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Stress-strain state index of the Imex quarry rock mass, Bioko Island, Equatorial Guinea

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Abstract

Purpose. The purpose of this research is to determine the index of the rock mass stress-strain state in the Imex quarry, Bioko Island, Equatorial Guinea.

Methods. To determine the number of required samples by the method of stratified random sampling, the t-Student principle is used. The physical-mechanical properties of rocks have been determined by tests and methods of saturation, pycnometry, hydrostatic weighing, axial loads and clock-type indicators. The classification of the degree of weathering has been carried out to assess its impact on the physical-mechanical properties of rocks and rock mass on the basis of direct observation in different areas of the studied rock mass. To determine the rock mass stress-strain state, the Hoek-Brown failure criterion is used, including laboratory tests to determine the models, dimensions and shapes of ruptures.

Findings. Significant changes in rocks, high values of stress and weathering, which generate distributions of new forces in the rock mass and originate instability and large deformations, as well as a high porosity index, average values of compressive strength and a high value of elasticity modulus, have been revealed. Significant differences in the degree of weathering in the prevailing zones, from insignificant values of weathering in the northern areas to moderate values of weathering in the south, have been confirmed.

Originality. Information is presented on the physical-mechanical properties, the degree of weathering and the stress-strain state index of the rock mass in the Imex quarry, Bioko Island, Equatorial Guinea.

Practical implications. Knowledge about the rock quality, management and implementation of technological processes during operation can be used as a useful material for the construction industry.

Keywords: *rock mass, weathering, stress, instability, deformation*

1. Introduction

The stresses in a rock mass are conditioned by the weight of the overlying rocks and the geological resistance of the rock mass. Both of these indicators are closely related to a series of elements and parameters that are key to the mechanical behavior of rocks and rock mass [1]. The first indicator includes the physical-mechanical properties that integrate values to quantitatively determine the rock mechanics. The second indicator is weathering, which makes it possible to characterize the real state of rocks and its influence on the global behavior of the rock mass.

According to [2], this stress field is altered by rock cutting, tectonic activity, and the presence of weathering agents. In some cases, this alteration introduces stresses that can exceed the rock strength [3].

On the one hand, the weakening of adjacent rocks within the boundaries of a slope or rock cut leads to instability and deformations, which are manifested in progressive slope closure and the rock detachment. In extreme cases, they are manifested as rock bursting, which occurs when the rock is fragile and subjected to high stresses [4], [5].

On the other hand, the presence of rock weathering changes the natural stress field and introduces a new one, which may exceed its load-bearing capacity and subject it to a load higher than the natural one, where these conditions affect its properties [6]. Therefore, in order to anticipate possible deformations and instability problems in the mass, it is necessary to determine the mechanical rock behavior that integrates the stress-strain state and the degree of rock weathering [7].

The stress-strain state linked to the degree of the mass weathering has always been focused when developing the models of rock destruction in tunnels and, to a lesser extent, in quarries. This constitutes a problem that manifests itself in the loss of rock stability in the slopes and permanent deformations when the rock mass is exposed to stresses associated with the mechanical rock behavior in quarries [8], [9].

Therefore, the purpose of this work is to determine the index of the mass stress-strain state according to rock weathering degree in order to contribute to the knowledge of the rock mass mechanical behavior in the Imex quarry, located in the African continent, specifically in the southern part of Bioko Island, province of Luba, Equatorial Guinea Figure 1.

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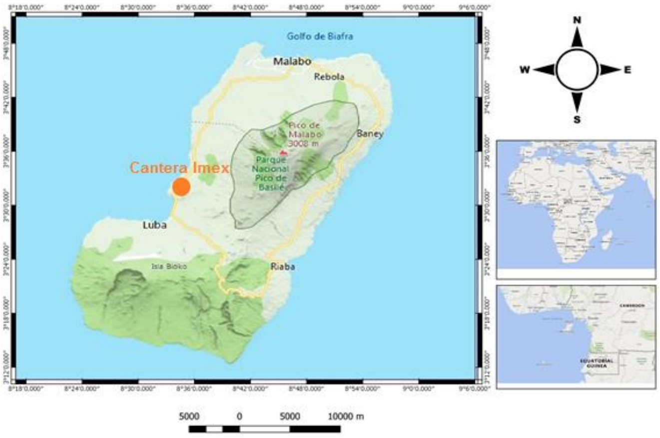

Figure 1. Geographic location of the Imex quarry, Equatorial Guinea

The Imex quarry is located between the villages of Basacato del Oeste and Long Street, about 32 km from the city of Malabo. The quarry is very young. It has been exploited for 6 years, has a length of 79 hectares and geographical coordinates: 3°34′51″ N, and 8°36′44″ E; at an altitude of 46 m above sea level.

Bioko Island originated at the end of the Primary and the beginning of the Tertiary Era, marked by the separation of the African Plate from what is today the South American Plate when moving west. This separation, which began in the Secondary Era, have led to a vast deep earth's crust fracturing, causing magma to rise to the surface, and later resulted in the birth of four islands in the Gulf of Guinea or the Gulf of Biafra [10].

Bioko Island is formed along the Cameroonian Volcanic Line, one of the main geological faults of the African continent, which extends from the Atlantic Ocean to Cameroon. This line includes other volcanic islands in the Gulf of Guinea such as Annobón, São Tomé and Príncipe, as well as the massive Mount Cameroon volcano [11], [12].

The island is composed almost entirely of rocks of volcanic origin, mostly basaltic, of various phases of volcanism, where volcanic eruptions are accompanied by finer materials preserved between the various volcanic lava flows present in the modern soils [13].

The Imex quarry deposit consists primarily of basaltic rocks deposited by volcanic lava flows, especially rich in calcium and magnesium, where volcanic eruptions are accompanied by fine materials preserved between various volcanic flows.

The geological conditions are similar to the rest of the quarries in this southern band, originating in the basaltic lava family with a porphyritic texture and a generally prismatic structure, with a rough and uneven surfaces. The quarry is 227 m long, marked by a single face 7.8 m high.

The purpose of this work is to determine the index of the mass stress-strain state in the rock mass of the Imex quarry, Bioko Island, Equatorial Guinea.

2. Methods

2.1. Determining the physical-mechanical properties of intact rock

Physical and mechanical properties are determined by direct and indirect methods using indexes and empirical correlations, which allow obtaining quantitative values of intact rock.

To determine the values of the physical-mechanical rock properties, such as porosity, volumetric mass, density, axial compressive strength and elasticity modulus (Young's modulus), sampling is conducted. It is based on assumptions that take into account almost the same characteristics throughout the deposit and extent, slope height and length of the deposit in the prevailing sectors (North and South of the Imex quarry).

To determine the required number of samples, stratified random sampling is carried out using the t-Student principle based on the following equation taken from [14]:

$$\left(\frac{Z_{\alpha/2} \cdot Y)}{d}\right)^2, \quad (1)$$

where:

$Z_{\alpha/2}$ – value of the normal table (Gaussian normal distribution).

Y – typical rock mass behavior;

d – maximum permissible error.

Ignorance of the rock mass behavior (Y) in the above equation leads to the interactive pilot sampling process for sigma estimation ($\overline{X}$) using of electronic tabulators, which allows calculating the number of representative samples.

To determine the arithmetic mean value ($\overline{X}$) of the samples, the equation proposed by [15] is applied:

$$\overline{X} = \sum \frac{X_i}{n}, \quad (2)$$

where:

X_i – sample value.

In order to determine the physical-mechanical rock properties (porosity, density, volumetric mass, compressive strength and elasticity modulus), tests have been conducted in the laboratory of the National University of Equatorial Guinea (UNGE), under the ASTM-D2216 standard and using tests and methods of saturation, pycnometry, hydrostatic weighing, axial loads and clock-type indicators.

2.2. Assessing the degree of weathering

The classification of the degree of weathering is carried to assess its effect on the physical-mechanical properties of rocks and the rock mass (porosity, deformability and the strength). For this purpose, the classification in [16] is used, which is essentially based on discoloration and decomposition or disintegration of the rock, based on direct observation in different sectors of the mentioned rock mass and the core fracturing to analyze the continuity of rock weathering.

2.3. Stress-strain assessment

To determine the stress-strain state of a rock mass, which allows predicting and assessing mechanical and mathematical behavior, as well as stress-strain models of rocks, the criterion from [17] is used due to its wide application for determining stresses and strains of systems. This method includes laboratory tests to determine the models, dimensions and rupture shapes by changing the rock mass mechanical behavior.

Parameters such as Geological Strength Index (GSI), intact rock constant (m_i), reduced value of constant mi (m_b) and constants (s and a) dependent on the rock mass characteristics are estimated using the RocData computational software. The disturbance factor, taken according to [8], allow determining the equations of the rock mass stress state:

$$\sigma_1 = \sigma_3 + \sigma_c \left(m_b \frac{\sigma_3}{\sigma_c} + s \right)^a , \quad (3)$$

where:

σ_1 and σ_3 – highest and lowest principal stresses at the moment of rupture (MPa);

σ_c – uniaxial compressive strength of the rock (MPa);

m_b, s and a – rock mass constants, calculated according to [17]:

$$m_b = m_b \cdot e^{\left(\frac{GSI-100}{28-14D}\right)}; \quad (4)$$

$$s = e^{\left(\frac{GSI-100}{9-3D}\right)}; \quad (5)$$

$$a = \frac{1}{2} + \frac{1}{6}\left(e^{-\frac{GSI}{15}} - e^{-\frac{GSI}{20}} \right) \quad (6)$$

For an intact rock block, it is assumed: s = 1 and a = 0.5. D is the rock mass disturbance factor, for slopes the value of D varies from 0.5 to 1.0 (depending on the used method of rock removal), the value 1 is taken.

The rock mass deformation modulus is determined from the following expression:

$$E_{rm} = E_i \left(0.02 + \frac{1 - \frac{D}{2}}{1 + e^{\frac{60+15D-GSI}{11}}} \right), \text{ MPa}, \quad (7)$$

where:

E_i – Young's modulus of the intact rock (MPa);

D – factor of disturbance or alteration of the rock mass.

3. Results and discussion

3.1. Physical-mechanical properties of rocks

The average values of physical-mechanical properties, statistically analyzed according to the t-Student principle distribution, are shown in Table 1, where basaltic rocks from the Imex quarry are presented. It can be observed that the mass has a high porosity index (7.0 %), average values of compressive strength (166.4 MPa) and high elasticity modulus [9], [18].

Table 1. Physical-mechanical properties of rocks

Porosity, %	Volumetric mass, g/cm^3	Density, g/cm^3	Compressive strength, MPa	Elasticity modulus, MPa
7.0	1.6	2.5	166.4	1893.6

3.2. Grade of weathering

It has been confirmed from the studies carried out in the northern and southern sectors of the Imex quarry (the most predominant sectors), that the rock mass belongs to Grade II, slightly weathered, and in the northern and southern sectors – to Grade III, moderately weathered according to [5], [16]). This considerably increases the rock porosity and the rock mass deformability while decreasing the rock strength; it also influences the rock discoloration, as seen in Figure 2.

3.3. Stress-strain state of the rock mass

The quantitative and qualitative values of the parameters for determining the stress-strain state index of a rock mass are ranked within the intervals described in [10], depending on the GSI value calculated from the assessment of the surface state of joints (roughness, grade of weathering and filling of fractures).

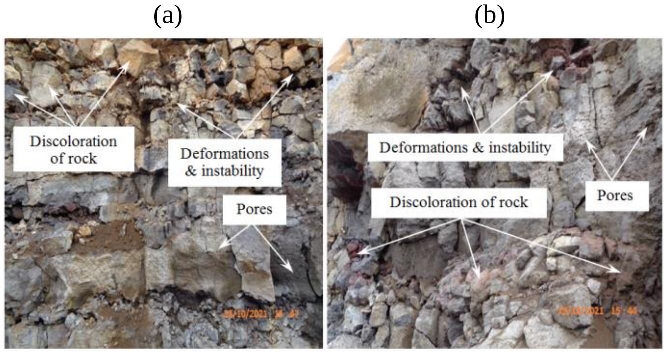

Figure 2. Effects of weathering on rocks: (a) Northern sector; (b) Southern sector

Table 2 shows the results of the parameters that allow calculating the stresses and deformations of the mass (occurring in the northern and southern sectors of the Imex quarry). It can be observed that for the basaltic rock belonging to the northern sector, GSI and m_b have slightly higher values than those of the southern sector. However, the "s" coefficient is 2.3 times higher. The remaining parameters (D, a and E_i) are similar for both sectors.

Table 2. Parameters for determining the stress-strain state of the mass (Imex Quarry)

Kind of rock (grade of weathering)	Calculation parameters					
	GSI	D	m_b	S	a	E_i, MPa
Basalt, slightly weathered	77	1.0	4.836	0.0216	0.501	1893.6
Basalt, moderately weathered	72	1.0	3.383	0.0094	0.501	1893.6

The GSI, m_b, s, a and E_i parameters, presented above, allow obtaining quantitative values of principal stresses (σ_1 and σ_3) and the rock mass deformation modulus (E_{rm}) (Table 3).

Table 3. Stresses and deformability of the rock mass (Imex Quarry)

Kind of rock (grade of weathering)	Stress estimation criteria (σ_1 and σ_3), MPa	E_{rm}, MPa
Basalt, slightly weathered	$\sigma_1 = \sigma_3 + 166.4\left(0.0216 + \frac{4.836\sigma_3}{166.4}\right)^{0.501}$	23.65
Basalt, moderately weathered	$\sigma_1 = \sigma_3 + 166.4\left(0.0094 + \frac{3.383\sigma_3}{166.4}\right)^{0.501}$	17.74

Figures 3 and 4 show the curves of stress-strain state of rocks and a possible rupture zone between principal stresses. It has been noticed that when parameterizing the resistance curve of maximum and minimum stresses, one more curvature (shear and normal stresses) is formed between the vertex and the rupture zone, depending on the rock mass stress-strain state [17].

On the one hand, the mechanical behaviour of rocks and the mass depending on the stress-strain index shows that in slightly weathered rocks (Fig. 3) the maximum and minimum stresses, to which they are subjected, range from 71.03 to 4.734 MPa. However, the shear and normal stresses are 20.98 and 12.19 MPa, respectively. The deformation modulus takes the value 23 657.56 MPa. On the other hand, in moderately weathered rocks (Fig. 4), the maximum and minimum stresses are: 58.98 and 4.783 MPa.

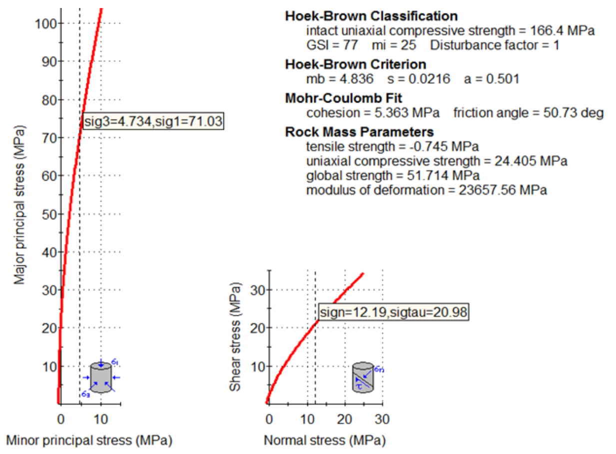

Figure 3. Stress-strain state curves of slightly weathered rocks

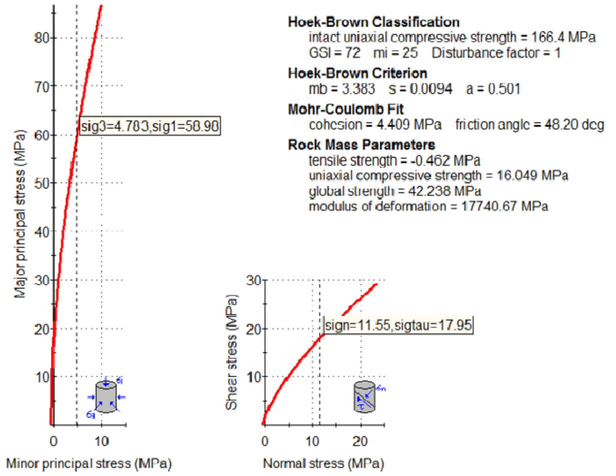

Figure 4. Stress-strain state curves of moderately weathered rocks

The shear and normal stresses are: 17.95 and 11.55 MPa, respectively. The rock deformation modulus in this sector takes values of 17 740.67 MPa, in both cases relatively high, according to [19], [20].

The obtained values of stresses and deformation modulus indicate the presence of changes in the stress-strain state of the rock mass as a result of the high rate emerging stresses and the degree of weathering. This generates a modification or distribution of new forces in the mass, resulting in changes in the mechanical behavior of the mass and producing a series of internal effects such as displacements, instability and large deformations. All this has a significant impact on the mass state, causing effects similar to those in the research [7], [20], [21].

4. Conclusions

The analysis of stress-strain state index of rocks and rock mass, carried out by means of stress-strain curves using the RocData computational software in the Imex quarry, indicates significant changes in the mechanical behavior of the rock mass, such as high values of stresses and rock weathering. These factors generate the distribution of new forces in the rock mass and originate instability of rocks in the slopes, as well as large deformations in the rock mass, which corresponds to the operating site of the studied quarry.

In the rock mass of the Imex quarry, tests conducted in the laboratory of the National University of Equatorial Guinea (UNGE) have revealed a high porosity index, average compressive strength values and high elasticity modulus of intact rocks, which gives the rocks a heterogeneous and anisotropic character, conditioned by the presence of factors in the rock mass weathering and nature of rocks.

In the two most predominant zones of the rock mass of the Imex quarry, significant differences in the degree of weathering, from slightly weathered in the northern sector to moderately weathered in the southern sector, have been confirmed by direct observations. This greatly affects the physical-mechanical properties of rocks and the mechanical behavior of the rock mass, causing rock discoloration and an increase in porosity and elasticity modulus, as well as loss of rock strength in the rock mass.

It has been determined that the studied rock mass has varied mechanical behavior in the northern and southern sectors, as well as varied degree of weathering in each sector. This is manifested in the volume of porosity, deformations, discoloration of rocks and instability of the mass. At the same time, the northern sector (slightly weathered) is more unstable and with greater rock discoloration, while, the southern sector (moderately weathered) is less unstable, but with a higher degree of deformations and rock porosity.

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Індекс напружено-деформованого стану гірського масиву кар'єру Імекс, острів Біоко, Екваторіальна Гвінея

А.А. Нгема, І.Р. Гонзалез, М.К. Піре

Мета. Визначення індексу напружено-деформованого стану гірського масиву на основі комплексу аналітичних та лабораторних досліджень для умов кар'єру Імекс, острову Біоко, Екваторіальна Гвінея.

Методика. Для визначення кількості необхідних вибірок методом стратифікованої випадкової вибірки використовується t-критерій Стьюдента. Були визначені фізико-механічні властивості гірських порід за допомогою випробувань і методів насичення, пікнометрії, гідростатичного зважування, осьових навантажень та індикаторів годинникового типу. Проведено класифікацію ступеня вивітрювання для оцінки його впливу на фізико-механічні властивості гірських порід і масиву на основі безпосереднього спостереження на різних ділянках досліджуваного масиву гірських порід. Для визначення напружено-деформованого стану масиву гірських порід використовується критерій руйнування Хоека-Брауна, що застосовується у лабораторних випробуваннях для визначення моделей, розмірів і форм розривів.

Результати. Були виявлені значні зміни гірських порід, високі значення напружень і вивітрювання, які породжують розподіл нових сил у масиві та викликають нестійкість і великі деформації, а також високий індекс пористості, середні значення міцності на стиск і високе значення модуля пружності. Були підтверджені значні відмінності ступеня вивітрювання в переважаючих зонах, а саме, від незначних значень вивітрювання у північних районах до помірних значень вивітрювання на півдні.

Наукова новизна. Встановлено фізико-механічні властивості, ступінь вивітрювання та індекс напружено-деформованого стану гірського масиву в кар'єрі Імекс, острів Біоко, Екваторіальна Гвінея.

Практична значимість. Проінформованість про якість гірських порід, управління та запровадження технологічних процесів під час експлуатації може бути корисним матеріалом для використання у будівельній галузі.

Ключові слова: *гірський масив, вивітрювання, напруження, нестабільність, деформація*