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https://hdl.handle.net/2324/6767907

出版情報：Energy and Earth Science (EES). 4 (2), pp.1-16, 2021. Scholink
バージョン：

Energy and Earth Science
Vol. 4, No. 2, 2021
www.scholink.org/ojs/index.php/ees
ISSN 2578-1359 (Print) ISSN 2578-1367 (Online)

Original Paper

Evaluation of the Influence of In Situ Stress on the Stability of Mine Pit Walls: A Case Study of Songwe Mine

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Received: April 15, 2021 Accepted: April 22, 2021 Online Published: May 25, 2021
doi:10.22158/ees.v4n2p1 URL: http://dx.doi.org/10.22158/ees.v4n2p1

Abstract

The investigation of the influence of in situ stress in Open Pit Mine (OPM) projects has not been accorded a deserved attention despite being a fundamental concern in the design of underground excavations. Hence, its long-term potential adverse impacts on pit slope performance are overly undermined. Nevertheless, in mines located in tectonically active settings with a potential high horizontal stress regime like the Songwe mine, the impact could be considerable. Thus, Using FLAC3D 5.0 software, based on Finite Difference Method (FDM) code, we assessed the role of stress regimes as a potential triggering factor for slope instability in Songwe mine. The results of the evaluated shearing contours and quantified strain rate and displacement values reveal that high horizontal stress can reduce the stability performance of the pit-wall in spite of the minimal change in Factor of Safety (FoS). Since mining projects have a long life span, it would be recommendable to consider "in situ stress-stability analyses" for OPM operations that would be planned to extend to greater depths and those located in tectonically active regions.

Keywords

In situ stress, dilation angle, finite difference method, flow rule

1. Introduction

For decades, the investigation of the influence of in situ stress has been conventionally limited to underground mining studies. In underground mining the analyses focus on failures such as squeezing, spalling and rock bursting which could impact mine safety and production. Despite being a fundamental concern in the design of underground excavations, in situ stresses for open pit projects are still not regarded as influential. However, Stacey (2007) highlighted the significance of investigating the role of in situ stress in OPM on slope instability since excavation creates stress imbalance. As the demand for mineral resources increases to cater for the world booming population, surface mining operations are advancing to greater depths. Open pit mining operations are generally cost-effective allowing a high grade of mechanisation and large production volumes and where feasible extract mineral deposits of a very low grade which could not be mined economically using underground methods (Sjoberg, 1996). However, slope instability is a major challenge to OPM operations. Llano-Serna, et al. (2016) quantify that roughly, two open pit failures occur worldwide annually. The instability of the slopes documented by far is governed by the slope geometry, rock mass strength, geological structures, shock loading, and hydraulic conditions. Stress regimes are hardly factored in among potential triggering factors for mine pit-wall instability.

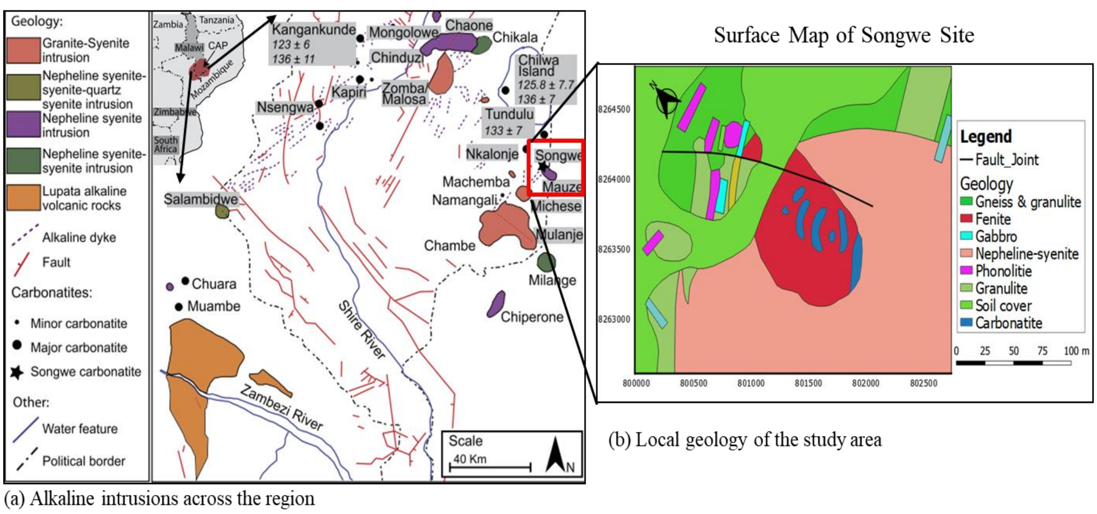
A study by Sjoberg (1996) on the Bingham Canyon mine, currently at 850m depth, concluded that the large scale failures involving up to 2 metric tonnes of material were due to a combined effect of pre-existing discontinuities and excessive water pressure leading to plane shear failure and rotational shear failure respectively. However, though not considered among the factors (Sjoberg, 1996) reported that the stress state in the mine was characterised by horizontal stresses being higher than the vertical stress with a k-ratio of greater than 1.1. In South Africa, the Sandsloot open pit mine is a typical example of an active tectonic environment that encountered instability. The tectonism is characterised by three major joint sets, which relate to the emplacement of the Potgietersrus Limb. The mine in the area experienced slope failure that prompted a comprehensive study to establish the triggers. Without any reference to in situ stress among controlling factors, Bye and Bell (2001) attributed the principal cause of the slope instability at the mine to the steep dipping and persistent joints.

At Buzhaoba mine in China, the failure that occurred was loosely attributed to tectonic stress as a dominating factor (Chen et al., 2019). According to the analysis, the principal stress direction that was theorised and simulated at 123^{o} showed that as the excavation progressed to a deeper horizon, the cumulative effects of stress were exhibited through rock mass deformation and instability along the direction of the principal stress. In the case of Songwe mine, it is sited within the active tectonic setting of the Malawi Rift System (MRS) that is part of the main East African Rift System (EARS). Therefore, this work builds on the hypothesis that high in situ stresses, especially in tectonically active environments, could have a critical influence in OPMs. Accordingly, this contribution is aimed at evaluating the accruing influence of in situ stress and its role as a potential triggering factor for slope instability.

1.1 Location and Geology of the Study Area

Songwe mine is expected to perch at Songwe Hill situated in Phalombe district southern Malawi (**Figure 1a**) .The Hill has a North-South diameter of 800m and measures 450m East to West. In terms of regional geology, the area is underlain by crystalline rocks of Precambrian to lower Palaeozoic age referred to as the Malawi Basement Complex which are intruded into by alkaline intrusive bodies (Garson & Smith, 1965; British Geological Survey, 2009). The emplacement of these alkaline intrusions occurred during the Late Jurassic—Early Cretaceous period which affected an area approximately 300-400 km in diameter in the south of Malawi and in Mozambique (**Figure 1a**).

The local geology of the study area is principally composed of; carbonatite and fenite surrounded by a massive intrusion of syenite (**Figure 1b**). Carbonatite, which is the ore hosting rock, occurs in three categories namely: coarse-grained calcite carbonatite (sovite); fine-grained carbonatite (alvikite); and Fe-rich ferroan calcite carbonatite (Broom-Fendley et al., 2017; Broom-Fendley et al., 2017b; Simandl & Paradis, 2018). Fenites form an aureole around the carbonatite intrusion. Large blocks of encapsulating fenite show evidence of being *in situ*, hence the carbonatite intrusion never reached the surface beyond roofing fenite (Broom-Fendley et al., 2017). Structurally, the site is within the active tectonic environment of the Malawi Rift System (MRS) that is part of the main East African Rift System (EARS). Therefore, faulting and the development of joints may not be an uncommon phenomenon. However, the structural disruption at the carbonatite complex is not vividly reflected on a large scale except for a major fault on the eastern side of the hill that runs NW to SE. The subtle evidence of structural deformation is revealed in sharp lithological breaks across the hill.



(b) Local geology of the study area

(a) Alkaline intrusions across the region

Figure 1. Location and Geology of Study Area (Modified after Broom-Fendley et al., 2017)

2. Method

2.1 Numerical Methods

Numerical methods are capable of simulating natural failure process and representing deformation and displacement of the failing rock mass (Diederichs et al., 2007; Matsui & San, 1992; Hammah et al., 2004; Dawson et al., 1999). Analysis based on a numerical approach involves dividing the rock mass into elements assigned with the idealised stress-strain relation and properties that describe how the material behaves. The most commonly applied numerical methods in slope stability analysis are divided into three categories: (i) continuum methods, (ii) discrete methods, and (iii) hybrid continuum/discrete methods. In this study, a continuum code based on the finite difference method (FDM) using FLAC^{3D} 5.0 software (Itasca, 2012) was applied in simulating the potential slope instability.

The FDM approach was preferred because the constitutive models are treated with no modification to the solution algorithm as such the modeling is justifiably more accurate for plastic collapse loads and plastic flow (Itasca, 2012). The analysis was performed in elasto-plastic state in finding the solution with the Mohr-Coulomb constitutive model and failure criterion. The Shear Strength Reduction (SSR) technique embedded in the FDM code achieved the determination of slope performance. The SSR involves a methodical iterative search of the Factor of Safety (FoS) value that stretches the slope to the limits of failure. The roller boundary conditions were assigned in the *x*- and y-direction thereby fixing the boundary planes in the *x*- and y-direction respectively, pinned boundary condition (i.e., constrained in the *x*-, *y*- and *z*-directions) was applied at the bottom of the model and the top of the model was left unconstrained.

2.2 Model Construction

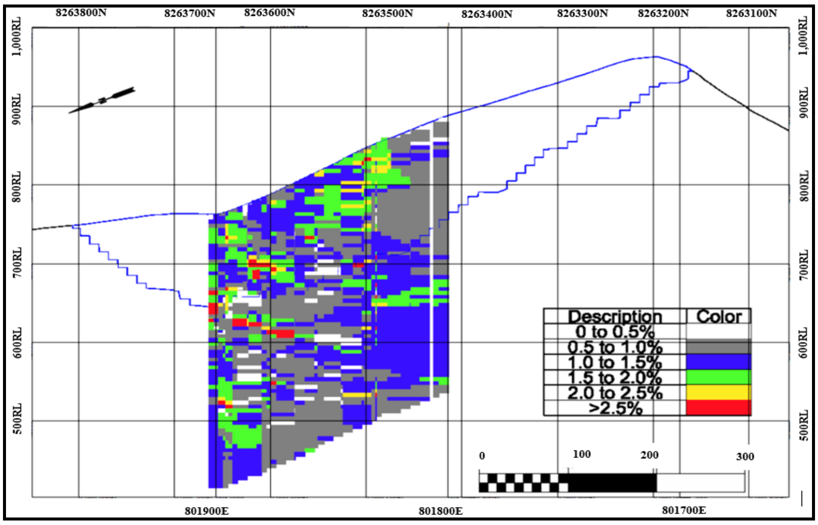
The hill dimensions guided the numerical model of the pit. The OPM at the site is anticipated to cover almost the whole stretch of the hill. The overall dimensions of the final pit are expected to be approximately 650 m North to South and 400 m East to West. Regarding pit height, it is planned that the deepest level will be 300 m when measured from the highest Reduced Level (RL) of the pit on the southern side of the pit (**Figure 2**). Accordingly, the simulation model stretches 1000 m in length, 400 m in height, and the width measures 400 m. The 100 m addition in length on both ends was to make sure that the boundary conditions do not influence the solution when stepping. Monitoring points were added at the mid-section of the pit to observe displacements and induced stresses on the pit walls. The excavation of the stack benches (dimension 15 m height and 7.5 m width) was done in three sequential stages.

Three conceptual cases were generated with respect to pit height. In the first scenario, shear strain behaviour on the pit-slope was investigated at the current planned depth of 250 m. The planned depth is within the bounds of proven ore reserve hence the geological confidence is high. The second scenario is for 280 m depth and the third case is based on the ultimate depth of 300 m. At this depth, the geological confidence is relatively low since less than 10% of the drilled holes reached 300 m. The analysis was performed at the trial steep overall angle of 45 º(Moses et al., 2020) in the non-associated flow rule (ψ=0°) and associated flow rule (ψ≠0°). The two flow rules are conducted to comprehend both the worst-case and idealistic scenario of rock mass deformation. The material properties used in this study are presented in **Table 1**. Rock density(γ), uniaxial compressive strength (UCS), Young's modulus (E), tensile stress(σ_t), friction angle(φ), cohesion (c), Poisson ratio (v) and dilation angle (ψ) were obtained from laboratory rock strength tests conducted except for Syenite lithological unit, which were sourced from literature.

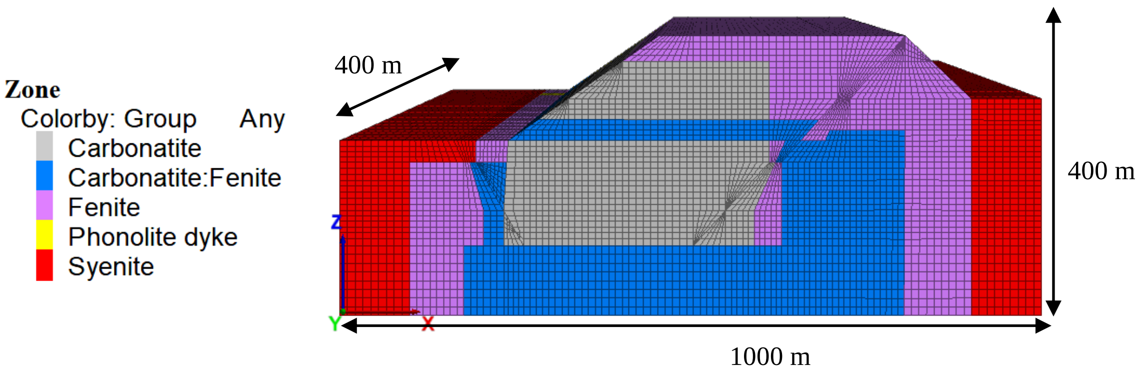
Table 1. Mechanical Properties of the Rock Units

Rock Type	**UCS (MPa)**	**γ (g/m^3)**	**E (GPa)**	**σ_t (MPa)**	**φ (Deg)**	**C (MPa)**	**Ψ (Deg)**	**V**
Carbonatite	83.2	2.78	45.30	8.6	35	0.32	2.3	0.28
Fenite	118.6	2.70	44.40	10.4	36	0.30	3.5	0.29
Phonolite	150.4	2.88	64.30	11.5	37	0.45	3.5	0.29
Syenite*	70.0	2.55	53.40	3.37	30	0.28	-	0.25

Note. *Based on empirical values (Katz et al., 2000; Croll et al., 2014).



(a) cross section of Songwe open pit mine



(b) Model extents

Figure 2. Cross Section of the Mine and Numerical Model

3. Result and Discussion

In evaluating the stability of excavation, the Factor of Safety (FoS) is utilised as an index to determine the performance of the excavated sections. In this study, the evaluation of the safety of the pit slope is based on the Mohr-Coulomb failure criterion as presented in the equation in **Figure** 3, which is a classic approach in geotechnical studies (Labuz & Zang, 2012). The application of the criterion in FDM utilises the Shear Strength Reduction (SSR) technique that entails a systematic iterative search for a value that stretches the slope to the limits of failure. When FoS, derived as a ratio between supply (shear strength) and demand (shear stress), is ≥ 1 the excavated face is described as stable and if < 1 it is unstable.

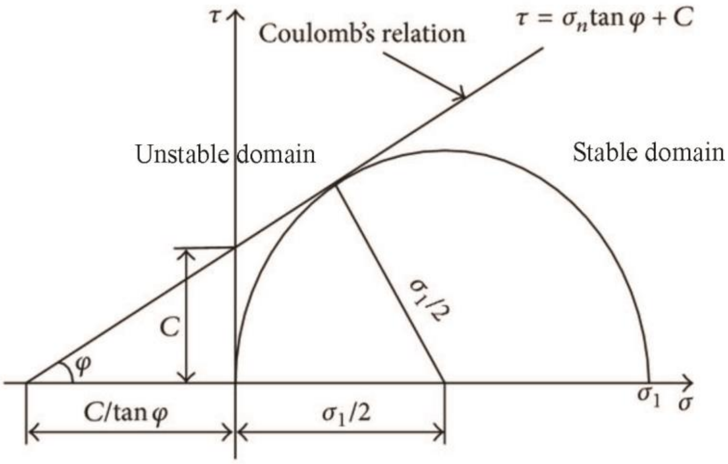


Figure 3. Mohr Coulomb Failure Criterion Relation

Note. Where: τ is the shear strength; C is cohesion; φ is internal friction angle; σ_n is normal stress.

3.1 Pit Wall Stability

In most mining engineering projects, analyses are performed without incorporating dilation angle as a parameter since the interest is in the worst-case scenario. However, we considered both the non-associative flow rule (ψ=0°) and the associative flow rule (ψ≠0°) because dilatancy is one of the crucial phenomena of geo-materials during shear distortion of elements in a material. The results of the analysis are shown in **Figure 4**. The simulation outcome indicates that the pit walls are satisfactorily stable at 250 m pit height. The values of FoS are well above the threshold of 1.2 as recommended by (Adams, 2015; Read & Stacey, 2010; Sullivan, 2013) for OPM. However, the performance of the pit walls falls under the threshold implying unreliable stability as the excavation extends to a deeper horizon.

The comparative analysis of the non-associated flow rule (ψ=0°) and associated flow rule (ψ≠0°) illustrates that taking into account ψ improves the stability performance of the pit wall slopes. The dilation angle of the rock mass appears to increase the shear strength of the rock mass under shearing conditions. This increase in strength can be ascribed to the rearrangement of the constituent mineral grains in the rock mass as shearing occurs. In an intact rock state, the mineral grains are interlocked and as such, they do not have the freedom to move. When stressed, the contiguous mineral grains gravitate towards each other, which ultimately produces a bulk expansion of the material due to occlusion. The findings concur with the pioneering empirical formulas by Bolton and Reynolds on the effect of dilation angle (Logani, 1973). We can observe that the consideration of ψ is vital to yield accurate and realistic slope stability besides the fact that engineering considers the worst-case scenario.

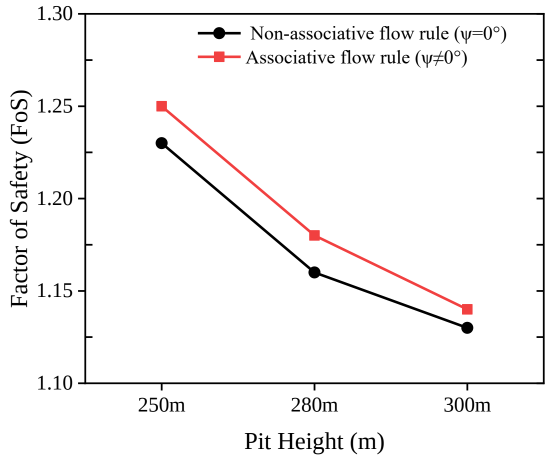


Figure 4. Pit Stability Condition at Different Excavation Depth

To appreciate the influence of dilation angle on slope performance in details, we undertook a parametric analysis by varying the values of dilation angle. The averaged dilation angle was changed within the range of 0°-20°. The findings of the parametric analysis are given in **Figure 5**. The results affirm that the dilation angle enhances the stability of the excavated faces. Higher values of dilation angle yielded relatively larger stability values when compared to the conventional non-associative flow rule. This phenomenon underscores the positive correlation of the associated flow rule of ψ in increasing the shear strength of the rock mass on excavated slopes under shearing conditions. Having appreciated the stability conditions under a unit stress condition (k=1), the study explores further for varied stress conditions, and the results of the analysis are based on the non-associated flow rule (ψ=0°).

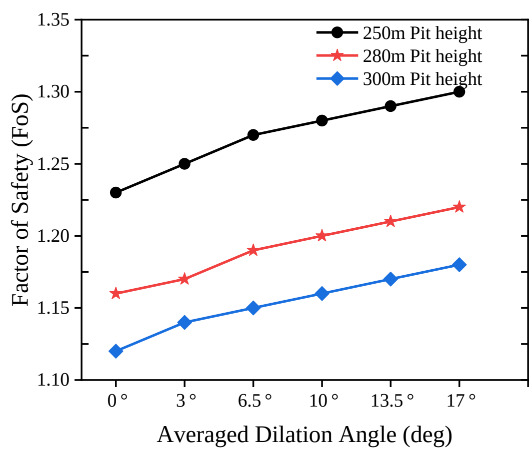


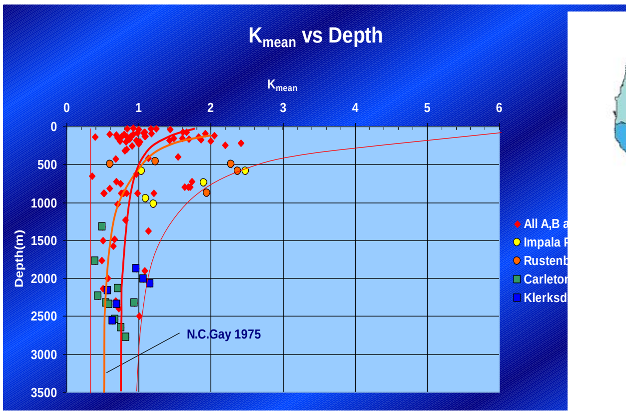
Figure 5. Parametric Analysis of the Influence of Dilation Angle on the Stability of Pit Walls

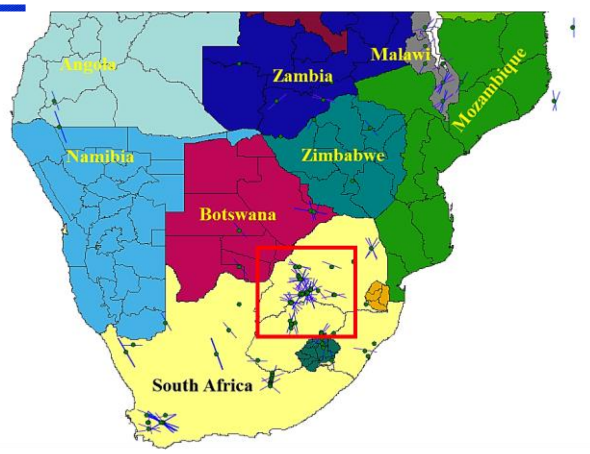
3.2 Influence of In-situ Stress in Open Pit Mine

The pre-mining initial stress state is an important aspect in numerical modeling for equilibrium stepping and determination of mining induced stress. To understand the influence of the in-situ stress state during rock excavation, the virgin stresses were analysed. In this research project, due to unavailability of site-specific data, which is technically complex and expensive to collect, the pre-mining stresses were approximated from mean South African regional stress compilation in OPMs; Impala, Parabola, and Rustenburg mines grouped as A, B, and C respectively, Carolusberg and Klerksdorp mine which portray identical directional pattern to Malawi (**Figure 6**).

Thus, different stress ratios (σ_{Hmax}/σ_v) were considered to appreciate the influence they could have on the stability of the pit walls. Based on the regional data, it can be observed that the mean ratio between vertical stress and major horizontal stress can be tested up to k=2.5 in open-pit mines. The initial run of the simulation was based on the in situ stress ratio of k=1 and then varied at 0.5 intervals. The results of the analysis are displayed in **Figure 7**. The outcome shows that the stability of the pit, as adjudged quantitatively from FoS, could negligibly be affected even under high-stress conditions. As observed from **Figure 7**, the factor of safety remains the same under different stress regimes except when the pit start to extend to deeper levels at 280 m and 300 m pit height which recorded a marginal decrease from 1.16 to 1.15 and 1.12 to 1.11 at k=1 with the increase in stress ratio respectively.

Since the determination of stability is quantitative, this phenomenon explains why in situ stress is conventionally considered in underground mines. However, a qualitative evaluation of the stability state through shearing contour analysis reveals that the pit wall stability conditions would be different under high-stress regimes that could potentially influence the long-term performance of the slope. Although the factor of safety experiences minimal reduction, it is evident that the pit wall shearing becomes intense and the straining of the walls becomes effusive under high-stress ratio conditions. In this situation, it should be appreciated that with the passage of time, the pit walls could potentially fatigue under high in situ stress. In addition, if the depth extend further, the minimal accrual could translate into a significant value of FoS. Thus, as a “first check” in the evaluation of the stability of a pit slope, we apply the strain-based approach to failure prediction and determine if further attention regarding monitoring could be necessary to incorporate the Trigger Action Response Plan (TARP) for instability in different stress regimes.





(a) Mean stress ratios for representative OPM (b) Location of data representative mines

Figure 6. The Averaged Ratio of Vertical Stress and Maximum Horizontal Stress

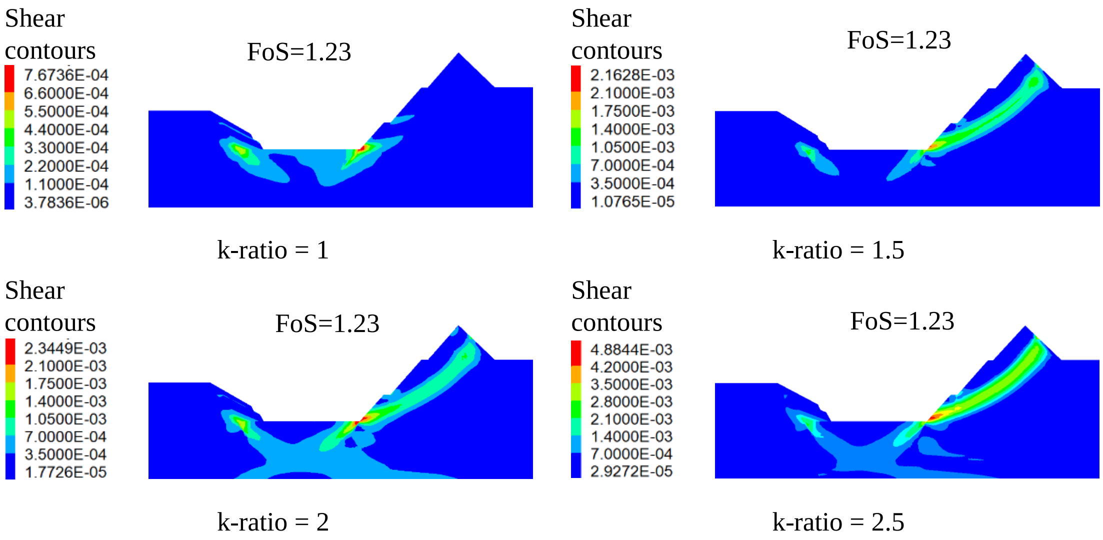
3.3 The Strain Criteria Approach to Failure Prediction

The essence of pit wall stability analysis is to evade or inhibit failures by adopting an optimal mine design. Therefore, the strain-based approach, as applied in this study, could provide guidance regarding strain thresholds for pit wall performance in diverse stress conditions. Strain is the ability of a stressed material, in the presence of a stress field, to deform. Generally, rock mass succumbs to the application of stress which is due to the rearrangement of the natural in situ stress field when the slope is excavated. The extent of straining is consequent to the slope geometry and slope construction and in situ stress conditions. The strain-based approach to assessing pit slope stability utilises the fundamental principles of the strain formula after Brix & Newcomer (2003) given as.

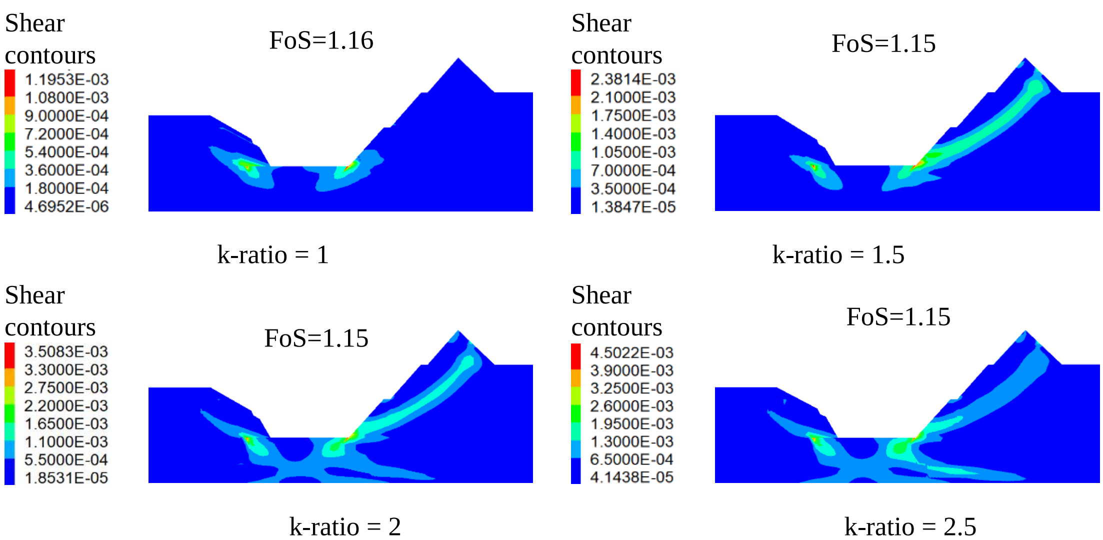
$$\varepsilon = \frac{\Delta x}{H}$$

where: Δx=the maximum deformation of the pit wall, H=the total height of the wall and ε=the strain in percentage.

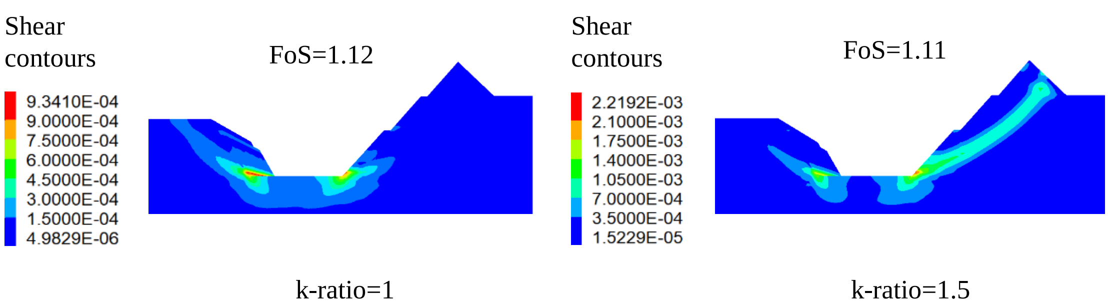
Based on over 12 case studies, Brox & Newcomen (2003), Newcomen & Dick (2016) and Zavodni in Hastrulid (2001) developed the strain percentage criteria for the principal failure modes in various rock mass classes. The threshold strain levels for rock mass were established to have a lower bound strain at collapse of 0.1% and upper bound strain to collapse of 3% (Newcomen & Dick, 2016; Coetsee et al., 2020). The results of the stability performance of pit wall, based on strain approach, against failure under different stress regimes are given in **Figure 8**. It can be observed that the peak strain rate increases with stress regimes. That is, as the k-ratio increases, the straining correspondingly increases.

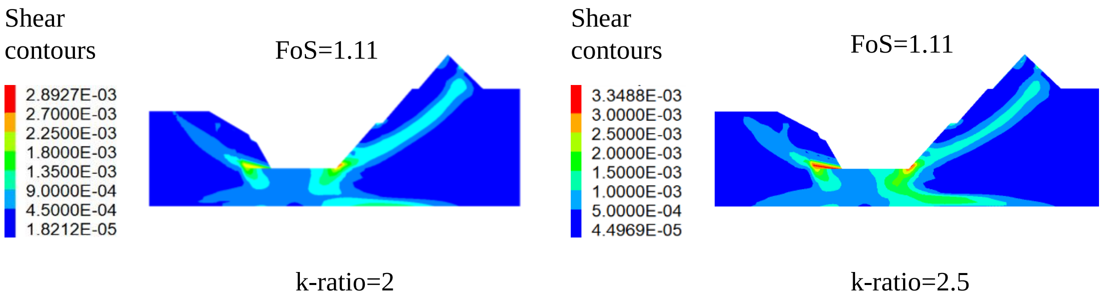


(a) Shearing pattern of pit walls at 250 m pit height



(b) Shearing pattern of pit walls at 280 m pit height





(c) Shearing pattern of pit walls at 300 m pit height

Figure 7. Shearing Pattern under Different Stress Conditions

This trend is in tandem with the qualitative shearing conditions of the pit wall previously presented in **Figure 7**. However, the percentage of strain in this study demonstrates that the pit walls would be almost 60% below the lower bound strain to collapse in all the simulated cases. The highest strain rate of almost 0.04% is recorded at 300 m height with the highest possible in situ stress condition of k=2.5. Thus, at this rate of straining the pit walls stability performance would still be guaranteed though relatively high. The pit height is also an important determinant of straining on pit slopes. The outcome shows that as the pit extends to a deeper horizon, the strain rate congruently increases. At the Ultimate Pit Limit (UPL) of 300 m, the strain values are comparatively high against 280 m and 250 m pit heights. For example, at the stress condition of k=2.5, the strain values are 0.029% at 250 m, 0.032% at 280 m and 0.036% at 300 m pit height.

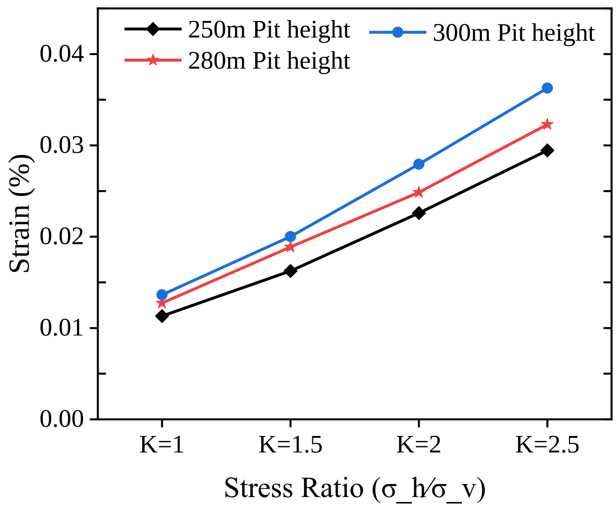
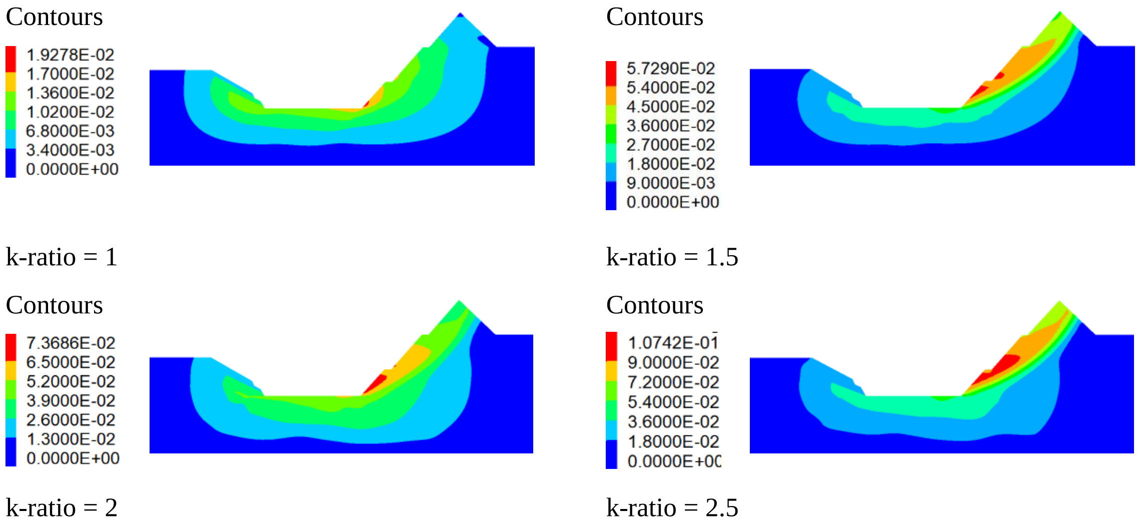


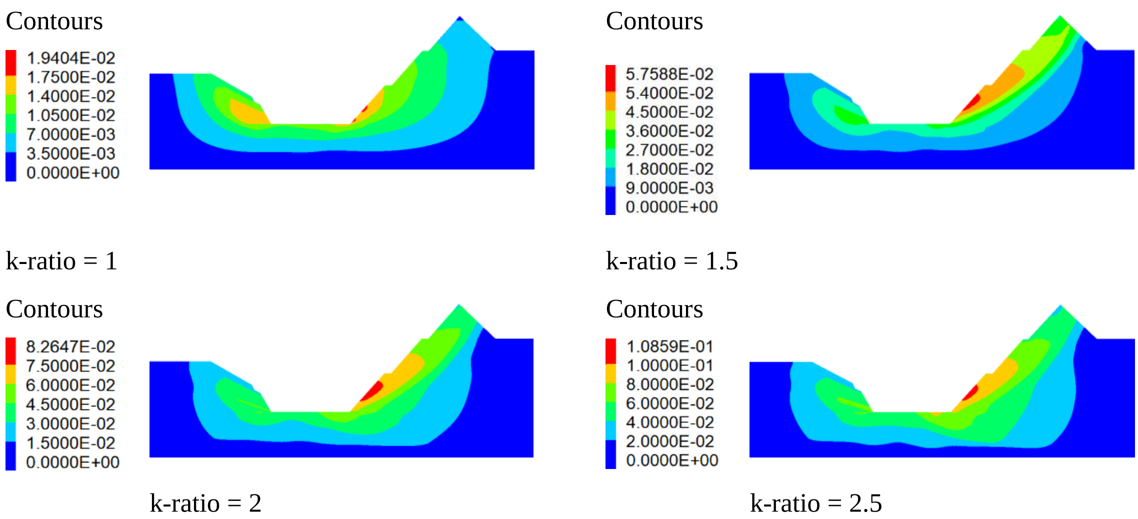
Figure 8. Peak Strain of Pit Walls against Potential Failure under Different Stress Regimes

3.4 Displacement Pattern

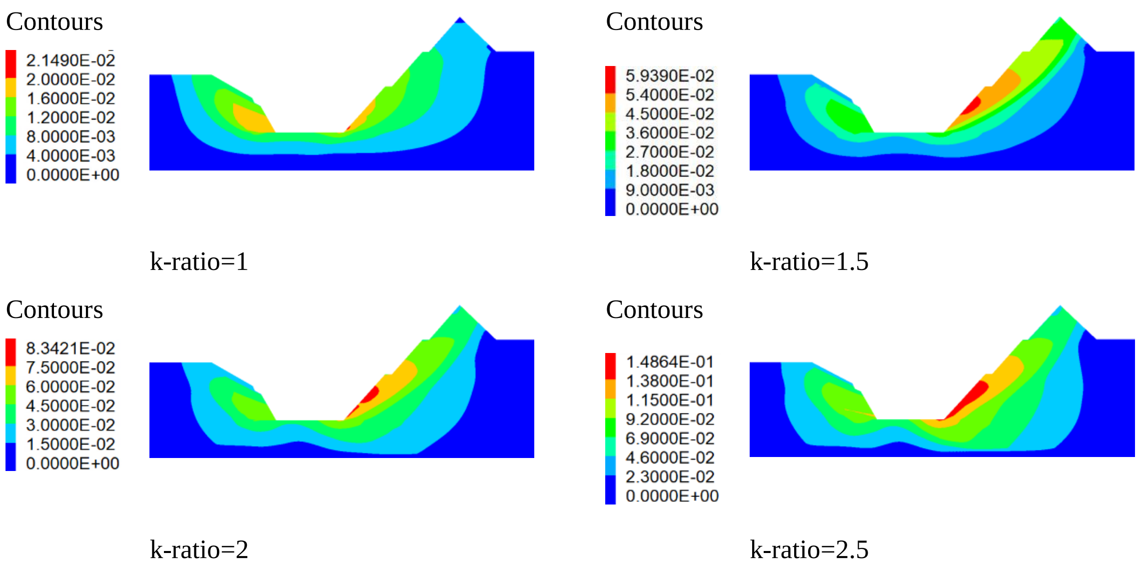
To check the criticality of the stability state, in connection to the strain analysis, the extent of displacement was evaluated under different stress conditions. The results of total displacement with respect to k-ratio are depicted in **Figure 9**. It can be observed that the pattern of displacement is in harmony with the strain state such that an increase in stress ratio led to increase in the extent of total displacement. At 250 m pit height, the peak displacement values are 19 mm, 57 mm, 74 mm, and 107 mm at k=1, k=1.5, k=2 and, k=2.5 respectively.



(a) Pit wall displacements at 250 m pit height



(b) Pit wall displacements at 280 m pit height



(c) Pit wall displacements at 300 m pit height

Figure 9. Pit Wall Displacement under Different Stress Conditions

As excavation progressed, the extent of displacement gradually increased. That is, at 280 m pit height, the displacement values recorded are 19 mm, 58 mm, 83 mm and 109 mm in the order of increasing stress ratio. And at the currently planned UPL the displacements are 21 mm, 59 mm, 83 mm, and 149 mm at k=1, k=1.5, k=2, and k=2.5 respectively. The deformations around the pit are generally induced by relaxation on the excavated pit sections. Corollary, increase in maximum initial horizontal stress appear to counter the gravity loading effect, hence lateral material movement becomes more dormant to vertical movements. From the displacement trends, we can observe that in situ stress condition is indispensable for consideration in OPM as they could have a long-run compounding effect on pit wall performance.

4. Conclusion

The significance of investigating the role of in situ stress in OPM cannot be over-emphasised as surface mining operations are advancing to greater depths with the safety of mines being among paramount concerns. In this contribution, the influence of in situ stress and its role as a potential triggering factor of slope instability was assessed. The evaluation of the shearing contours and quantified strain rate and displacement values demonstrate that high horizontal stress regimes can reduce the stability performance of the pit-wall. Even though the quantitative outcome based on FoS gives a guised impression of no significant impact as values of stability remain almost constant, this scenario could have adverse impacts on the long-term stability performance of the pit slope since mining projects extend for years. This calls for a perspective transformation of the conventional approach of confining in situ stress impact in solely underground excavations. Therefore, this work suggests that “in situ stress-stability analysis” is a worth consideration for OPM operations that would be planned to extend to greater depths, and those located in tectonically active settings.

Acknowledgement

The authors express their sincere gratitude to Mkango Resources Company for providing the required geotechnical data for the study to be conducted.

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