



Stability design of slopes in carbonatite complexes characterised by brecciation

by D. Moses¹, J.A. Onyango²

Affiliation:

¹Department of Geography and Earth Sciences, School of Applied Science, University of Malawi, Malawi

²Department of Mining, Materials and Petroleum Engineering, Jomo Kenyatta University of Agriculture and Technology, Kenya

Correspondence to:

D. Moses

Email:

dmoses@unima.ac.mw

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ORCID:

D. Moses

<http://orcid.org/0000-0002-9387-4094>

J.A. Onyango

<http://orcid.org/0000-0002-5558-4125>

Abstract

Carbonatites are generally competent rock masses with rock mass rating class II rating 60–74. In spite of their competency, they tend to be affected by weak features like manganese-iron veins and/or in situ rock damage due to brecciation associated with carbonatite complexes. Rock slope failure in such hard rocks is complex since such structures within the rock mass form weak links that could potentially control slope instability. In this contribution, a numerical simulation using phase2 v 7.0 was carried out to investigate the influence of in situ rock damage on the stability of mine pit walls. The outcome reveals that, the existence of breccia in the competent rock mass has the capability to reduce the slope stability performance particularly at gentle dipping angles of emplacement in close range to the slope toe. However, as the emplacement position of breccia moves away from the pit wall, the stability performance increases at gentle dipping angle $<50^\circ$. On the contrary, at the dipping angle of 50° the performance of slope reduced, and at steeper angles $>50^\circ$ the impact becomes negligible. Thus, from a series of analyses, mine design in brecciated rock masses, the ratio of 1:5 between the breccia distance from slope toe and pit depth should be implemented to counter its impact, and if the breccia is within or close to the pit limit, a deliberate effort must be made to mine it out.

Keywords

Songwe Hill, carbonatite, finite element method, in situ rock damage, breccia

Introduction

In recent years, the significance and applications of the rare earth elements (REE) for modern technologies, particularly for the permanent magnets used in the generators of wind turbines and the motors of electric vehicles, have led to an increased research focus on alkaline rocks and carbonatites (Goodenough et al., 2021). Carbonatites, which are igneous rocks containing more than 50% modal primary carbonates and less than 20 wt. % SiO_2 (Simandl, Paradis, 2018; Woolley, Church, 2005; Xu et al., 2015), are generally competent rock masses with rock mass rating class II rating 60–74 (Moses et al., 2020). However, carbonatite complexes are highly affected by the later stage hydrothermal and carbo-hydrothermal phases where expelled fluids in fissures lead to the formation of new weak features like manganese-iron (Mn-Fe) veins and/or damage of the rock. Thus, rock slope failure in these hard rocks is complex since structures within the rock mass form weak links that could potentially control slope instability. Stead and Wolter (2015) highlighted instances of the significant impacts of sheeting, exfoliation, and joints on slope stability. Generally, when considering structurally controlled stability in hard rocks, emphasis is given to the role of discontinuity persistence, orientation, and intensity. But the complexity of failure mechanisms in rock slopes is when a combination of pre-existing geological weak planes and failure of intact rock induce instability. Intact rock can be subjected to physical damage of different forms as discussed by Brideau et al. (2009) presented in a summarised form in Table 1.

The concept of damage of intact rock and rock mass relates to the degradation of their strength properties. The physical damage usually takes place in planes of weakness ranging in scale from micro-cracks to faults. Atkinson (1987) articulates that the formation of planes of weaknesses occurs through three basic modes of fracture: opening, sliding, and tearing. The ultimate effect of the damage processes is the degradation of the intact rock properties towards damaged rock mass and the rupture in intact rock is regarded as the accumulation of the damage (Brideau et al., 2009).

The determination of the rock damage condition has mostly been made possible through rock mass classification systems. Among sundry classification schemes, Geological Strength Index (GSI) has proven to be pivotal in the rock damage characterisation process with respect to stability analysis. A number of

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Table 1

Types of rock slopes damage (Brideau et al., 2009)

Type of damage	Process
Brittle	Initiation, comminution
Ductile	Rigid block overlying soft rocks.
Creep	Sub-critical crack growth.
Fatigue	Low/high frequency loading/unloading cycles (glaciation, isostasy, pore water pressure fluctuation, freeze–thaw, wet/dry, seismicity).
Thermal	Heating and cooling cycles.
Tectonic	Preconditioned damage due to faults, folds and in situ stress.
Anthropogenic	Excavation, blasting.
Physio-chemical	Hydrothermal alteration, weathering, corrosion.
Geomorphic	Stress induced damage associated with valley formation, cambering, erosion, thermal cycling.

studies have investigated the control of folds and faults, shearing, and clay-infill of joints on the stability of rock slopes. A study by Bye and Bell (2001) revealed that steep dipping and persistency of the joints at Sandsloot open pit in South Africa were principal causes of the slope instability at the mine, triggering failure.

Faults and fault damage have also been recognised to compromise the performance of the slopes by affecting the regional geology, rock mass, and stress conditions in large open pits. The impact of fault characteristics are directly linked to stress heterogeneities created by the interaction between the faults and the mining induced stresses generated during excavation, leading to localised high plastic shear strain and high extensional strain around the fault (Severin, 2017; Stead, Wolter, 2015). Additionally, Stead and Wolter (2015) demonstrated that structural features, such as folds, bedding planes, faults, and discontinuities commonly affect hydrogeological conditions, a crucial factor in slope stability, acting as either water conduits or aquitards. Simulated models that incorporated groundwater showed a tremendous slope instability due to groundwater pressures.

Bachmann et al. (2004) also examined the influence on slope stability of both damage due to weathering and the presence of large-scale fractures using three-dimensional scaled analogue physical models. The experimental results demonstrated that the introduction of a weathered material on the surface of the rock mass controlled the ease, depth, and extent of the slope failure. However, the presence of large scale fractures had little effect on slope stability. Based on the findings by Bachmann et al. (2004), the fractures controlled the lateral extent of the slope failures. Recently, Qian et al. (2017) investigated the influence of rock mass disturbance caused by blasting on rock slope stability and found that the thickness of blasting damage zone substantially lowers the rock slope stability. A similar study was conducted by Zheng, et al. (2018) but the focus was on comparing limit equilibrium (LE) approach against numerical approach. Further from confirming findings by Qian et al. (2017), the results revealed only 5.6% discrepancy between the LE and numerical analyses results. In this contribution,

a consideration is given to in situ rock damage in a brittle form as a result of a unique phenomenon of brecciation associated with carbonatite complexes and its role in preconditioning instability on mine pit walls.

Location and geology of the study area

Songwe Hill is situated in Phalombe district in the South-eastern region of Malawi. On international borders, Malawi shares boundaries with Tanzania to the north, Zambia to the west and Mozambique surrounds the country from east to west. The study area of Songwe Hill is adjacent to Mozambique separated by the syenitic intrusion of Mauze Mountain (Figure 1a). 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 is intruded 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. At various localities, the basement complex is overlain by a sequence of Permo-Carboniferous to lower Jurassic sedimentary rocks of the Karoo super-group and superficial Tertiary to recent Karoo sediments. The local geology of the study area is principally composed of carbonatite and fenite surrounded by a massive intrusion of syenite.

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. Fenites form an aureole around the carbonatite intrusion. It is postulated that the carbonatite intrusion never reached the surface since the fenite is continuous with only rare carbonatite veinlets (Broom-Fendley, et al., 2017). In terms of the texture, the fenites are of a coarse-grained equigranular igneous texture, strongly suggesting an igneous protolith. Structurally, Songwe Hill lies within the active tectonic environment of the Malawi Rift System (MRS), which is part of the main East African Rift System (EARS). Thus, faulting and development of joints may not be an uncommon phenomenon but the structural disruptions at the site are not reflected on a macro scale, except for a mappable fault at the foot of the hill as shown in Figure 1b.

Witley et al.(2019) attempted to present subtle evidence of structural deformation, which they argued to be reflected in sharp lithological breaks across the area. They concluded that the lithological breaks that corresponded to the faults were interpreted from the ground magnetic fields. However, it must be admitted that the fault traces were considered as an approximation, given that the resolution of the magnetic image was low at the scale of the geological map. One exceptional phenomenal feature of interest is the in situ damage of the rock mass due to brecciation (Figure 1c) revealed from the geological and geotechnical logging of the diamond drill core.

Brecciation mechanism

Breccia (Bx) is a term commonly used for an enigmatic rock group that comprises a variety of discrete broken fragments of rocks, every so often angular and bound together by a fine grained matrix and occasionally vitreous matrix, which may or may not resemble the composition of rock fragments (Shukla, Sharma, 2018). Woodcock and Mort (2008) made an effort to classify breccias using a criterion that can easily be applied in the field. These rock masses can be identified in different geological settings mostly associated with

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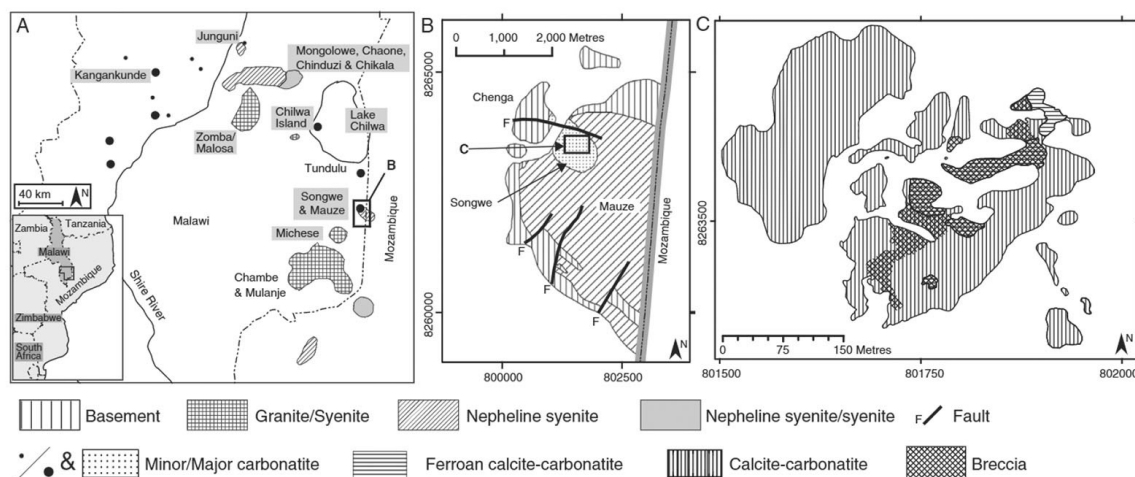


Figure 1—Location and the geology of the study area (Broom-Fendley, et al., 2017)

various ore types. In carbonatite complexes, breccia is a common structural feature. Shukla and Sharma (2018), Sibson (1986), and many other authors have discussed mechanisms of brecciation in different geological environments, including the volcanic setting. Among many mechanisms of brecciation, this study reveals two phenomena that can be attributed to be the occurrence of the breccia at the study site of Songwe Hill, namely: hydro-fracturing and tectonic forces along a pre-existing plane of weakness.

The hydro-fracturing process for brecciation involves high-pressure fluids. This hydrothermal process readily affects carbonate-rich rocks. In this process, the pre-existing rock interacts with water-rich hydrothermal solutions that increase the fluid pressure within a fissure, and the effective pressure decreases leading to fracture propagation (see Figure 2a). Elliott et al. (2018) explain that the occurrence of breccias at several carbonatite complexes corroborates the explosive release of fluids and volatiles from an evolving magma underneath. For Songwe carbonatite, Broom-Fendley, et al. (2021) stress that based on the angular nature of the clasts and the comminuted groundmass, the breccia formed by in situ rapid volume expansion, most likely as a result of subsurface explosive release of volatiles from the proposed underlying carbonatite bodies. Thus, the explosive hydrothermal brecciation and the metasomatic action of hydrothermal fluids can indeed be considered to be responsible for the generation of the breccia. On the other hand, tectonic disturbances resulting from fault movements can also account for the brecciation as the area is located in a rifting setting with potentially high stresses acting along the weak plane causing rock comminution but the certainty of it is not fully verified at the study site. Accordingly, the brecciation associated with the fault system forms due to the grinding action of rock blocks along a plane of weakness.

Methods and model construction

For decades, most slope stability analyses have been performed using limit equilibrium methods (LEM). The underlying concept of the LEM is that the rock mass behaves as a rigid material and that the shear strength is mobilised at the same time along the entire failure surface (Brideau et al., 2009). Based on this assumption, LEM can only be adequate for analysing simple failure modes and small-scale analyses. However, demand for mineral resources has seen surface mining operations expanding to greater depths in order to meet the needs of growing industries. This trend requires modelling that covers complex conditions found in rock masses

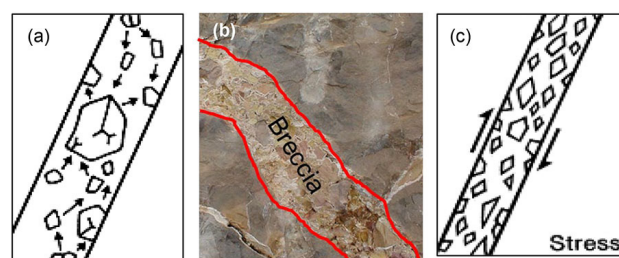


Figure 2—Brecciation mechanism in carbonatite-alkaline complexes; (a) hydro-fracturing, (b) illustration of a breccia, and (c) tectonic damage

like nonlinear stress-strain behaviour, anisotropy, and changes in geometry. Thus, the development of numerical codes over the last decades has revolutionised rock mass modelling, thereby superseding the traditional methods. Numerical modelling has now been described as a valuable tool to enhance the understanding of the response of rock masses to excavation (Hart, 2003). Currently, there are numerous methods; continuum, discontinuum, and hybrid continuum/discrete methods that have been developed in an effort to represent the characteristics and behaviour of rock masses. Regardless of the method selected based on the nature of the problem to be addressed, parameters like material properties, intact rock discontinuities, boundary conditions, hydrogeological regime, and permeability are considered in evaluating the stability of the excavations. In this study numerical method of continuum is applied in simulating the rock slope stability using finite element method (FEM) codes.

To carry out the analysis, conceptual models were built in Phase2 v 7.0. The dimensions of the model measured 600 m in length and 400 m vertical extent from the highest reduced level (RL) mimicking the hill. Two main 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, which is the depth within the bounds of the proven ore reserve, hence the geological confidence is high. The second scenario is for the global slope height (GSH) of 300 m. At this depth, the geological confidence is relatively low since less than 10% of the drilled holes reached 300 m. In both cases, the analysis was conducted at different pilot overall slope angles (OSA) that could be practical in the design. Thus, OSA was varied from 45° to 40°. The excavation of the stack benches (dimension 15 m height and 7.5 m width) was carried out in three sequential stages as depicted in Figure 3.

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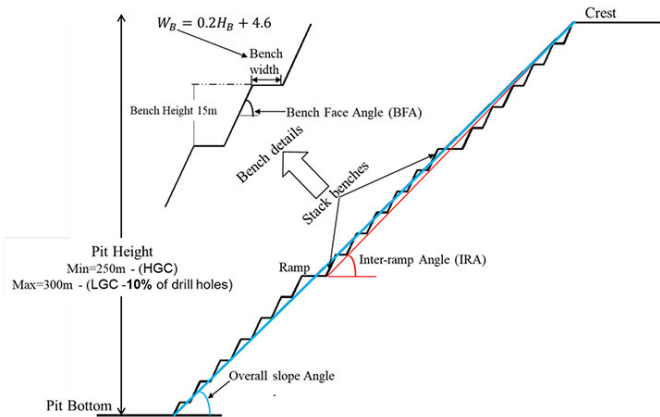


Figure 3—Conceptual pit configuration of the Songwe mine

Three cases were generated with respect to the conceptual extent of the brecciated rock section. In the first case, shear strain behaviour on the pit slope was investigated without including the brecciated section. The second scenario incorporates the 10 m brecciated rock section and the last case having a 20 m thickness of brecciation (Figure 4). According to the field survey, the 10 m brecciation thickness is considered the closer representation of the brecciated zone for the study site. The emplacement of the breccia is estimated to be dipping at $\geq 50^\circ$ and as Broom-Fendley, et al. (2021) established, the breccia grades down into an underlying carbonatite body at great depth. To cater for uncertainties, the emplacement angle was varied for parametric analysis from 30° to 70° at an equal interval of 10° .

In carrying out the study, the material properties were obtained from uniaxial compressive strength (UCS) tests, triaxial compressive strength tests (TCS), and literature.

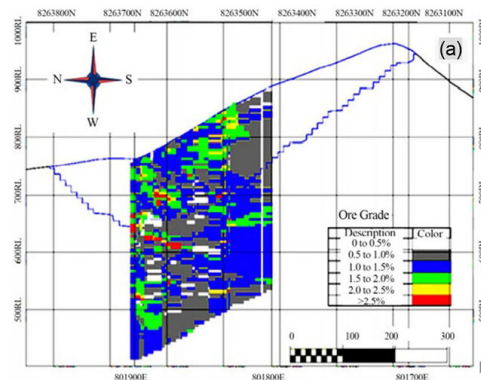
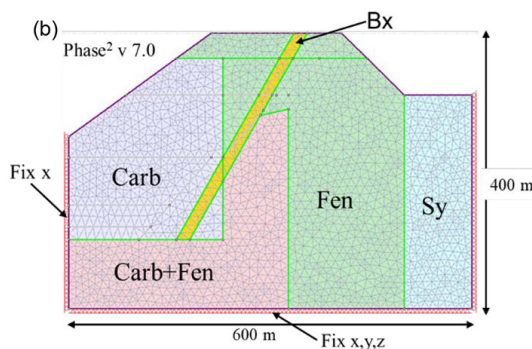


Figure 4—Conceptual model: Bx = breccia, Sy = syenite, Carb = carbonatite, Fen = fenite



The material properties used in this simulation are given in Table 2

Results

The principal objectives of the open pit slope stability analyses are: to investigate the pit slope stability conditions, probable failure mechanism, slope sensitivity or vulnerability, and to design optimum pit slope angles in terms of safety, reliability, and economic lucrativeness. Generally, stability of open pit slopes depends on geometry of slope, rock mass characteristics, and shear strength behaviour of the joints (Soren et al., 2014). In slope stability analysis, factor of safety (FoS) is used as an index to determine the stability conditions. The factor of safety is a ratio between shear strength and shear stress to determine the stability of excavated sections. The basic minimum requirement for stability assurance when assessing the performance of excavated sections is that FoS should be equal to 1, which is a state of plastic equilibrium. However, in mines, the minimum requirement is > 1 . Generally, the benchmark value varies by region and mining guidelines enforced by different countries. After a compilation of data from numerous open pit mines (OPM), Adams (2015), Read and Stacey (2009) and Sullivan (2013) established that the minimum criterion for safety assurance in OPM is for FoS to be ≥ 1.2 . In this work, since the results are based on a 2-D numerical modelling in an out of the plane mode, the benchmark FoS tolerable has been pegged at 1.3.

To vividly comprehend the influence of brecciation, the research object of the qualitative analysis presented only covers the GSH of 300 m at a slope angle of 45° . On the other hand, the quantitative analysis caters for all the pit heights and slope angles. From Figure 5, one notices a significant change in the shear failure path prior to and after the inclusion of breccia, in which case there is a rotational/circular and translational potential failure respectively. The circular

Table 2

Mechanical properties of the rock units

Rock type	Uniaxial compressive strength (MPa)	Density (g/cm ³)	Young's modulus (GPa)	TensileStrength (MPa)	Friction angle (°)	Cohesion (MPa)	Poisson Ratio
Carbonatite	83.2	2.78	45.3	8.6	35	0.32	0.28
Fenite	118.6	2.70	44.4	10.4	36	0.30	0.29
Breccia	37.5	2.35	17.6	3.37	30	0.10	0.22
Syenite*	70.0	2.55	53.4	3.37	30	0.28	0.25

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

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failure path prior to the inclusion of brecciated rock develops at inter-ramp level in the second excavation, and then the shearing strain concentrates at the slope toe.

On the other hand, the translational failure path is well developed at gentle angles of emplacement of the breccia, especially at 40° and 30°. The performance of the slope at these angles is critically low since the overlying block is supplied with a failure plane characterised by low cohesion and friction resistance along the in situ damage section. At a relatively steep emplacement angle of the brecciated rock, that is, 50° and 60°, the failure plane is characterised by a combination of circular and translational shearing. That is, the circular shearing failure plane joins the translational shearing failure plane induced in the breccia. At a much steeper angle of say 70°, the failure path is almost identical to the condition prior to inclusion of brecciated rock, implying a negligible influence, which is reflected in the FoS being almost equal.

Orientation of breccia

The emplacement of the breccia into the carbonatite complexes is of interest to understand how it would have a bearing on the stability of the pit wall. From the quantitative analysis results, regardless of the angle at which the breccia is orientated, its mere existence reduces the stability performance of the pit wall but as the dip angle of the breccia gets gentler, the impact becomes enormous. At the dip angles of 70°, 60° and 50° the FoS slightly reduces at OSA of 40° and 41° with the 70° orientation having almost the same FoS value as prior to the inclusion of the brecciated rock section (see Figure 6). However, at steep slope angles, that is to say 43° and 45°, the stability performance of the pit-wall significantly reduces with the 50° orientation registering a sharper drop, and the FoS values fall

further below the threshold at all simulated pit heights. When the breccia is emplaced at gentler angles, i.e., 30° and 40°, the stability of the pit-wall falls below the benchmark value of mine stability at all slope angles (40°–45°). Thus, to attain a good performance of the slope in this condition it would require safeguarding the slope toe against the breccia position by ensuring that there is an optimal buffer zone.

Thickness of the brecciated zone

The thickness of the brecciated rock appears to have an equivocal influence. On a steep slope angle (45°), at breccia dipping angles of 60°, 70° and 30°, the thickness has a fair influence because the slope stability value reduces, though not quite prominent. However, at dip angles between 50°–40°, the impact on the pit slope performance becomes significant (see Figure 7). This can be ascribed to the increased weak surface area within the translational failure plane trajectory, which adjoins the nascent circular shearing trajectory. However, on gentle slope angles, that is to say 40° and 41°, the impact of breccia is negligible at all dipping angles of the breccia as shown in Figure 7. We can thus deduce that thickness of the brecciated rock has a considerable impact at moderately gentle angles of the emplaced breccia with steep angles, in this case study at 43° and 45°, otherwise it would not have a significant influence on the stability performance of the appropriately optimised gentle slopes, that is, 41° for this study case.

Displacement pattern

The study also assessed the influence of brecciation on pit wall displacement. In this case, the 45° OSA at 300 m was used as a research case study. The trend of total displacement is presented in Figure 8 and Figure 9.

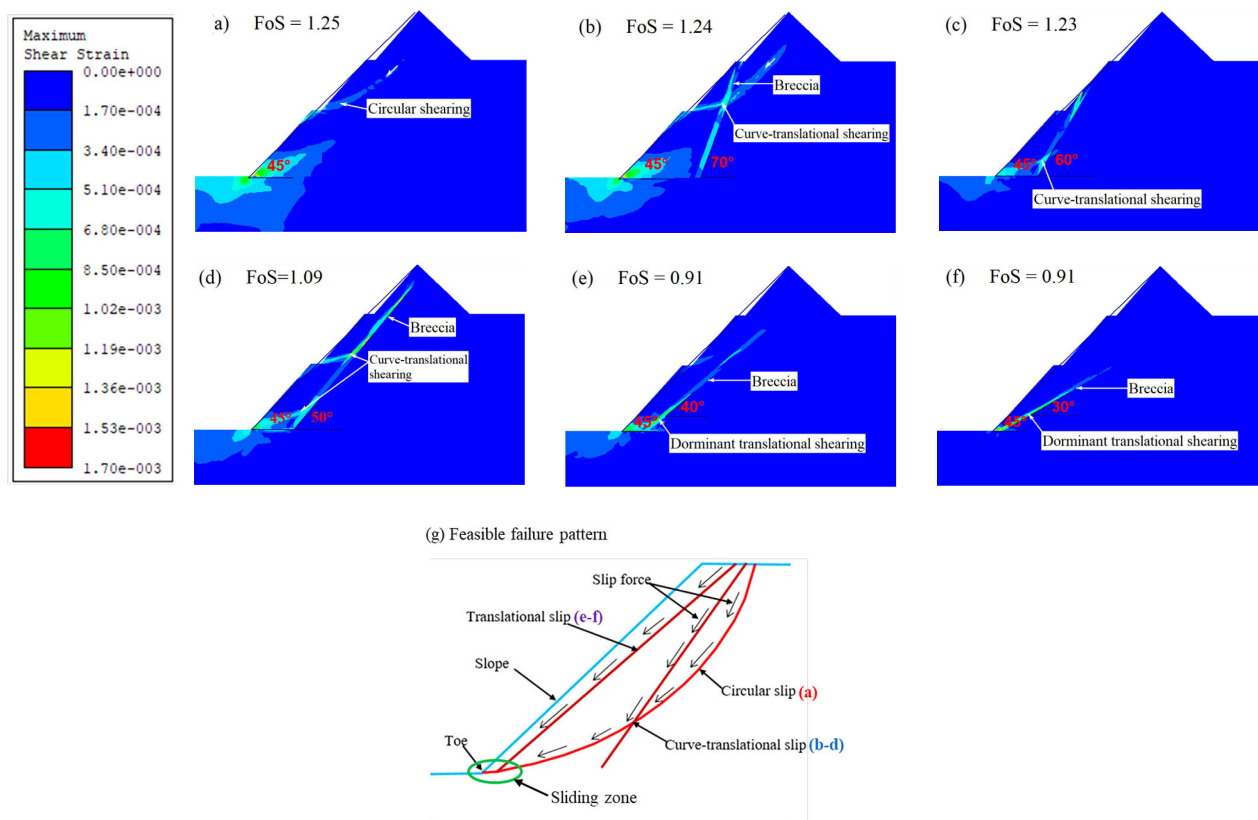


Figure 5—Pit wall stability conditions under 10 m brecciated unit

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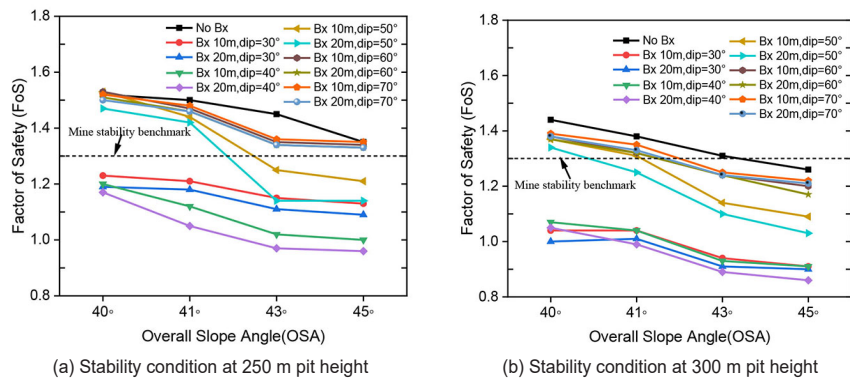


Figure 6—Stability conditions with and without a brecciated zone

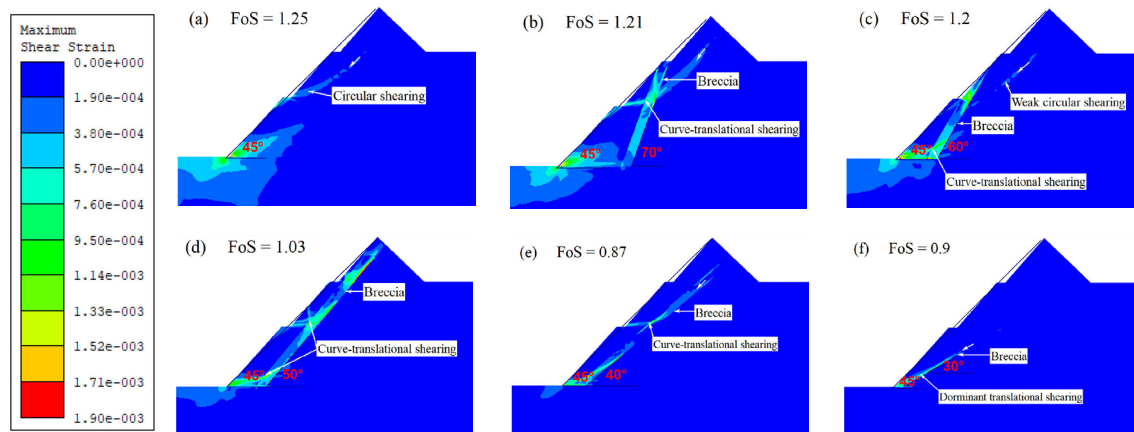


Figure 7—Pit wall stability conditions under 20 m brecciated unit

It can be seen from the Figures 8 and 9 that the orientation of the breccia has an apparent control on the movement of the geological materials on the slopes. Prior to the introduction of the breccia, the peak displacement is in the last excavation phase close to the toe of the slope where the shearing stress and strain is concentrated. When the breccia is introduced, the peak displacement at steep dipping angle of breccia locates in the upper section of the slope where the brecciated section is emplaced. This phenomenon can be identified at 50°, and 70° but in the case of 60° the peak displacement is down to the slope toe due to minimal impact of the breccia at an intersection with the slope face. At gentle dip angles of the breccia where translational shearing strain is predominant, the peak displacement is at the slope toe with an evident trajectory provided by the brecciated zone. With respect to brecciation extent, the change in the thickness of the breccia to 20 m (Figure 9) slightly changes the impact area but the section of the peak displacement remains the same with 10 m breccia thickness (Figure 8). From the analysis, it can be deduced that the displacement trajectory of materials on the pit walls is controlled by the orientation of the brecciated section in the rock mass rather than the thickness.

Impact of breccia position from the slope toe

As a parametric analysis, the study evaluated the impact of the position of the breccia and the pit wall with reference to the slope toe. In this regard, the position of the breccia was changed from the initial position by a factor of 10 from 10 m to 50 m. The initial positions of the breccia with respect to the angle of orientation were 10 m at the most gentle dip angle and 90 m at steeper dip angles, respectively.

For qualitative analysis, four scenarios were identified when the position of the breccia was changed. The first scenario is when the dip of the breccia is at an angle of 30° as presented in Figure 10. As would be anticipated, as the emplacement position of breccia is increased away from the pit wall, the stability performance of the slope increases. At an increase of 10 m, the FoS was observed to be 1.08 and at 50 m increase the FoS improved to 1.21 representing a 12% change in FoS. Basically, moving the dipping brecciated section minimises the effect of translational shearing strain within the breccia because the buffer zone between slope toe and breccia increases. This trend was similar to the 40° dip angle of the breccia. On the contrary, in the second case where the dip angle of breccia is 50°, the stability trend is dissimilar.

As shown in Figure 11, when the position of the breccia is moved 10 m away from the slope, the performance of the slope begins to decline and at 50 m increase, the stability further declines. The FoS after a 10 m increase is 1.36 from the initial 1.39, and at 50 m the FoS reduced to 1.26. The reason for this trend is that the breccia wholly locates immediately behind the pit wall, thereby creating an extended plane of translational shear failure plane, which weakly joins up with the circular shear failure plane. This was observed only for gentle slope angles of 40° and 41°. However, at relatively steep slope angles, i.e., 43° and 45°, the pit wall stability performance improved as the position of breccia increases away from the pit wall.

In this third scenario, it can be observed that when the slope angle is steepened, the breccia locates closer to the pit wall. This provides the conditions for the curve-translational potential slip as the circular shearing failure path combines with the translational shearing failure path. When the breccia is moved further away from

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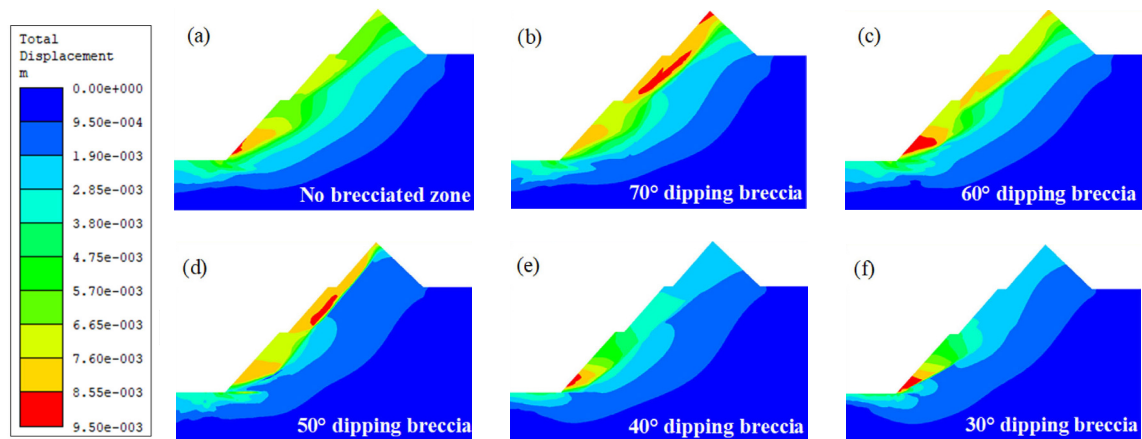


Figure 8—Pit wall displacement under 10 m brecciated unit

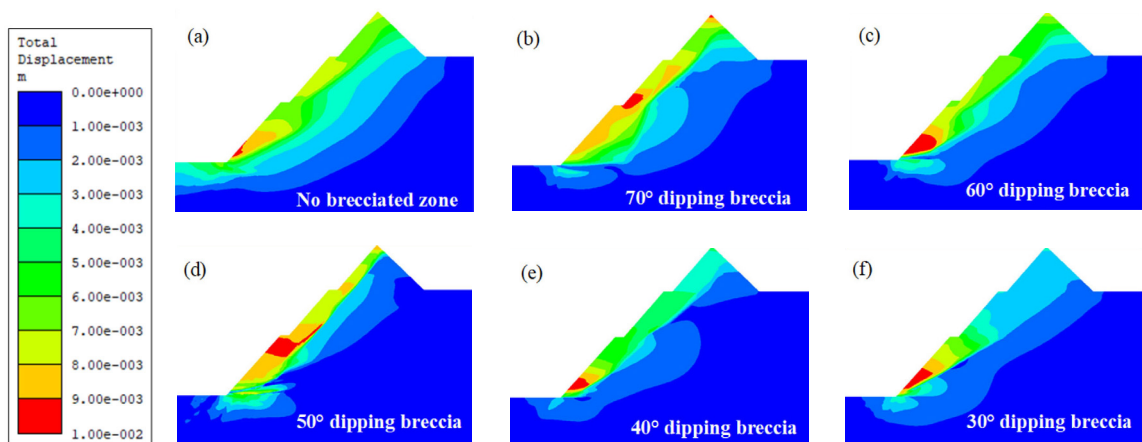


Figure 9—Pit wall displacement under 20 m brecciated unit

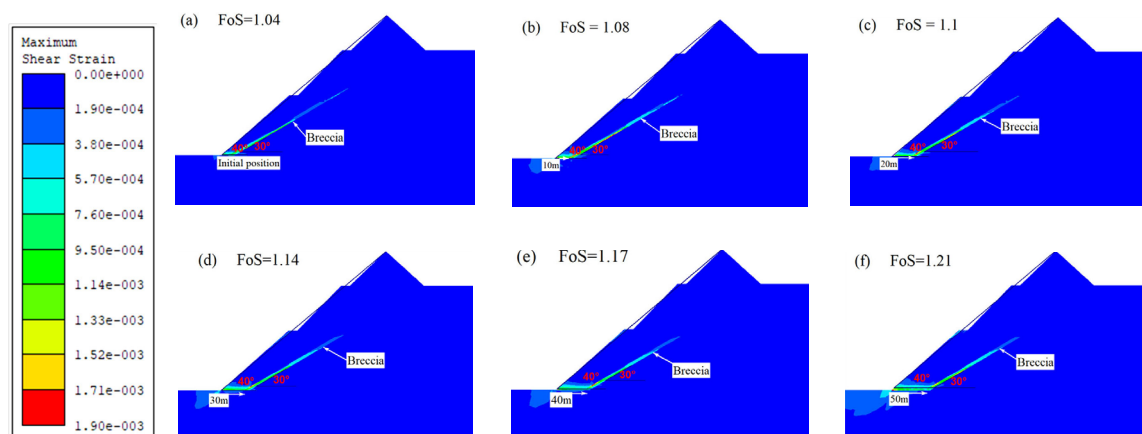


Figure 10—Pit wall stability with respect to the position of breccia at a dip angle of 30°

the initial position, especially at ≥ 30 m, the circular shearing failure path and the translational shearing failure path become disjointed, as shown in Figure 12.

This phenomenon reduces the combined circular and translational shearing impact in the pit wall, which implies a discrete influence of the shear paths and the stability performance of the slope is enhanced.

In the fourth scenario, which is shown in Figure 13, it can be noted that a steep dip angle of the breccia at 70° barely has an effect on the stability of the pit wall when the position of the breccia is

changed. Quantitative results presented as a summary in Figure 14 show a similar pattern at 60° dip angle of the breccia. In both cases, the safety factor remained almost the same. Thus, it can be deduced that in steeply dipping breccia, the translational shear impact within the damaged rock section is minimal and also at the designed slope angle part of the breccia is truncated.

In situ stress regimes and brecciation

Rock masses are inherently inhomogeneous and geological features such as breccias can greatly change the stress field, which can have

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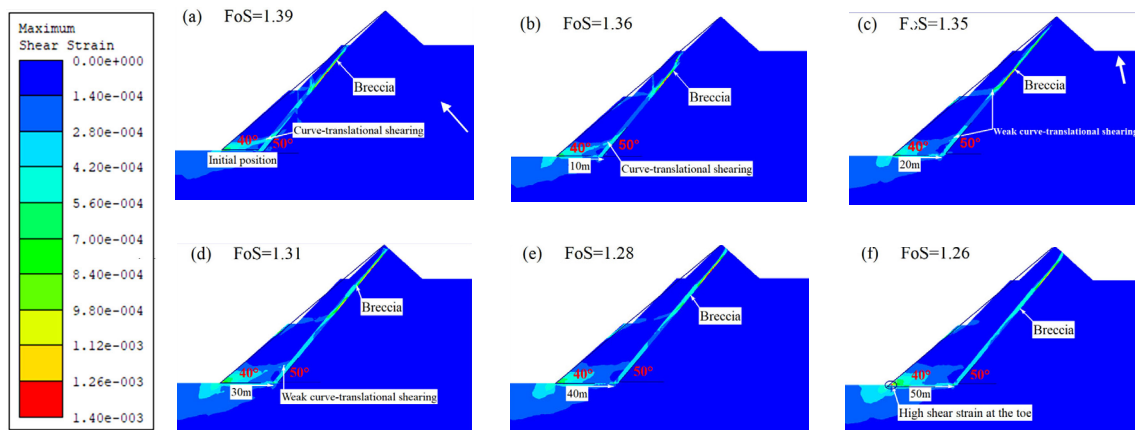


Figure 11—Pit wall stability with respect to the position of the breccia at a dip angle of 50° with slope angle of 40°

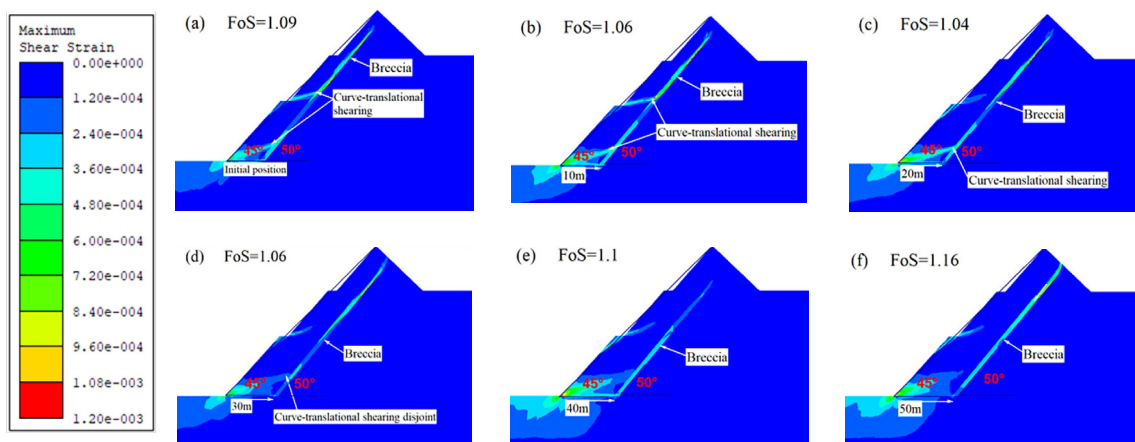


Figure 12—Pit wall stability with respect to the position of the breccia at a dip angle of 50° with a slope angle of 45°

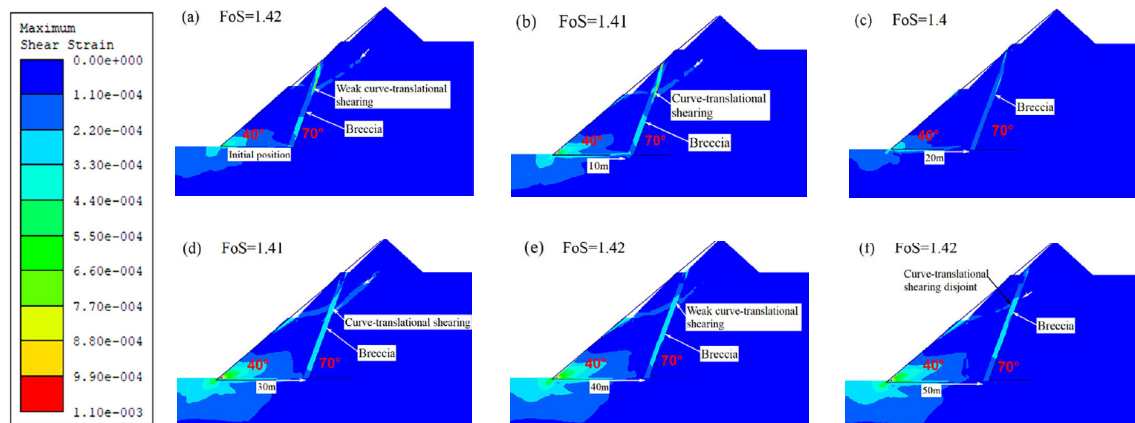


Figure 13—Pit wall stability with respect to the position of the breccia at a dip angle of 70°

a bearing on the stability of the excavation. To comprehend the impact of the interactions between the stress regimes and breccia, simulations were undertaken at different stress ratios. The analyses involved scenarios of high horizontal and vertical stress regimes. The research case studies for analyses were selected at slope angles of 40° and 45° with the dip of the breccia at 50° at a GSH of 300 m. The results of high horizontal stress ratio are presented in Figure 15 and Figure 16. It would be anticipated that high horizontal stress could lower the performance of the pit wall as the induced stress gets redistributed to the excavated section. However, the existence of the breccia close to the slope appears to increase the performance of the slope. As shown in Figure 15 and Figure 16, stress magnitudes

tend to be greatly dissipated, and stress orientations rotate as much as the dip angle of the breccia on crossing it. The changing of the direction of stress is manifested in the shear strain failure path along the breccia. At a stress ratio of $k=1$, the shear strain is concentrated at the toe of the slope and there is a weak adjoining of circular and transformational shear path. This combination evidently lowers the stability performance of the pit slope. However, when the vertical stress is reduced as horizontal stress increases, the horizontal stress gets redistributed and changes its orientation and aligns with the breccia dip. Thus, the breccia acts as a buffer to the slope and the shear strain at the slope toe is dissipated rendering the slope performance enhanced.

Stability design of slopes in carbonatite complexes characterised by brecciation

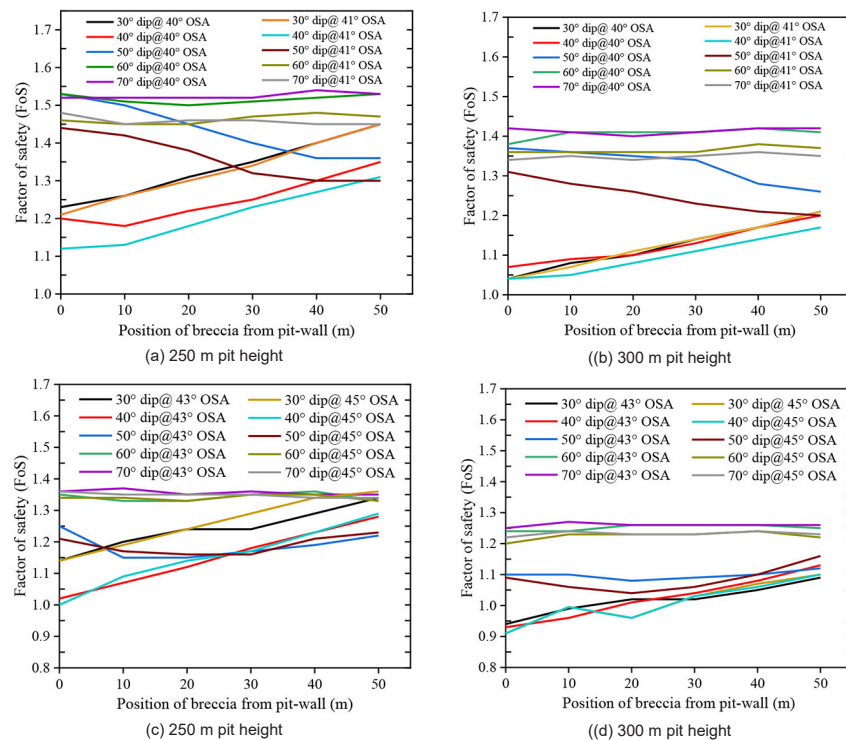


Figure 14—Summary of stability conditions of the pit wall with respect to the position of the breccia

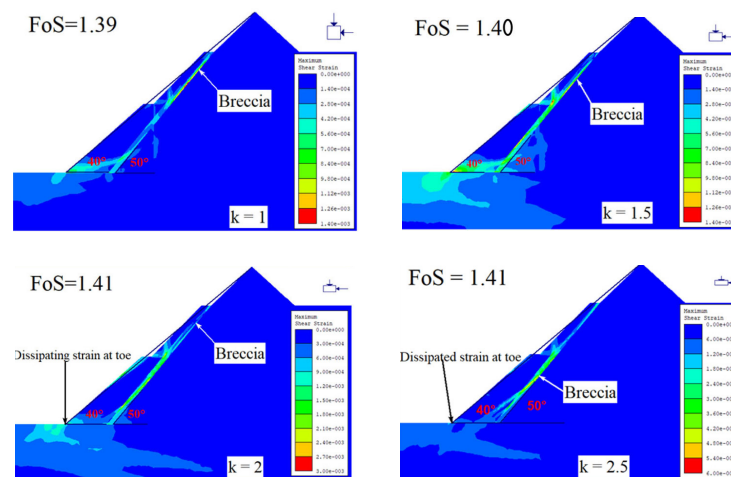


Figure 15—Shearing pattern under high horizontal stress conditions for 40° at 300 m pit height

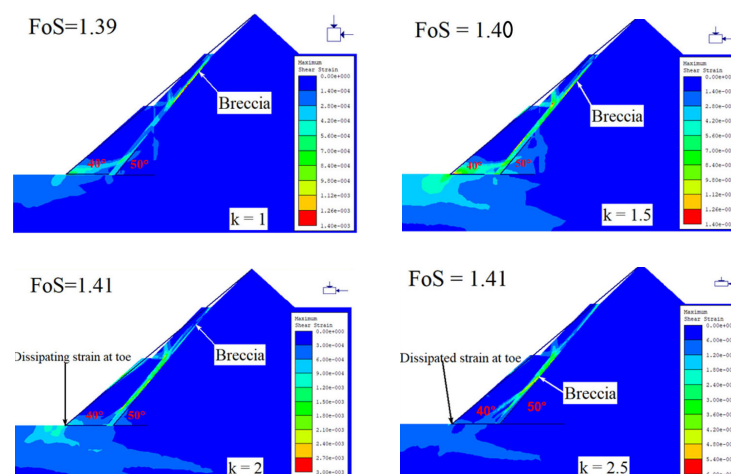


Figure 16—Shearing pattern under high horizontal stress conditions for 45° at 300 m pit height

Stability design of slopes in carbonatite complexes characterised by brecciation

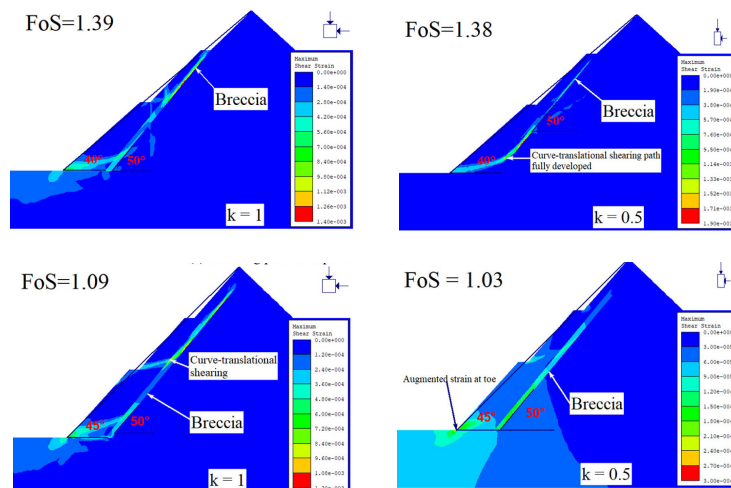


Figure 17—Shearing pattern under high vertical stress conditions

On the contrary, a high vertical stress regime slightly reduces the slope stability performance as shown in Figure 16. The FoS at a gentle slope angle of 40° reduced from 1.39 to 1.38 and at a steep angle of 45° the FoS decreased from 1.09 to 1.03. However, it must be noted that the mechanisms leading to low stability performance of the pit slopes is different at gentle and steep angles. On gentle slopes, it can be observed that the mechanism involves adjoining of the circular and translational shear failure paths, which causes potential curve-translational failure. On the other hand, at steep slope angles, the mechanism does not involve adjoining of circular and translational shearing failure path but rather distinct translational failure path and the intensification of shear strain at the toe of the pit slope. The concentration of the strain at the toe basically minimises the bearing capacity of the toe to the overlying burden, hence reduced stability performance. Although, the African average regional stress is determined to be at $k = 1.5$ as presented in the work of (Stacey, Wesseloo, 1998), the regional tectonic stresses may vary from one area to another depending on structural setting. Thus, the results of $k = 0.5$ are significant to anticipate this phenomenon in normal faulting predominated areas.

Countermeasures

In general, it is noted that the existence of the breccia poses a threat to the stability of the pit slope and an intervention is necessary to counter its impact. A range of innovative and effective methods of rock reinforcement and artificial support have been widely used in civil engineering and underground mining applications but hardly in open pit mines (Martin, 1987). The stabilisation of slopes in mining presents a distinct range of issues and challenges from those in civil engineering. Read and Stacey (2009) articulate that in mining, the economics and practicality of artificial support are affected by the larger volumes of rock to be supported. Generally, the length and height of slopes in mining are often much greater, and the service life of artificial support is often short, especially where a number of different cutbacks are to be undertaken. Experience from different projects (Martin, 1987) has demonstrated that slopes approximately 100 m high were the maximum that could be artificially supported with 30 m long cable bolts but reported subsequent failure of a large number of anchors due to tension. Beyond the 100 m height, failure occurs behind the supported volume, creating larger, deeper seated masses, which are more difficult to control (Read, Stacey, 2009). From this background,

in large open pits, for global wall reinforcement to attain stable slopes with aggressive wall angles could be challenging, if not unachievable.

Thus, from a series of analyses executed and presented in a summarised graph in Figure 14, a pattern of failure with respect to the slope toe was observed and an approach is suggested to deal with the breccia in slope design. The proposal is based on the relationship of FoS, excavation depth, and the position of the in situ damaged rock. In this proposition, it is recommended that for OPM design in brecciated rock masses, the ratio of at least 1:5 between the breccia distance from slope toe of the pit limit and pit depth should be adopted to counter the impact of the breccia. For instance, at the pit depth of 100 m, a distance of 20 m between the slope toe and breccia should be left as a buffer, while at 250 m, the pit limit should be designed such that the slope toe is 50 m from the breccia and at 300 m pit depth the slope toe should be at 60 m.

If the brecciated unit is within or close to the pit limit, a deliberate effort must be made to mine out or truncate the breccia because it has the capability to cause instability when there is a load above it. The ultimate intention is to increase the resisting forces along the translational shear plane generated within the damaged rock section. Furthermore, the traditional approach of making the slope gentle could be a more pragmatic remediation that could be applied in the event of the shallow angle emplaced breccia in the rock mass. Based on this case study, the stable performance of the pit slopes at the GSH of 300 m would be assured at 38° and 36° OSA for a breccia emplaced in the pit wall at 40° and 30°, respectively. The intervention obviously implies an increase in the stripping ratio for the mine, but it can prove a necessary step if undesirable risks, which could render operations utterly uneconomical, were to be sidestepped.

Conclusion

In this study, the stability conditions and deformation behaviour of the geological units on the pit slopes were evaluated by considering the existence of breccia. This was achieved by numerical methods carried out with a finite element code using Phase2 v 7.0 software. The analyses were performed in elasto-plastic state with a Mohr-Coulomb constitutive model and failure criterion. The analysis shows that the competency of the carbonatites can permit the overall slope designs to be developed at steep angles, 45° - 50° at shallow depth ≤ 250 m, but caution has to be taken at greater depth

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and when weak rock sections due to brecciation are considered. Basically, as observed, the existence of breccia in carbonatite complexes has the capability to reduce the stability performance of the excavated pit wall and the enormity of the impact increases at the gentle dip emplacement angle in close proximity to the slope toe, hence, slope angle optimisation could aid in finding a poise between safety and mining economic benefits. In the case of the study area, the OSA of 41° is recommended as an optimal design at a GSH of 300 m. Regarding the breccia, the ratio of 1:5 between the breccia distance from slope toe of the pit limit and pit depth is advocated to counter the impact of breccia and if breccia is within or close to the pit limit, a deliberate effort must be made to mine out or truncate it. However, this conservative design could be adjusted to a flexible design in the course of operations as more geotechnical and geological data regarding the breccia is collected. Furthermore, the traditional approach of making the slope gentler could be a more pragmatic remediation that could be applied in the event of the gentle dip angle of emplaced breccia in the rock mass.

Conflict of interest

The authors declare no conflict of interest regarding the publication of this paper.

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