Rock slide simulation with the combined finite-discrete element method. *International Journal of Geomechanics*, 12 (6):711-721.
- [3]. Basha BM and Moghal AAB (2013) Load resistance factor design (LRFD) approach based seismic design of rock slope against wedge failure. *Geo-Congress 2013, ASCE Held 3-7 March, 2013, San Diego, California, USA*.
- [4]. Bowal VM and Xia Y (2018) Stability Analyses of Jointed Rock Slopes with Counter-tilted Failure Surface Subjected to Block Toppling Failure Mechanisms. *Arabian Journal for Science and Engineering*, 43(10): 5315-5331
- [5]. Bowal VM and Kasanda T (2020) Wedge Failure Analyses of the Jointed Rock Slope Influenced by Foliations. *Geotechnical and Geological Engineering*, 38(5): 4701-4710
- [6]. Bowal VM (2020) Wedge Sliding Analysis of the Rock Slope Subjected to Uplift Forces and Surcharge Loads Conditions. *Geotechnical and Geological Engineering*, 38(1): 367-374.
- [7]. Chen C, Xia YY and Bowal VM (2017) Slope stability analysis by polar slice method in rotational failure mechanism. *Computational and Geotechnical engineering*, 81(1):188-194
- [8]. Chen H and Guo Q (2022) Evaluation of Slope Stability within the Influence of Mining Based on Combined Weighting and Finite Cloud Model. *International Journal of Energy, Exploration & Exploitation*, 41(2):23-29.
- [9]. Deng DP (2020) Limit equilibrium solution for the rock slope stability under the coupling effect of the shear dilatancy and strain softening. *International Journal of Rock Mechanics and Mining Science*, 134(1):104-121.
- [10]. Firincioglu BS and Ercanoglu M (2021) Insights and perspectives into the limit equilibrium method from 2D and 3D analyses. *Engineering Geology*, 281 (1):571-578.
- [11]. Gong WP and Bowal VM (2021) Analytical technique for stability analyses of the rock slope subjected to slide head toppling failure mechanisms considering groundwater and stabilization effects. *International Journal of Geo-Engineering*, 39(8): 5753-5765
- [12]. Pham VS and Nguyen L (2024) A Novel Method for Spatial Structural Kinematic Analysis. *International research journal of innovations in engineering and technology*. <https://doi.org/10.47001/irjiet/2024.808019>
- [13]. Khosravi MH, Sarfaraz H, Esmailvandi MA and Pipatpongsa T (2017) A numerical analysis on the performance of counter-weight balance on the stability of undercut slopes. *International Journal of Mining and Geo-Engineering*, 51(1), 63-69.

- [14]. Kiria R, Andrii A and Novikov L (2024) Influence of open pit depth on the choice of conveyor transport type. *Geotekhnicheskaâ mehanika National Academy of Sciences of Ukraine (Co. LTD Ukrinformnauka)*, 168(1): 97-104.
- [15]. Lancine D, Chang SG and Bowa MV (2020) Influence of rainfall pattern on the slope stability of the Lumwana (the Malundwe) Open Pit. *Geotechnical and Geological Engineering*, 38:1337–1346.
- [16]. Li X, Li D, Xu, Y, Feng, X (2020) A DFN based 3D numerical approach for modeling coupled groundwater flow and solute transport in fractured rock mass. *International Journal of Heat Mass Transfer*, 149:119-129.
- [17]. Muhammad S, Fourie A (2014) The effect of rainfall patterns on the mechanisms of shallow slope failure. *International Journal of Science and Technology*, 31:2088–9860.
- [18]. Nelson SA (2013) Class notes on slope stability, triggering events and mass movement. *Hazards, Tulane University*, Pp2-17.
- [19]. Obregon C and Mitri H (2019) Probabilistic approach for open pit bench slope stability analysis – A mine case study. *International Journal of Mining Science and Technology*, 29(4):629-640
- [20]. Raza I, Ullah H, Ehsan, MI, Khalid P, Iqbal MZ & Rasheed S (2025) An integrated geophysical and geotechnical solutions for assessing slope instability challenges in open-pit mining: safeguarding mining operations. *Bulletin of Engineering Geology and the Environment*, 84(2), 83.
- [21]. Read J and Stacey PF (2009) *Guidelines for Open Pit Design*. CSIRO Publishing, Melbourne Pp. 280-288
- [22]. Reshetnyak SP, Melikhova GS, Yu V and Melikhov MV (2008) Problems of deep open-pits closure in the Kola Peninsula: Proceeding of 10th International Mine Water Association Congress, Technical university of Ostrava, 171–174.
- [23]. Sarfaraz H, Khosravi, MH and Pipatpongsa T (2021a) Numerical Stability Analysis of Undercut Slopes Evaluated by Response Surface Methodology. *Journal of Mining and Environment*, 12(1): 31-43.
- [24]. Sarfaraz H, Khosravi MH, Pipatpongsa Tand Bakhshandeh Amnieh H (2021b) Application of artificial neural network for stability analysis of undercut slopes. *International Journal of Mining and Geo-Engineering*, 55(1):1-6.
- [25]. Shukla SK and Hossain MM (2011) Stability analysis of multi-directional anchored rock slope subjected to surcharge and seismic loads. *Soil dynamics and earthquake Engineering journal*, 31:841–844
- [26]. Swedge (2006) Program for evaluating the geometry and stability of surface wedges in rock slopes. *Rocscience Inc., Toronto*, PP 184-192.
- [27]. Wyllie DC and Mah CW (2004) *Rock slope engineering in civil and mining engineering*, 4th edition. Taylor and Francis Group, London, Pp. 45–65
- [28]. Youchen L and Sijing C (2011) Rational depth of transferring open-pit into underground mining at Nanfen Iron mine, China. In *International conference on E-Business and E-Government (ICEE)*, China, May6–8, publisher IEEE, 2426–2429.
- [29]. Zhang P, Gao, Y, Liu, Y and Yang T (2025) Evaluation of Slope Stability and Landslide Prevention in a Closed Open-Pit Mine Used for Water Storage. *Applied Sciences*, 15(15), 8659.
- [30]. Zyryanov I, Akishev AN and Sherstyuk NM (2021) General concept of determining the parameters of non-mining walls of ultra-deep diamond deposits development open pits. *Gornyi Zhurnal (Ore and Metals Publishing House)* Pp. 48-53.