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MOHR-COULOMB CRITERION FOR THE ASSESSMENT OF MELONERAS ROCK MASS

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ABSTRACT

Rock mass comprises elastic and plastic zones. Both could experience stress depending on the level of perturbation provoked by mining activities. Intact rocks are most proper to be used to model the elastic part and the understanding of the stress state will aid in preparing suitable rock stability and explosive programs. The Mohr-Coulomb (MC) failure criterion established a set of linear equations in major stress space that describes the conditions for which an isotropic material will fail. Two major rock components of the Meloneras rock mass were identified and core samples of each of the rock types were taken to Geomineras and Hydraulic Resources laboratories to determine the physical and mechanical properties of each of the rock types. Mohr-Coulomb graph was drawn based on its equation and the stress analysis of the serpentine and gabbro rock mass was realized. It was deduced from this study that the state of stress (□,□) of the serpentine rock of Meloneras mine is (4.41MPa, 15.93MPa) with the fracture plane oriented at 74.5o and that of gabbro rock is (33.96MPa, 8.00MPa) at 76.5o. Any stress higher than this state will result in rock mass failure. Therefore, the stress state of the Melonera Mine should be used as a basis for the design of the support system and the blasting pattern during construction and extraction activities to ensure excavation stability and an effective production plan.

KEYWORDS: Stress; Mohr – Coulomb; Serpentine; gabro; rock mass

INTRODUCTION

The Mohr-Coulomb (MC) failure criterion established a set of linear equations in major stress space that describes the conditions for which an isotropic material will fail by any effect due to the neglect of the intermediate principal stress (δ_{II}) (Labuz & Zang, 2012). When all major stresses are compressive, laboratory experiments show that the criterion applies reasonably well to rock, in which the uniaxial compressive strength δ_0 is much greater than the uniaxial tensile strength T, e.g. $\delta_0 T>10$. Due to the fact that the theoretical uniaxial tensile strength T_0 predicted from MC is not measured in the experiment, some adjustment is needed. Mohr's condition was founded on the assumption that failure depends only on major stress (σ_I) and minor (σ_{III}), and the shape of the failure envelope, the loci of stress and tension (σ,τ) acting on a failure plane, can be linear or nonlinear while Coulomb's condition was based on a linear failure envelope to determine the critical combination of (σ,τ) that will cause failure on some plane. Meanwhile, the linear failure criterion with an intermediate stress effect was implemented by Meyer & Labuz (2013). The research made by Coulomb proposed the relationship in Eq. 1.

$$|\tau| = C_0\sigma\tan\theta \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Eq. 1}$$

where C_0 is the inherent shear strength otherwise called cohesion (c), and θ, is the angle of internal friction, with the coefficient of internal friction (φ) is tan θ and two material constants. The representation of Eq. 1 in the Mohr diagram is a straight line inclined to the σ-axis by the angle θ. By constructing a Mohr circle tangent to the line (a stress state associated with failure) and using trigonometric relations, the alternative form of equation (I) in terms of principal stresses is obtained.

The degree of correctness of Kupfer-Hilsdorf-Rusch's failure envelope was evaluated (Kupfer, et al., 1969) and that of Mohr-Coulomb failure criteria (Fossen, 2010; Labuz & Zang, 2012) using the research method which involve constructing a Finite Element Model (FEM) program, written in the Microsoft Visual Basic language that incorporated the mathematical formulations of the two failure criteria and was shown that for conventional concretes with a cylindrical compression strength not exceeding 75 MPa, both failure envelopes resulted in the same predicted ultimate load carrying capacity and for compression strengths exceeding this value, the Kupfer-Hilsdorf-Rusch's failure criteria predicted a higher ultimate load due to the confinement effect in bi-axial compression.

Even though the Mohr-Coulomb failure criterion is the most widely used, some Researchers have observed inadequacy in its application. The Coulomb equation seems to be contradictory in that its physics might be obscure and no sliding surface exists in the intact body until the cohesion of rock is broken, thus, the concept of internal friction is unsatisfactory. Some investigators also argued that the conventional interpretation of the Coulomb fracture criterion cannot be correct because there is no slip on the fracture plane until after the fracture (Scholz, 1990; Mogi, 2006). On the other hand, Mogi (2006) expounded a very simple model for the physical interpretation of the Coulomb fracture criterion and showed that the Coulomb-Mohr criterion is not strictly empirical, but that it can be explained by a reasonable physical model. Others argued that there is good agreement between the observed fracture strength of certain brittle rocks and the prediction of the Coulomb criterion, taking the coefficient of internal friction 0.5–1.5; some of these values were, however, higher than the coefficients of sliding friction. Also, in experimental results under a wider pressure range, the strength versus pressure curves of some rocks are markedly concave towards the pressure axis at low confining pressure and near the brittle-ductile transition pressure. So, the Coulomb criterion does not always hold for a wide pressure range, and the strength versus pressure curves are rather expressed by a power function (Mogi, 2006).

Geo-structural analysis of the Meloneras mine

The Meloneras field sector (as shown in Figure 1) is located in the Province of Villa Clara, Cuba and the deposit is found within the rocks of the northern Ophiolithic Complex, which are located on the sedimentary sequences of the continental margin and in turn, are overlaid by the vulcanites of the Cretaceous insular arc in a section of Central Cuba. The deposit is located within a belt of serpentine and serpentinized ultra-mafic rocks (more than 90% of the area) that represent a giant tectonic gap composed of fragments and blocks of rocks of the ophiolithic complex and other rocks included in an intense shale plastic mass, forming the typical serpentine melange. The rest of the area is occupied by macroscopically massive serpentinite wedges or macrobudines and ultramafite bodies or blocks with a lesser degree of serpentinization (mainly peridotites), gabbros, diabases, dacitic porphyries, among others. Among the schistine serpentines, the most abundant are those mainly composed of first and second-generation lizardite serpentinites. It is also the most abundant variety in puddings. In a much smaller proportion, there are varieties of antigoritic serpentinite. The encasing rock of the mineral zone in the Meloneras deposit is found within a wedge or large tectonic scale that extends in an approximate east-west direction with a length of 325 m and a width that varies between 10 and 90 m, composed of massive serpentinites fractured and sometimes strongly tectonized. The wedge widens towards the east like a fan and on the surface, it is divided by a wedge of schistine serpentinite, although in the depth it disappears and the nesting body appears as one. The massive serpentine rocks that make up the embedding body are characterized by the abundance of small bodies, veins, and veins of leukocratic gabbro, whose dimensions range from the first few meters to tens of meters (Orestes et al., 2010).

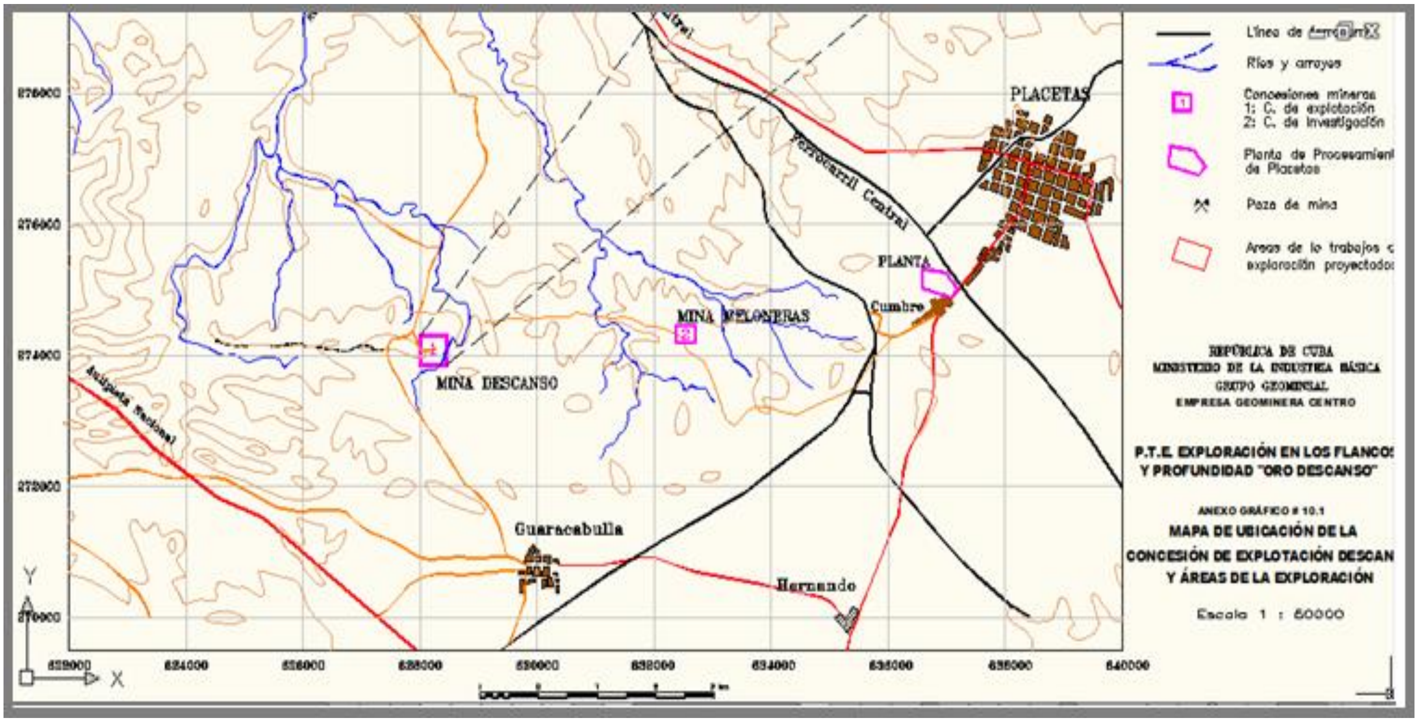

Figure 1. Location map of the Meloneras mines (Source: Geominera del Centro, 2013)

Criteria for the analysis of the stresses that occur in rock mass

During the excavation through rock mass, the alteration of the natural stress field occurs and new ones are induced in such a way that it exceeds its bearing capacity which causes its collapse or makes it work with at a higher load than the natural one. Then, the properties of the rock mass are thereby affected by these conditions. Protodiakonov established the concept of rock strength based on Mohr's theory; the breakdown of the material under the combination of the limit resistance and the limit shear stress (τ, σ) of the intact rock to predict the bearing capacity of the rock mass. However, the rock zone that is already plastic cannot properly represent the stress state of the mass that surrounds the excavation, this constitutes the limitation of the criterion (Martínez, 2011). Deere defined the term Rock Quality Designation (RQD) which describes the quality of the rock in the mass being drilled and to predict its quality, but did not consider its mechanical properties. While the criterion of Boluchof considered the block structure of rock mass, its shale, and monolithic constituents, it valued the parameters that are identified with the coefficient of structural weakening, it considered the anisotropy due to the cracking and the mechanical properties that describe the elastic and plastic behavior of the mass for the stability analysis (Zhang, 2005). To assess the rock mass that surrounds the tunnel, Barton developed the Q system that considered the following parameters: cracking, roughness, crack alteration, groundwater, and SRF (strength reduction factor), which is a reducing factor.

Barton & Bandis (1990) established a model that allows determining the shear stress of a discontinuity that is under the action of normal stress and is based on the parameters of the coefficient of roughness, the compressive strength of the crack wall, and the residual friction angle of the fractures. On the other hand, Barton developed an empirical correlation for the estimation of the unconfined compressive strength of the rock mass (Barton, 2002). At the beginning of the century, Martínez (2002, 2011) developed a forecasting methodology based on Mohr's theory that has given good results to assess the behavior of the rock mass. In this research, the criterion of Mohr and Coulomb was selected to analyze the stress state of the Meloneras mine because it is the most widely used in evaluating the bearing capacity of all kinds of rock mass, although it has limitations that it can only give better results in the confined mass and presents a high error when estimating the plastic zone that shows a non-linear character (Mogi, 2006). The generalized criterion of Hoek et al. (2002) has gotten the solution for the evaluation of the elasto-plastic or plastic behavior of the rock mass and the use of the Mohr-Coulomb criterion is limited to the elastic zone of the mine excavation.

MATERIALS AND METHOD

Serpentine and gabbro rocks were the major components of Meloneras rock mass, observed in the study area. Ten core samples were taken, for each rock type, from the Meloneras Mine's rock inventory and their physical and mechanical properties were determined at the Geomineras and Hydraulic Resources laboratories, both located in *Santa Clara* (Romero et al., 2016) and *Holguín* respectively.

Procedure for the determination of the physical-mechanical properties of the rocks in the Meloneras mine

Specific gravity

The specific gravity (γ_e) test was carried out using the Pycnometric method, the sample weight (G) and the volume (Va) occupied by the solid part of the core samples were measured and Eq. 2) was employed for its calculation.

$$\gamma_e(\mathrm{g/cm^3}) = \frac{G}{V_a} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Eq. 2}$$

Volumetric weight (γ_v)

The Hydrostatic Weighing method was used in this experiment. The mass (m) and the volume (V) of the samples were measured and equation (III) was used for its determination.

$$\gamma_v(\mathrm{g/cm^3}) = \frac{m}{V} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Eq. 3}$$

Humidity (ω)

It was determined by the difference in weights between the sample and the dry sample, under natural conditions. Mathematically it is determined by the following equation:

$$\omega = \frac{g_{1-}g_2}{g_2} * 100\% \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Eq. 4}$$

where,

g_1 is the weight of the sample when wet, (g).

g_2 is the weight of the sample when dry, (g).

Compressive strength (σ_c), Young's modulus (E), and Poisson's coefficient (μ)

Core samples of length (L) and diameter (D) were prepared according to the International Society of Rock Mechanics (1981) standard, where the ratio of the length to the diameter equals 2: 1 (Tavakoli, 1994). During the uniaxial test with the servo-controlled testing machine, the sample was placed in the center of two steel plates that have the same diameter, and the uniaxial compression load was applied continuously and constantly until the sample broke and the total load (Pmax) was measured at the point of failure, the axial (ε_a) and lateral (ε_d) deformation were also measured. Then, the Uniaxial compressive strength, the modulus of elasticity (E) and Poisson's ratio (μ) were determined by Eq. 5, 6, and 7 respectively (Labuz & Zang, 2012).

$$\sigma_c(\mathrm{MPa}) = \frac{P_{\text{máx}}}{A_o} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Eq. 5}$$

For which,

P_{max} is the breaking load,

A_o is the cross-sectional area of the sample.

$$E\ (MPa) = \frac{\sigma_a}{\varepsilon_a} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Eq. 6$$

$$\mu = \frac{\varepsilon_l}{\varepsilon_a} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Eq. 7$$

where σ_a is the axial stress

ε_a is the axial deformation,

and ε_l is the lateral deformation

As it was necessary to use samples with a diameter smaller than 37 mm, Eq. 8 was used to normalize the discrepancy:

$$\sigma_{cD} = \frac{\sigma_{cd}}{D/d^{0.18}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Eq. 8$$

where σ_{cD} is the compressive strength of the largest diameter (D)

σ_{cd} is the compressive strength of the smallest diameter (d)

Tensile strength (R_t)

This index was determined using the Brazilian method, whereby the cylindrical core sample prepared for the test was laid between the planes of a press to subject it to a breaking load (P). The Tensile strength was calculated using the following expression:

$$R_t\ (kgf/cm^2) = \frac{2P}{\pi dl} = 0.637\frac{P}{dl}\ \ldots\ldots Eq. 9$$

where p is the breaking stress of the sample, kgf,

π is 3.142

d is the sample diameter (cm) and l is, the sample length (cm)

Stress analysis using the Mohr-Coulomb criterion

The parameters that define this theory are the limit stresses corresponding to the stress state as well as the limit angle (β_O). This angle is less than $\alpha = (45+Ø/2)$ which theoretically defines the position of the rupture surface, for the uniaxial case. As the stress state increases due to the presence of horizontal stress, βo decreases. It should be noted that the magnitude of the stress state determines the deformation and rupture of the material (Martínez, 2011). With this rupture criterion, the cohesion and the coefficient of friction were estimated by intact rock parameters.

$$T_f = C_i + \sigma_n \tan Ø_i \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Eq. 10$$

where T_f is the shear stress,

C_i and $Ø_i$ respectively are the cohesion and internal friction angle

σ_n is the normal stress in the slip plane

tan $Ø_i$ is the coefficient of internal friction

RESULTS AND DISCUSSION

Tables 1 and 2 present the values of the physical and mechanical properties of Serpentine and Gabro rock mass at the Meloneras Mine. The uniaxial compressive strength of Meloneras mine’s Serpentine rock is 58.05 MPa for saturated sample and 61.19 MPa for dry sample. The tensile strength is 2.93 MPa for saturated sample and 4.66 MPa for dry sample. Its volumetric weight is 2.74t/m3 and the humidity is 0.4 %. On the other hand, Gabbro’s uniaxial compressive strength is 133.7 MPa (saturated sample) and 150.83 MPa (dry sample), and the tensile strength is 8.65 MPa (saturated) and 8.86 MPa (dry). Its volumetric weight is 3.00 t/m3 and the humidity is 0.26. All the above data were based on statistical analysis at 95% accuracy as shown in Tables 1 and 2.

The values shown above reveal that the compressive strength of both saturated rock masses was lower than that of the dry samples which means that the presence of water could weaken the rock strength. Also, gabbro rock is heavier in weight and harder than the serpentine rock.

Table 1: Physico-mechanical properties of the serpentine rock from the Meloneras mine

Rock	Statistical parameters	Uniaxial compressive strength (MPa)		Uniaxial compressive strength (MPa)		Volumetric weight (t/m^3)	w (%)
		Sat	Seco	Sat	Seco		
Gabro	Average $\bar{x}$ for α = 0,95	58.05	61.19	2.93	4.46	2.74	0.4
	Standard deviation	30.00	25.77	0.95	2.12	0.115	0.14
	Minimum value	12.66	12.66	1.18	1.18	2.52	0.2
	Maximum value	97.81	94.37	4.51	7.26	2.84	0.6
	Degree of freedom (n-1)	25	16	9	9	15	7

Table 2: Physico-mechanical properties of gabbro rock from the Meloneras mine

Rock	Statistical parameters	Uniaxial compressive strength (MPa)		Uniaxial compressive strength (MPa)		Volumetric weight (t/m^3)	w (%)
		Sat	Seco	Sat	Seco		
Gabro	Average $\bar{x}$ for α = 0,95	133.7	150.83	8.65	8.86	3	0.26
	Standard deviation	27.77	32.88	1.58	2.49	0.15	0.13
	Minimum value	84.96	85.94	6.18	3.83	2.28	0.1
	Maximum value	182.07	189.63	10.69	10.20	3.21	0.4
	Degree of freedom (n-1)	14	8	9	9	29	23

In Table 3, it can be observed that the values of the elastic properties of gabbro (Young modulus (6768.14MPa), Poisson ratio (0.18), Cohesion (14.76 MPa), Deformation modulus (48696.75MPa)) are greater than that of the serpentine rock (Young modulus (5095.92MPa), Poisson ratio (0.12), Cohesion (5.48MPa), Deformation modulus (38092.57MPa)). Young's modulus depends on the material composition and temperature and entails the rock's ability to withstand the applied load with minimum deformation. Therefore, gabbro can resist greater load than serpentine rock; this was confirmed during the in-situ observation inside the Mine, whereby the serpentine zone was observed to be the most deformed and destroyed, and also, the intermolecular strength within the particles of gabbro is stronger.

Table 3: Values of the elastic properties of Meloneras rock mass

Parameters	**Massive serpentine**	**Gabbro**
Young Modulus (MPa)	5095.92	6768.14
Poisson's ratio	0.12	0.18
Cohesion (rock mass), MPa.	5.48	14.76
Deformation modulus, MPa	38092.57	48696.75

On the other hand, figures 2 and 3 show the Mohr-Coulomb circle envelopes for massive serpentine and gabbro in the dry state respectively. The stress state (σ-τ) coordinates that are under the envelope represent the stable conditions of the rock mass, those that are found upon it represent the limit stress state and those above the envelope represent the condition that cannot be obtained under static loading (Hudson & Harrison, 2000; Hoek, 2007). The rupture plane is oriented at an angle θ (Eq. 11)

$$\theta = 45^0 + \left(\frac{\emptyset}{2}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Eq. 1$$

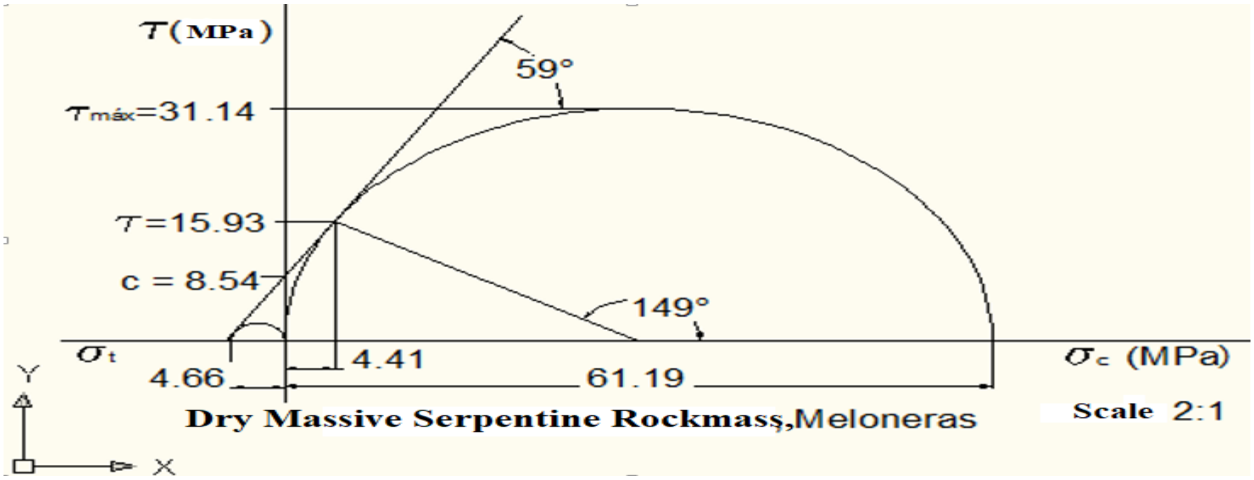

Figure 2: Mohr's circle for the dry massive serpentine, Meloneras mine

In Figures 2 and 3, the cohesive force of massive dry serpentine is 8.54 MPa and that of gabbro is 18.13 MPa which is higher than the former, these represent the maximum tangential stress that can be mobilized on any plane of the rocks when normal effective stress on that plane is zero.

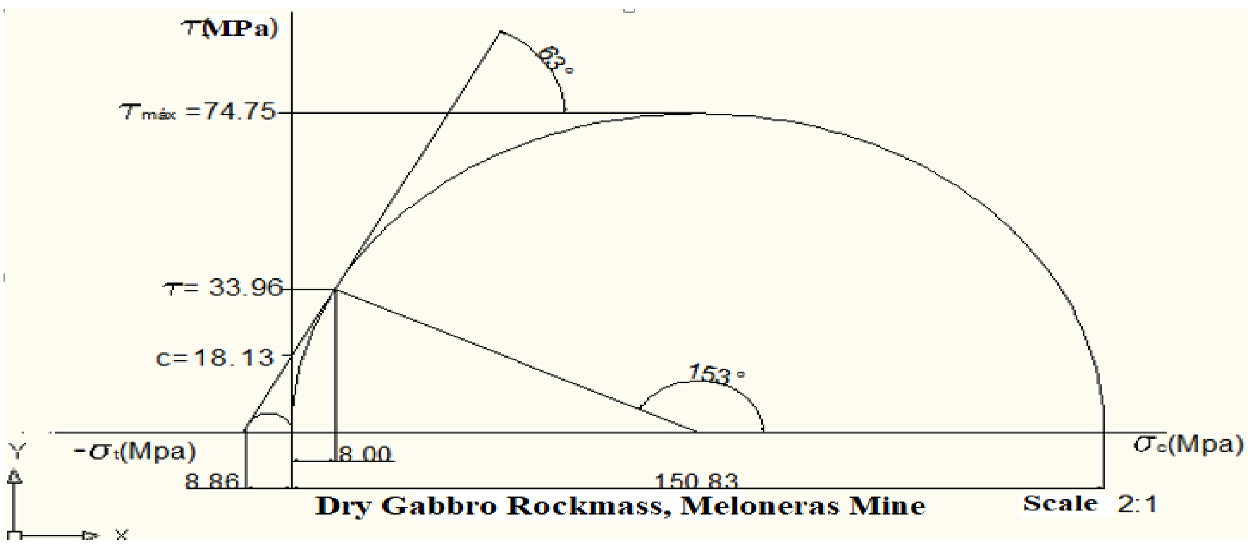

Figure 3. Mohr's circle for dry gabbro, Meloneras mine

Moreover, the maximum tangential stress mobilized on the rock plane becomes greater as the normal effective stress acting on that plane increases. In other words, the higher the level of effective stress, the more resistance the rock can generate. The failure envelopes of serpentine and gabbro rock are features that express the combination of stress magnitudes that will cause the rocks to fracture. If the Mohr circle representing the combination of stresses intersects the material's failure envelope, then the material will fracture; if the Mohr circle does not intersect the failure envelope the material will not fracture. The failure envelope also allows the prediction of the orientation of the macroscopic fracture plane that will be formed when the rock fails. In an isotropic rock, this will be the plane that has a state of stress represented by the point on the Mohr circle that lies on the failure envelope.

The state of stress (σ,τ) on the serpentine and gabbro planes are (4.41MPa. 15.93MPa) at the orientation of fracture plane of 74.5º and (33.96MPa, 8.00MPa) at 76.5º respectively. They are the orientation and magnitude of stresses that will cause the serpentine and gabbro rocks of Meloneras mine to fracture or fail. Furthermore, the angle of internal friction for serpentine and gabbro are respectively 59º and 63º and their Coulomb coefficients (tanφ) are 1.66 and 1.96, the values which indicate the rocks'' fracture behavior at intermediate confining pressures within the earth's crust and measure the resistance of the sliding of one rock block over another; the greater the Coulomb coefficient, the greater the resistance to rock fracture.

CONCLUSIONS AND RECOMMENDATIONS

In this study, the criterion of Mohr-Coulomb was used to assess the rock mass of the Melonera mine, and the following conclusions were deduced:

i. the values of the elastic properties of gabbro (Young modulus (6768.14MPa), Poisson ratio (0.18), cohesion (14.76 MPa), deformation modulus (48696.75MPa)) are higher than serpentine rock (Young modulus (5095.92MPa), Poisson ratio (0.12), cohesion (5.48MPa), deformation modulus (38092.57MPa).
ii. the intermolecular strength within the particles of gabbro is stronger than that of the serpentine rock mass.
iii. the value of the state of stress (τ,σ) of the serpentine rock of Meloneras mine is (4.41MPa, 15.93MPa) at the fracture plane orientation of 74.5º while that of the gabbro rock is (33.96MPa, 8.00MPa) oriented at 76.5º. Any rock mass found in this state of stress will fail to fracture and any found under it will be found stable.
iv. This assessment has expanded frontiers on the safe design of effective explosive patterns, erection of proper supporting systems for failure prevention, identification of troubleshooting areas, and establishment of regulations for safety purposes and compliance.
v. It is therefore recommended that, at the Meloneras Mine, the construction activities and blasting pattern should be accompanied by the state of the stress analysis to develop a support system with integrity and to design an effective blasting pattern.

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