MINE DESIGN AND SLOPE STABILITY ANALYSIS FOR CARBONATITE DEPOSITS UNDER HIGH-STRESS CONDITIONS IN GREAT RIFT VALLEY AREA, AFRICA

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論 文 名：MINE DESIGN AND SLOPE STABILITY ANALYSIS FOR CARBONATITE DEPOSITS UNDER HIGH-STRESS CONDITIONS IN GREAT RIFT VALLEY AREA, AFRICA（アフリカ大地溝帯の高地圧下におけるカーボナタイト鉱床の採鉱設計と斜面安定解析に関する研究）

区　　分：甲

論　文　内　容　の　要　旨

Rare earth elements (REE) are presently in explosive demand due to their application in high-tech devices such as computer memory, rechargeable batteries, autocalytic converters, super magnets, and mobile phones. But the economically exploitable REEs tend to occur in limited geological environments and carbonatites are highly likely to be potential hosts of REE, hence they are a specifically targeted rock mass. Malawi, Africa is among the few countries endowed with exceptional carbonatite intrusions and among the intrusions, Songwe Hill has proven economical for mine development. Since the deposit at the site is near the surface, open-pit mining (OPM) has been proposed for the development of the deposit. However, OPM is beleaguered with stability problems culminating in failures due to principally poor designs that overlook some integral components. One overlooked aspect as a mining bottleneck is *in situ* stress, which has only been considered in underground mining based on the premises that the stress environment in OPM is dilationary other than confining and that failures are gravity-driven. Nevertheless, stress regimes, particularly in tectonically active regions like the East African Rift Valley system, can inevitably play a key role in the failure process on excavations. On the other hand, despite carbonatites being competent rock mass, they are characterised by in situ damage due to brecciation and have multi-faceted angular blocks generated by fractures and discontinuity sets. The failure mechanisms in such hard rocks entail initiation and progression of failure along the existing weakness planes, even in intact states. In order to develop an optimal mine design in such carbonatite deposits under high stress conditions in Great Rift Valley area, an integrated approach entailing rock mass characterization, kinematic and numerical methods was applied as a design guideline. The main contents of the research can be summarized as follows:

Chapter 1: Introduces the significance of REE, their production and consumption disequilibrium, and the geological environments of occurrence. The emplacement of the unique Songwe carbonatite complex, which is a host of REE, is also discussed. The carbonatite complex was basically intruded into the country rock through magmatic activity from an alkaline rich magma. The later stages of Songwe carbonatite complex emplacement, is featured with carbonatite transition from a magmatic to a hydrothermal regime where expelled fluids lead to fenitisation, fluorite and Mn-Fe veining disseminating throughout the rock mass. The chapter also gives the background of the research, research objectives and methods.

Chapter 2: To evaluate the geological and geotechnical conditions of the carbonatite rock mass. A field survey revealed distinctive features that the carbonatite complex is characterised by *in situ* rock damage due to brecciation, which is a result of hydro-fracturing involving high-pressure fluids due to tectonic forces trending along pre-existing plane of weakness, and has high discontinuity frequency per unit area occurring parallel to the horizontal stress direction. To understand the rock quality in relation to mining, qualitative and quantitative rock mass classification systems, namely Geological Strength Index (GSI) and Rock Mass Rating (RMR) respectively, were applied to describe the rock mass. Based on the evaluation, the carbonatite rock masses can be described as competent with RMR class II rating 60-74, and GSI value range of 55-69. In spite of the competency, they tend to have multi-faceted angular blocks generated by three or more discontinuity sets, which pose a potential for structural controlled instabilities.

Chapter 3: Gives a discourse on the potential modes of slope failure in the discontinuity dominated carbonatite rock mass as revealed in Chapter 2, performed using the kinematic approach. The kinematic checks were executed using Dips V6.0 software designed to analyze features related to engineering analysis of rock structures. The outcome of the analysis indicates that the carbonatite rock masses have high potential of planar slope instability at steeper angles, for the case of Songwe at 45°. Since carbonatites occur in tectonically active regions, the high horizontal stresses acting parallel to discontinuity planes intersecting the orientation of the slope faces could act as a catalyst to failures. In order to minimize the risk of failure, slope angle optimization to a gentler angle can be adopted as a counter-measure. For the case study area, the risk of failure was observed to be high in the south and east sections of the pit, hence a slope angle optimization to 40° was suggested, which could reduce the risk of failure to safety by 44%. Meanwhile, relatively steep angles in the opposite sections are implementable at safety viz. 43° in the north and 42° in the west sections.

Chapter 4: Presents analyses of stability conditions and deformation behavior of pit slopes under prevailing high stress conditions in Great Rift Valley area in order to come up with ultimate optimal design guidelines. This was achieved by numerical methods carried out with finite difference method and finite element method codes using FLAC^{3D} V5.0 and Phase^2 V7.0 software respectively. The analyses were performed in elasto-plastic state with Mohr-Coulomb constitutive model and failure criterion. Due to the competency of the rock mass, analysis shows that overall slopes can be developed at steep angles of 45-50° at a shallow depth of ≤ 250 m, but caution has to be taken at greater depths and when discontinuities are predominant. With regards to *in situ* stress, a qualitative evaluation of the stability state through shear strain analysis reveals that the pit wall stability conditions could be compromised under high-stress regimes such that non-uniformity of stress state leads to the development of a secondary potential failure surface (PFS) in addition to the primary circular PFS which has been the sole engineering concern in slope stability analyses. Furthermore, the displacement values, at the state of stress equilibrium (k=1), were found to be almost four times lower than at k=2.5 and two times lower when k=0.5. This demonstrates that non-uniform high stresses could indeed adversely affect pit wall performance. To test the criticality of the risk to failure, the strain criterion to failure, which is a ratio of the maximum deformation and the height of excavation, was applied and the shear strain rate indicates that the rock mass slopes may not be significantly endangered, a phenomenon accredited to its competence. For instance, the maximum possible strain rate of 0.04%, which is below the lower bound strain at collapse of 0.1% was recorded in the study case. In terms of *in situ* rock damage, the existence of breccia in the competent rock mass has the capability to reduce the stability performance of the pit wall and the enormity of the impact increases at gentle dipping angle in close range to the slope toe. However, as the initial position of breccia increases away from the pit wall, the stability performance increases at gentle dipping angles, namely 30° and 40°. On the contrary, at the dipping angle of 50° the performance of slope reduces, and at steeper angle of >50°, the impact becomes negligible. Thus, for OPM 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 breccia is within or close to the pit limit, a deliberate effort must be made to mine out or truncate it.

Chapter 5: Covers the aspect of mining economics. The objective is to give a forecast of the project performance in order to know the value of investing in the REE mining venture. The assessment is based on economic performance indicators namely; Net Present Value (NPV), Internal Rate of Return (IRR), and profitability index (PI). The results show that steeper slope angles have higher prospects of profit due to low stripping ratio than gentle angles but their safety is unreliable. This requires the mining trade off between resource recovery and safety. For the case study project, the indicators at a discounted rate of 10% indicate that the deposit can be developed at a profit with NPV, IRR and PI at US$658.54 million, 33%, and 2.6 respectively at the optimised slope angle that gives favourable equilibrium on recovery and safety. On a different note, sensitivity analysis of the mining parameters show that mineral price volatility is very sensitive based on project performance, hence at the core of the decision to mine the REE or not.

Chapter 6: Gives the mine excavation plan and design. Basically, final slope design has to consider the balance between mining profits and safety. In carbonatite deposits it has shown that overall slopes can be developed at steep angles at shallow depth yielding high returns. But, since the contact zones of carbonatites and fenite may be fractured and also the existence of brecciation coupled with high tectonic stresses, the ultimate slope design at greater depth ought to be at the optimal gentle angle. In the case of Songwe Mine, considering the topography and the mineralization extent, the extraction sequencing is suggested to commence from the sloping face of the hill where ore hosting rock is exposed to the surface to shorten payback period and then create subsequent push backs in a top-down approach targeting an OSA of 40° that guarantees geotechnical safety in high RL section in which case stripping will be required.

Chapter 7: Concludes the findings of this research.