ROCK MASS CLASSIFICATION OF LIMESTONE CONSIDERING KARST FORMATION AND ITS APPLICATION TO EVALUATION OF SLOPE STABILITY IN OPEN PIT LIMESTONE QUARRY

オニャンゴ, ジョアン アティエノ

出版情報：Kyushu University, 2023, 博士（工学）, 課程博士
バージョン：

（様式２）

氏　　名：Onyango Joan Atieno（オニャンゴ ジョアン アティエノ）

論文題名：ROCK MASS CLASSIFICATION OF LIMESTONE CONSIDERING KARST FORMATION AND ITS APPLICATION TO EVALUATION OF SLOPE STABILITY IN OPEN PIT LIMESTONE QUARRY（石灰岩のカルスト化を考慮した岩盤分類法と石灰石鉱山における採掘斜面安定性評価への適用）

区　　分：甲

論 文 内 容 の 要 旨

Quarrying in a weak carbonate rock mass environment laden with karst cavities, near a large water body, and also surrounded by human settlements requires extra care to ensure sustainable mining practices. It is therefore imperative to gain an understanding of the deformation behavior of the rock mass to design reasonable slopes for optimum recovery and ensure minimal hazards during operations. At Vipingo coral limestone quarry, instabilities such as planar failure, bench collapse/subsidence, and sinkholes, have occurred and caused some disruption of operations. This thesis presents findings related to the physico-mechanical characteristics and deformation characteristics of a weak coral limestone rock mass. Weak rocks possess intermediate characteristics between cohesive soils and strong rocks due to their relatively young age in the geological timescale. The weak carbonate rock mass structure is laden with numerous small-sized karst hollows which are often hard to identify by geophysical survey methods and are also difficult to model due to their unpredictable spatial and temporal distribution. Other than large caves, current numerical modeling and analysis software don't have a means of modeling karst voids and cavities. Rock mass classification schemes that guide designs in rock masses based on geotechnical characteristics have not made much provision for karst features inherent in carbonate rock masses. The complexity of the carbonate rock mass and the prevailing seepage conditions around the quarry motivated the research into an easier-to-implement numerical modeling approach for karst, which can be applied in the improvement of the accuracy of geotechnical models. This study advances the understanding of the behavior of coral limestone and provides a means of factoring in the karst defects of the rock mass into the numerical analysis models for slope design purposes. The study also gives directions on identifying potential failure mechanisms from the stress analyses. Following the stability assessment and observations of instability risks at the quarry, an optimal slope design is proposed as well as measures for maintaining the integrity of the slopes. Recommendations have been made in the form of guidelines for the mining of coral limestone near a large water body.

The findings from this research work are included in the following chapters:

Chapter 1: This section gives a background to the study. It touches on the mineral resource potential of Kenya and the prevailing conditions around mining practices. Karst formation processes and the main challenges encountered in coral limestone quarrying are discussed. The unresolved issues that led to interest in this study are mentioned, and the objectives of the study, the methodology, and the thesis structure are outlined.

Chapter 2: Detailed background information is given about the physical location, geology, hydrogeology, and a background to the quarry operations at Vipingo. The quarry is situated in an area of active karstification, with variable geological from the north to the south. The deposit is of the Pleistocene age, with high carbonate content of up to 95% and textural porosities manifesting in density values as low as 0.5 g/cm^3 for in situ average of around 1.5 g/cm^3. A field survey identified geohazards such as undercutting, planar and circular failures, toppling, rock falls, bench collapse, and sinkholes, which are linked to the karst processes. Large caves exist but small-sized karst features are more numerous. A slope model from RS2 software confirms that the current analysis tools do not accurately model the rock mass and thus do not represent the karst which is seen to impact the slope stability. The study delves into coming up with a means of modeling small-sized karst hollows to determine the threshold for concern regarding the impact of karst hollows on slope stability as well as identify probable failure modes instigated by karst hollows.

Chapter 3: This section evaluates the rock mass properties of the Vipingo quarry. Laboratory test results for the physical and mechanical properties of the intact rock are presented. The Geological Strength Index (GSI) method for classifying the carbonate rock masses is employed to assess the rock mass quality. The average rock density is 2.17 kg/m^3 in dry conditions and 2.29 kg/m^3 in wet ones. The average Uniaxial Compressive Strength (UCS) in dry condition is 17.2 MPa and that in saturated one is 11.4 MPa. The average P-wave velocity is 4.45 m/s while that of the S-wave is 4.41 m/s. This data is a significant contribution to the database of rock properties. This particular information on coral limestone properties will be the first one to be publicly

available. The rock mass is considered weak based on the International Society for Rock Mechanics (ISRM) classification since the average UCS of the intact rock is less than 25 MPa. The rock response to stress is generally elastic-brittle-plastic behavior, a characteristic that is best modeled by the nonlinear Hoek-Brown criterion. The UCS, porosity, and the GSI method for carbonates have been used to describe the rock quality of this rock mass that does not have any noticeable beddings and foliations. The rock mass quality lies between GSI values of 14 and 30.

Chapter 4: This chapter delves into the background of numerical modeling and analysis software for slope stability. The application of the Finite Element Analysis method is discussed as well as the principle of shear strength reduction as used in slope stability analysis. A methodology for modeling small-sized karst hollows is presented, being the Equivalent Porous Method (EPM). The type of data required for developing the EPM and the data collection method is presented. A mathematical expression is derived from the method of slices to represent the equivalent porous medium by a slice with a cavity. The process of modeling the karst hollows in MATLAB is presented, followed by the procedure for adding the karst matrix to a geotechnical model for slope stability analysis. A circular cross-section is settled upon for modeling the karst geometry based on the fact that circles limit errors in the geometry and only one dimension which is the equivalent diameter is sufficient to model them. The model is simplified as much as possible by reducing the number of vertices to ease the computational burden of a bulky model. The most important aspect of the karst hollows that has been considered in this study is the total area of the voids per unit area of the slope, which is termed the karst hollows density.

Chapter 5: A review of the major factors affecting the stability of slopes in weak rock masses is conducted followed by parametric Finite Element analysis to evaluate the response of slopes to the karst hollows of various sizes and densities. The significance of pore pressure is analyzed by considering seepage conditions from groundwater, the adjacent ocean water, and rainfall. The karst hollows have been modeled on a slope using the equivalent porous medium approach. With the presence of karst in the slope, the slope behavior varies greatly depending on the dimensions and density of the karst. When the slope has more small-sized karst hollows, a general strength reduction due to the presence of weak points in the rock mass is observed. For large karst hollows, the stability of slopes depends largely on the occurrence of the hollows in relation to the slope face. The analysis of seepage conditions corroborates research results of weak rock being very sensitive to pore pressure. Of the seepage conditions analyzed, the impact of the ocean water becomes significant when the bench level is more than 10 m below sea level and reduces as the excavation face moves far from the shoreline. In the case of groundwater, the slope stability is greatly compromised as long as the excavation goes below the water table. Quarrying below the water table therefore requires sufficient interventions to maintain the stability of the slopes. The seepage condition and the karst structure of rock mass are therefore crucial factors that must be considered in the slope design.

Chapter 6: This section assesses the stability condition of Vipingo quarry slopes under the current design where the benches are vertical. The geotechnical model is built using the karst matrix geometry as well as the seepage boundary conditions. Slope stability is assessed based on safety factor, shear strain contours, plasticity, and stress trajectories. The slopes are not safe under the current design since the safety factor is less than 1.0, with the lowest safety factor registered on the benches. Tensile and shear failure are concentrated around the karst hollows, and the highest shear strains are on the slope toe and shear planes develop on the bottommost bench. Increasing the density of smaller hollows results in a relatively small change in the factor of safety whereas larger hollows result in significant strength reduction if the large hollow is close to the slope face. The slope safety factor generally increases with increasing GSI and the small karst hollows have no significant impact on stability in strong rock of GSI above 40. Smaller hollows are likely to trigger planar or circular failure and rock falls. Larger hollows are mostly responsible for bench collapses and subsidence. The inference of failure modes from the stress analysis results serves as a verification of the numerical model for karst.

Chapter 7: It is ascertained that the quarry slopes are not safe for operations, therefore this chapter is concerned with determining the optimum bench configurations for safe quarry operations. The bench design is guided by safety considerations in bench height and practicability in bench width. The recommended Overall Slope Angle (OSA) for quarry operations are 55º, 46º, and 41º for the northern, central, and southern regions respectively. For long-term stability, the OSAs are 53º, 44º, and 38º for the northern, central, and southern regions respectively. A 10m bench width is recommended for practical bench widths between 3m and 5m. Long root vegetation has been suggested for improving the shear strength of the rock mass and consequently the slope stability. The slopes will be protected from pore pressures by using geofabrics or turf grass to keep water off the slope faces. Perforated drainage pipes will be installed at the bottom bench to direct water away from the slope and into the drainage channels that naturally drain into the ocean. It is concluded that quarrying in weak coral limestone adjacent to a large water body is doable at any depth and in proximity to the ocean provided that measures are in place to direct water away from the slopes.

Chapter 8: This section summarizes the findings from the research and proposes recommendations for future research.