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https://hdl.handle.net/2324/5208232

出版情報：Bulletin of Engineering Geology and the Environment. 81, pp.494-, 2022-11-08. Springer Nature
バージョン：
権利関係：

Slope Design in Brecciated Carbonatite Complexes under High Stress Regimes

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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 Mn-Fe 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 phase^2 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 angle 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°. On the contrary, at the dipping angle of 50° the performance of slope reduced, and at steeper angle >50° 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. If the breccia is within or close to the pit limit, a deliberate effort must be made to mine out or truncate it.

Keywords: 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, has 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 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 & 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 on 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 siscussed by Brideau et al. (2009) presented in a summarised form in Table I.

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).

Table I

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 studies have investigated on the control of folds and faults, shearing and clay-infill in joints on the stability of rock slopes. A study by Bye & 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 localized high plastic shear strain and high extensional train around the fault (Severin 2017; Stead & Wolter 2015). Del Rio et al. (2021) studied that active faulting induces deep-seated gravitational slope deformation (DGSD) leading to slope failure characterized by large volume landslides in mountain belts worldwide. Additionally, Stead & 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 3- 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 stabilty 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) approch 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 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 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 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. At various localities, the basement complex is overlain by 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 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 corresponded to the faults interpreted from the ground magnetic. 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.

Figure 1

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 grain matrix and occasionally vitreous matrix which may or may not resemble the composition of rock fragments (Shukla & Sharma 2018). These rock masses can be identified in different geological settings mostly associated with various ore types. In carbonatite complexes, breccia is a common structural feature. Shukla & 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, two phenomena 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 responsible for the generation of the breccia. On the other hand, tectonic disturbances resulting from fault movements also can account for the brecciation as the area is located in rifting setting with potentially high-stress 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 as presented in Figure 2.

Figure 2

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 masses behave 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 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 Phase^2 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 (see Figure 3). 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 depth within the bounds of 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 done in three sequential stages. Three cases were generated with respect to the conceptual extents of the damaged rock section. In the first case, shear strain behaviour on the pit slope was investigated without including the damage section. The second scenario incorporates the 10 m brecciated rock section and the last case having a 20 m thickness of brecciation. The 10m brecciation thickness is considered the closer representation of the damaged zone for the study site. The emplacement of the breccia is estimated to be dipping at roughly $\geq$ 50° 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 from 30° to 70° at an equal interval of 10°. The material properties used in this simulation are given in Table II.

Table II

Figure 3

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 slope 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 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 OPM, (Adams 2015; Read & Stacey 2009; 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 2D numerical modelling in an out of the plane mode, the benchmark FoS tolerable is 1.3.

The qualitative analysis of the influence of breccia is presented in Figure 4 and Figure 5, and a quantitative summary is presented in Figure 6. The research object of the qualitative analysis presented only covers the GSH of 300m at a slope angle of 45°. On the other hand, the quantitative analysis caters for all the pit heights and slope angles. From Figure 4 and Figure 5, we notice 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 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 a gentle angle 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 slipping 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 path is characterized by a combination of circular and translational shearing. That is, the circular shearing failure path joins up the translational shearing failure path 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 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 dipping angle of the breccia gets gentler, the impact becomes enormous. At the dipping 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 (Figure 6). However, at steep slope angles viz. 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.

Figure 4

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 index of slope stability reduces though not quite distinct. However, at dipping angles between 50° - 40°, the impact on the pit slope performance becomes significant (see Figure 5). 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 angle, viz. 40° and 41°, the impact of breccia is negligible at all dipping angles of the breccia as shown in Figure 6. We can thus deduce that thickness of the brecciated rock has a considerable impact at moderately gentle angle of the emplaced breccia with steep angles, in this case study at 43° and 45°, otherwise would not have a significant influence on the stability performance of the appropriately optimised gentle slopes, 41° for this study case.

Figure 5

Figure 6

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 object. The trend of total displacement is presented in Figure 7 and Figure 8. It can be seen from the figures 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 intersection with the slope face. At gentle dipping angle 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. On another note, the change in the thickness of the breccia slightly changes the impact area but the section of the peak displacement remains the same. 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.

Figure 7

Figure 8

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 dipping angle and 90 m at steeper dipping angle respectively. The qualitative results of the parametric analysis performed are given in Figure 9, Figure 10, Figure 11 and Figure 12, and the summary is given in Figure 13. Four scenarios were identified when the position of breccia was changed. The first scenario is when the dipping of the breccia is at the most gentle angle 30° as presented in Figure 9. As it 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 gentle dipping brecciated section minimizes 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° dipping angle of breccia. On the contrary, in the second case where the dipping angle of breccia is 50° the stability trend is dissimilar.

Figure 9

As shown in Figure 10, when the position of 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 path which weakly joins up with the circular shear failure path. 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 as presented in Figure 11

Figure 10

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 the initial position, especially at ≥ 30 m, the circular shearing failure path and the translational shearing failure path become disjointed. This phenomenon reduces the combined circular and translational shearing impact in the pit wall, hence the disjoint implies a discrete influence of the shearing paths and the stability performance of the slope is enhanced.

In the fourth scenario, which is shown in Figure 12, it can be noted that a steep dipping 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. A similar pattern is noticed at 60° dipping angle of breccia. In both cases, the safety factor remained almost the same. Thus, it can be deduced that in steeply dipping breccia, the translational shearing impact within the damaged rock section is minimal and also at the designed slope angle part of the breccia is truncated.

Figure 11

Figure 12

Figure 13

In situ Stress Regimes and Brecciation

The intrusions of carbonatites tend to be closely associated with the extensional tectonic settings like the East African Rift System (EARS) where the Songwe Hill and the Ol Doinyo Lengai carbonatite complexes are located. The strong affinity of carbonatite complexes to rifting settings implies intense magmatic activity where the intrusions are related to large igneous provinces. The carbonatite rock masses are inherently inhomogeneous and geological features such as breccias can change the stress field, which can have a bearing on the stability of slopes. To comprehend the impact of the interactions between the stress regimes and breccia, simulation was undertaken at different stress ratios. The analysis involved scenarios of high horizontal and vertical stress regimes. The research objects for analysis were selected at gentle slope angle of 40° and steep angle of 45° with the dip of breccia at 50° at a GSH of 300 m. The results of high horizontal stress ratio are presented in Figure 14 and Figure 15, whereas for high vertical stress regime the results are presented in 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 14 and Figure 15, stress magnitudes tend to be dissipated greatly, and stress orientations rotate as much as dipping angle of breccia on crossing it. The changing of the direction of stress is manifested in the shear strain failure path along the breccia. At stress ration of k=1, the shear strain is concentrated at the toe of the slope and there is a weak adjoining of circular and transformational shearing 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 align with the breccia dipping. Thus, the breccia acts as a buffer to the slope and the shear strain at the slope toe is dissipated making the slope performance enhanced.

Figure 14

Figure 15

On the contrary, high vertical stress regime slightly reduces the slope stability performance as shown in Figure 16. The FoS at gentle slope angle reduced from 1.39 to 1.38 and at steep angle 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 slippage. On the other hand, at steep slope angle, 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 minimizes 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 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.

Figure 16

Countermeasures

In general, we note that the existence of the breccia poses a threat to the stability of the pit slope and an intervention has to be undertaken to counter its impact. The stabilisation of slopes in mining presents a distinct range of issues and challenges from those in civil engineering. Read & 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 has demonstrated that slopes approximately 100 m high were the maximum that could be artificially supported with 30 m long cable bolts. 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). On the contrary, artificial support like rock or cable bolts, earth and rock anchors applied to rock slopes is relatively common practice in civil engineering applications where excavations are of moderate dimensions and the costs of structures (roads, bridges, high-rise buildings) are high compared to the excavation and support costs. From this background, in large open pits, 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 13, we observed the pattern of failure with respect to the slope toe 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, we recommend that 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 breccia. For instance, at the pit depth of 100, the 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 far from the breccia and at 300 m pit depth the slope toe should be at 60 m. If the breccia 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 shearing 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° OSA for a breccia emplaced at gentler angle. The intervention obviously implies an enormous increase in the stripping ratio for the mine, but it may prove a necessary step if undesirable risks, where the breccia is not truncated, were to be sidestepped.

Conclusion

In this study, the stability conditions and deformation behaviour of the geological materials on the pit slopes were evaluated by considering the existence of breccia. This was achieved by numerical methods carried out with finite element code using Phase^2 v 7.0 software.The analyses were performed in elasto-plastic state with Mohr-Coulomb constitutive model and failure criterion. The analysis shows that the competency of the carbonatites can permit the overall slopes designs to be developed at steep angles 45º - 50° at shallow depth ≤ 250 m, but caution has to be taken at greater depth 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 in them and the enormity of the impact increases at the gentle dipping emplacement angle in close range 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 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 operation 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 dipping angle of emplaced breccia in the rock mass.

Conflicts of Interest

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

Acknowledgement

The authors express their sincere gratitude to Mkango Resources Company for providing the data for the study to materialise.

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