Geomechanical characterization of the rock mass in tunnels

J. Chable
JC Estudios Geotécnicos, Jalisco, Mexico

J. Lopez
Comision Federal de Electricidad, Cuidad de Mexico, Mexico

ABSTRACT:

This article shows the results of the geomechanical characterization of the rock mass, to demonstrate the importance of generating field information on its geotechnical characteristics, according to the results of the geological and geotechnical conditions of the study site, since the intact rock does not represent the entire rock mass. According to the results of the geological-geotechnical condition of the site, it is divided into two study zones, a rock zone and a breccia zone, in which the procedure to define the geomechanical properties of heterogeneous materials is described, based on information of field and laboratory, data that will be of great importance to be able to evaluate the stability and the necessary treatments in the excavations of the later works.

1 OBJETIVE

The main objective of this article is to present the geomechanical characterization in rock and breccia areas, as well as its analysis together with the results obtained from field work and laboratory tests.

2 METHODOLOGY

In order to synthesize the geomechanical characterization methodology of the rock mass, a process diagram was made specifying the activities to be developed in each work area.

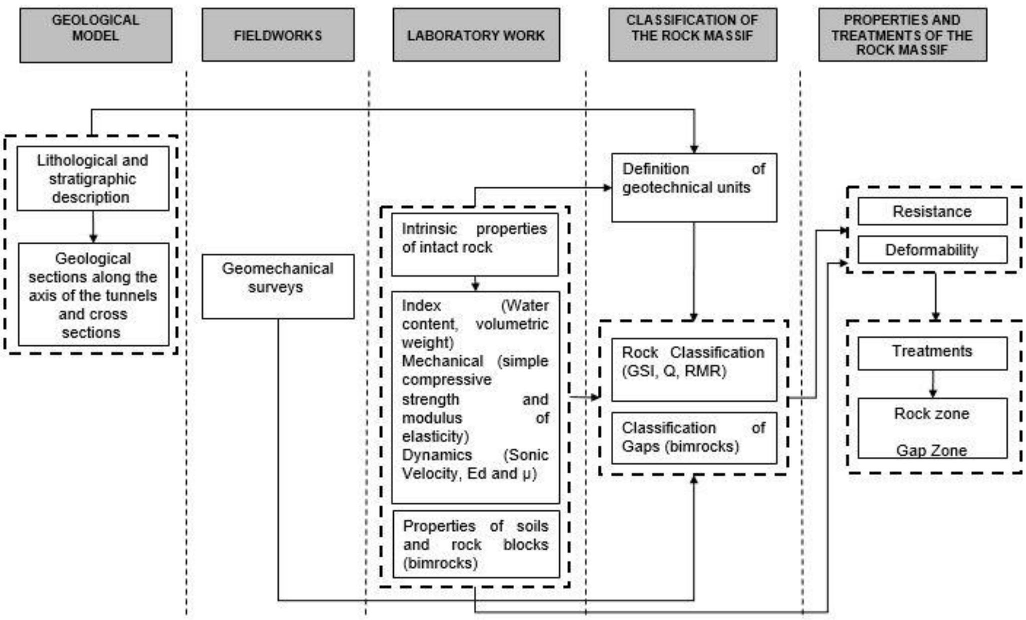


Figure 1. Geotechnical characterization process.

3 STRUCTURAL GEOLOGY

With the data obtained from the geological surveys carried out in the area, the stereogram of figure 4 was elaborated, these fault and fracture systems of the site also coincide with the orientations of the dominant systems at the regional level.

First, it began by identifying the orientations of the main fault and fracture systems in the study area.

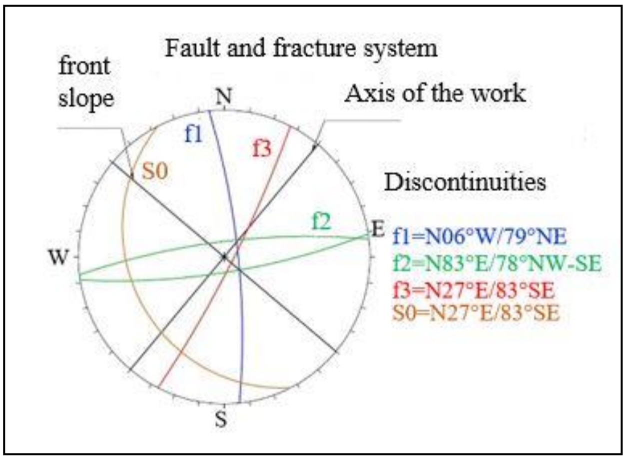


Figure 2. Stereogram with the orientations of the main fault and fracture systems.

4 LABORATORY WORK

In the laboratory work, healthy samples without alteration and without fractures are chosen to carry out simple compressive strength tests on them and thereby obtain the modulus of elasticity, as well as its dynamic properties (Ed and μ).

4.1 *Index properties*

The table 1 presents the average values corresponding to the water content and the volumetric weight of the tests carried out in the laboratory.

Table 1. Average values of index properties of the intact rock.

Description	Properties	UG-3a (Andesite)	UG-3b (Oxidized andesite)	UG-3c (Andesite Breccia)
Index Properties	Water content (%)	2.51	4.91	6.41
	Volumetric ambient weight (kN/m^3)	24.53	21.98	20.59

4.2 *Mechanical properties*

To evaluate the stress-strain behavior of the intact rock, simple compressive strength tests were performed to obtain the modulus of elasticity, as well as indirect and triaxial stress tests. The average results by rock type are shown in Table 2.

Table 2. Average values of mechanical properties of the intact rock.

Lithology	Description	σ_{ci} (MPa)	E_{t50} (MPa)	σ_t (MPa)	m_i	Relation of Poisson
Ug-3a	Andesite	74	14,675	6.41	12	0.12
Ug-3b	Oxidized andesite	23	7,350	4.15	12	0.13
Ug-3c	Andesite Breccia	7.5	5,566	3.49	9	0.11

4.3 *Classification of geotechnical units*

In the rock mass classification, the geological information was taken as a reference, together with the results of the laboratory tests, the geotechnical units were defined.

Based on the above, the classification of (Deere and Miller, 1966) was used, which takes into account the simple compressive strength and the Et50 modulus of the intact rock.

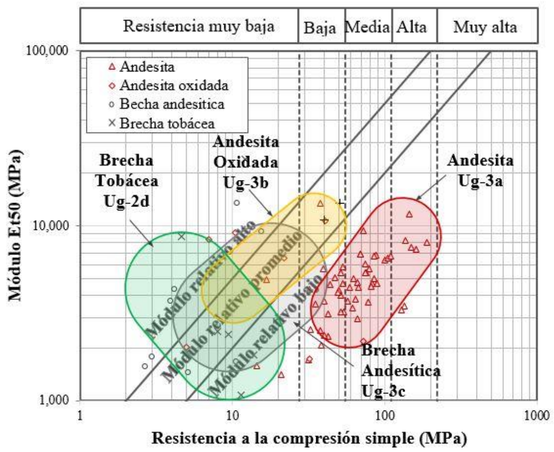


Figure 3. Classification of geotechnical units, Deere-Miller 1966 [5].

5 FIELD WORK

5.1 *Geomechanical surveys*

In the geotechnical characterization, during the field work, geomechanical surveys were carried out in the study area, in which an area of rocks and another of gaps were identified.

In the rock zone, geomechanical surveys were carried out with the methodology proposed by Bieniawski RMR 1989[6], Barton Q 2002 [7], Hoek GSI 2002 [8] and Morelli, 2017 [9].

In the breccia zone, the surveys were carried out with the methodology proposed by (Kalender et al. 2013) [10] for bimrocks.

Within these surveys, the degree of weathering of the rock is described, according to the method suggested by (ISMR, 1978) [11].

6 GEOMECHANICAL CLASSIFICATION

6.1 *Rock Zone*

For the geomechanical survey of the discontinuities in the rock zone, the following criteria were considered.

6.1.1 *Compressive strength of discontinuities, JCS*

To calculate the JCS value, the average rebound values are obtained with the Schmidt hammer for the different rock-rock contacts, to later calculate the resistance with the abacus of (Miller, 1965) [12], (Figure 4) or by means of the following equation:

$$\log_{10} JCS = 0.00088_{\gamma} r + 1.01 \quad (1)$$

Where, r is the average rebound value; ɣ is the volumetric weight of the rock in kN/m3; and JCS in MN/m2;

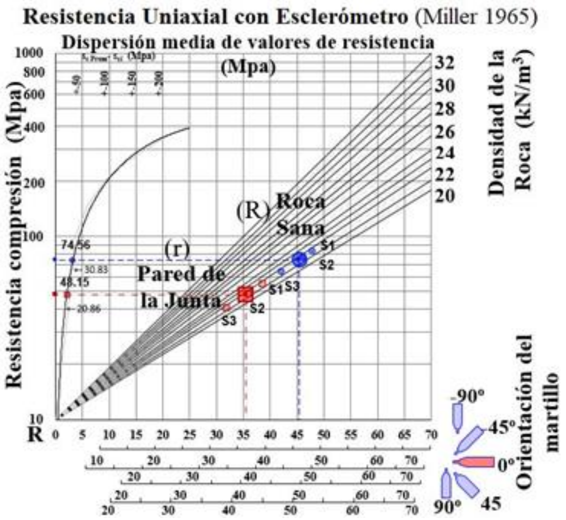


Figure 4. Abacus for calculating the JSC with the sclerometer in the field, from Miller 1965 [12].

6.1.2 *Roughness, JRC*

The roughness coefficient of the discontinuity (Joint Roughness Coefficient) was determined in the field on a small scale with the criterion (Barton-Choubey, 1977) [13], and on a large scale with that of (Barton, 1982) [14]. (Figure 5).

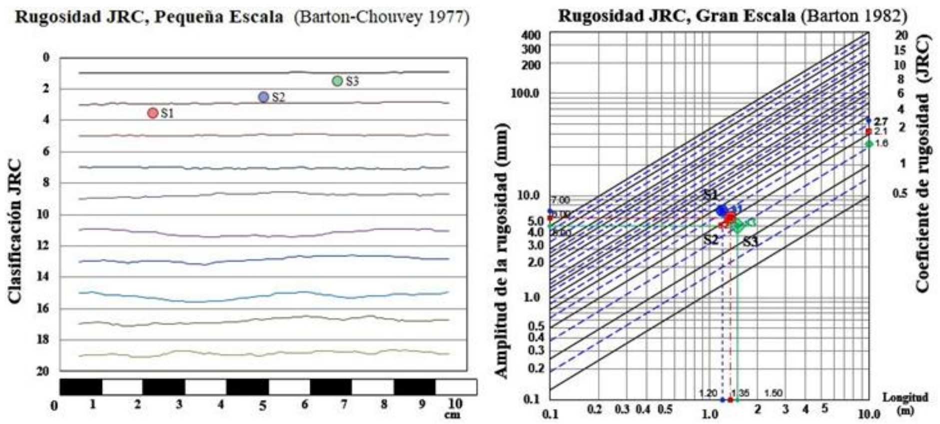


Figure 5. Abacus for calculating the JSC with the sclerometer in the field, from Miller 1965 [12].

6.1.3 *Shear strength of discontinuities*

To determine the shear strength of discontinuities in rock-rock contact, the Barton-Choubey criterion [13] was used:

$$\tau = \sigma_n tan\left[JRC_n + log_{10} + \left(\frac{JRC_n}{\sigma_n}\right)\right] + \varnothing_r \tag{2}$$

Where, τ and σ_n are the tangential and normal stresses on the plane of discontinuity ϕ_r, is the angle of residual friction; JRCn is the Joint Roughness Coefficient of the discontinuity; and JCSn is the compressive strength of the walls of the discontinuity.

To calculate the residual friction angle ϕ_r, the following equation was used:

$$\varnothing_r = (\varnothing_b - 20) + 20\left(\frac{r}{R}\right) \tag{3}$$

Where ϕ_b is the basic or sound rock angle, R and r are the rebounds of the sclerometer on sound rock and the joint wall, respectively, (figure 4).

The maximum friction angle is a function of the residual angle and the components of roughness and resistance of the discontinuities, given by the following equation:

$$\varnothing_{max} = JRC_n\left[log_{10}\left(\frac{JRC_n}{\sigma_n}\right)\right] + \varnothing_r \tag{4}$$

$$\text{If } \left(\frac{\boldsymbol{JCS}}{\sigma_n}\right) > 50, \quad \varnothing_{max} = \varnothing_r + 1.7(JRC) \tag{5}$$

The JRC and JCS values were normalized for the large-scale massif, according to the length of the discontinuities, by means of the equations:

$$JRC_n = JRC_0\left(\frac{\boldsymbol{L_n}}{\boldsymbol{L_0}}\right)^{-0.02JRC_0} \tag{6}$$

$$JCS_n = JRC_0\left(\frac{L_n}{L_0}\right)^{-0.03JRC_0} \tag{7}$$

The table 4 presents the estimation of the basic, residual and maximum friction angles in the discontinuities (rock-rock contact), for 3 fracturing systems in different geotechnical units.

Table 3. Basic, residual and maximum friction angle of discontinuities, Barton-Choubey criterion.

System	Friction angle	(Ug-3a)	(Ug-3a)
S1	ø (básico)	39	35
	ør (residual)	32	29
	ø (máximo)	41	40
S2	ø (básico)	35	35
	ør (residual)	31	30
	ø (máximo)	41	40
S3	ø (básico)	35	35
	ør (residual)	31	29
	ø (máximo)	41	40

6.1.4 *Geological Strength Index, GSI*

The GSI value (Geological Strength Index) was determined with the criteria of (Hoek et al. 2013) [15] using the equation:

$$\text{GSI} = 2J_{Cond76} + \left(\frac{RQD}{2}\right) \quad (8)$$

Where, JCond76 = Condition of the joint (Bieniawski 1976) [16], RQD = Rock Quality Designation.

Additionally, the criterion of (Morelli, 2017) [9] was used to estimate the GSI value (Figure 6), which results from plotting the SR (Structure Rating) as a function of the SCR (Surface Condition Rating), which are described next.

$$SR = 1.75\ ln(J_v) + 79.8 \quad (9)$$

$$SCR = R_r + R_w + R_f \quad (10)$$

Where, Jv = joint volumetric index; Rr, Rw, and Rf are parameters from [RMR 1989] for joint roughness, fill, and alteration, respectively.

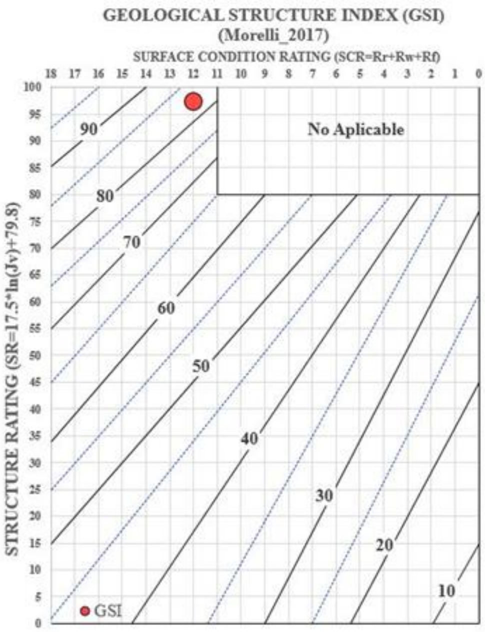


Figure 6. Calculation of GSI (Morelli, 2017) [9].

6.1.5 *Strength and deformability*

To calculate the resistance parameters of the Mohr-Coulomb criterion (c y ϕ) in the rock zone, the quality constants (mb, s, a) representative of the rock mass in the area studied were calculated through the criterion of (Hoek-Brown 2002) [8] , together with the GSI (Geological Strength Index) values. The approximation of the resistance parameters was obtained using the following equations:

$$\phi' = sin^{-1}\left[\frac{6am_b(s+m_b\sigma'_{3n})^{a-1}}{2(1+a)(2+a)+6am_b(s+m_b\sigma'_{3n})^{a-1}}\right] \quad (11)$$

$$c' = \frac{\sigma_{ci}\,[(1+2a)s+(1-a)m_b\sigma'_{3n}](s+m_b\sigma'_{3n})^{a-1}}{(1+a)(2+a)\sqrt{(1+(6am_b\,(s+m_b\sigma'_{3n})^{a-1}\,))/((1+a)(2+a)\,)}} \quad (12)$$

Where, $\sigma_{3n} = \sigma_{3max}/\sigma_{ci}$

The deformability parameters were defined from the results of the laboratory mechanical tests and application of the empirical formula proposed by (Hoek and Diederichs 2006) [17]:

$$E_m = E_i \left(0{,}02 + \frac{1-D/2}{1+e^{((60+15D-GSI)/11)}}\right) \tag{13}$$

Where: E_i is the modulus of the intact rock, equivalent to Et50 and D is the disturbance factor, (values from 0 for unaltered rock masses and up to 1 for highly altered massifs).

6.2 *Breccia Zone*

As indicated in reference [10], the characterization of the breccia or mixed materials was carried out based on the methodology proposed by (Kalender et al., 2013), to evaluate the mechanical properties of materials formed by geotechnically significant blocks within a finer textured matrix (bimrocks). The mechanical parameters of these materials are estimated from the following equations:

$$\varnothing_{br} = \varnothing_m \left[1 + \frac{1000\left[\left(\propto/\varnothing_m\right)-1\right]}{1000+5^{\left[(100-VBP)/15\right]}}\right]\left(\frac{VBP}{VBP+1}\right) \tag{14}$$

$$RCS_{br} = \frac{\left(A-A^{\left(\frac{VBP}{100}\right)}\right)}{(A-1)}\left(RCS_m\right) \tag{15}$$

$$c_{br} = \frac{\left(RCS_{br}\right)\left(1-seno\left(\varnothing_{br}\right)\right)}{2cos\left(\varnothing_{br}\right)} \tag{16}$$

The RCSm parameter (simple compressive strength of the matrix) was determined using several methodologies: with a Schmidt hammer (figure 7), to define the upper limit of resistance in areas where the cemented matrix was found, through laboratory tests on recovered cores and from empirical considerations according to the appearance of the matrix (ISRM, 1978) [11], figure 10.

The parameter ϕ_m (internal friction angle of the matrix), was determined from the results of the field tests (classification of the material and phicometer); as well as from laboratory triaxial tests.

The parameters *VBP* (volumetric proportion of blocks) and α (Angle of repose of the blocks) were determined from the number and shape of the blocks present in the characterized units. This information was primarily defined on representative excavation outcrops (figure 10).

According to (Sonmez et al. 2009) [18], the parameter A (figure 10) quantifies the contribution of the matrix and the blocks in the shear strength of the bimrock and can present values from 0 to 500. The value of *A* it increases when the adhesion between the blocks and the matrix increases, as well as when the angularity of the blocks increases (Table 4).

Based on the criteria described above, Table 4 presents the parameters identified in each geotechnical unit.

The deformability of the breaches was obtained in the field through pressure meter tests:

Table 4. Variation of parameter A (Sonmez et al., 2009) [17].

Test	Parameter A
No adhesion (cohesion) between blocks and matrix with rounded blocks.	0
Weak adhesion (cohesion) between blocks and matrix with half rounded blocks.	10
Moderate adhesion (cohesion) between blocks and matrix with half angular blocks.	50
Strong adhesion (but less than matrix cohesion) between blocks and matrix with angular blocks.	500

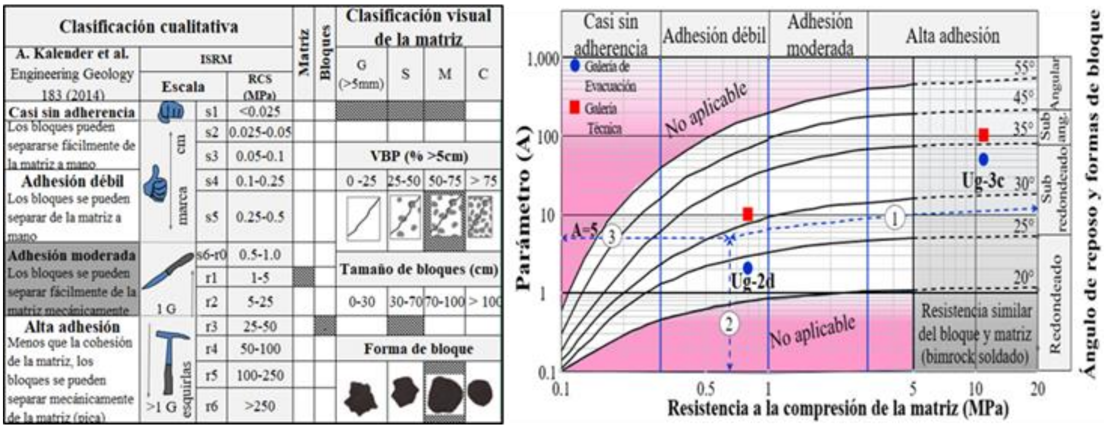


Figure 7. Bimrock qualitative, visual and “A” parameter classification (matrix and block size), (A. Kalender et al. Engineering Geology 183, 2014) [10].

Table 5. Characterization parameters of the gaps.

Geotechnical Unit	Block Size (m)	V.B.P (%)	Angle of repose	Parameter A
Ug-2d	0.15-0.25	25-50	22-32	2-10
Ug-3c	0.20-0.30	50-75	30-40	50-100

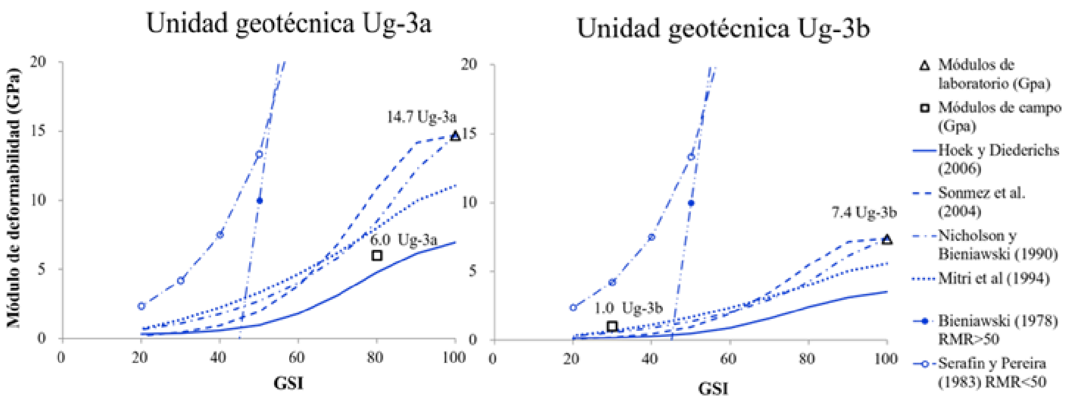
7 PROPERTIES OF MATERIALS IN ROCK AND BRECCIA ZONES

According to the criteria indicated in section 6, Table 6 presents the parameters determined for each geotechnical unit, being the equation of (Hoek and Diederichs, 2006) [17], the one that most closely approximates the parameters of the rock mass, (figure 11).

Table 6. Characterization parameters of the gaps.

Geotechnical Unit	RMR	Q	GSI	Rock Mass constant mi	Cohesion c (MPa)	Friction angle (°)	Deformability modulus Em (GPa)
Ug-3a (Andesita)	87	32	84	12	1	47	6
Ug-3b (Andesita Oxidada)	22	11	22	12	0.28	40	1
Ug-2d (Brechas Tobácea)	NA	NA	NA	9	0.15	30	0.1
Ug-3c (Brecha Andesítica)	NA	NA	NA	9	0.2	37	0.7

NA, Does not apply



.

Figure 8. Rock mass deformability with empirical equations, Hoek and Diederichs 2006 [15].

8 CONCLUSIONS

Derived from the geomechanical surveys that were carried out in the excavation area of the technical and evacuation galleries of the bitunnel, as well as the field and laboratory tests carried out, it was possible to zone the materials and determine the most appropriate methodologies to determine quality parameters, resistance, deformability and treatments of the rock mass.
In relation to the andesite lithological unit, two conditions were presented in the rock mass, one with average RMR values of 80 and the other with 22, as well as simple compressive strength of the intact rock of 74 and 23 MPa, respectively. Treatments ranged from selective anchoring for the most favorable condition, to metal frames and shotcrete for the most critical condition.
In the zone of andesitic and tuffaceous breccias, there is an average V.B.P. of 25-50% and a matrix of low resistance, which corresponds to a treatment of metal frames every meter and shotcrete with a thickness of 0.10 m.

REFERENCIAS

[1] DE CSERNA, Z., DE LA FUENTE, M., PALACIOS-NIETO, M., TRIAY, L., MITRE-SALAZAR, L.M., y MOTA-PALOMINA, R., (1987). Estructura geológica, gravimetría, sismicidad, y relaciones neotectónicas regionales de la Cuenca de México: UNAM, Instituto de Geología, Boletín 104, 71 p. 1

[2] SALINAS-GARCÉS, J. Geología del Complejo Volcánico San Miguel, Sierra de Las Cruces, Suroeste de la Cuenca de México, Tesis profesional de licenciatura, Universidad Nacional Autónoma de México, Facultad de Ingeniería, Ciudad de México, 2014. 2

[3] GARCÍA-PALOMO. A., ZAMORANO J.J, LÓPEZ- Miguel C. 2008. "El Arreglo Morfoestructural de la Sierra Las Cruces, México Central", Revista Mexicana de Ciencias Geológicas, V.25, Núm.1, p. 158-178. 3

[4] MOOSER, F, 1992, Nuevo mapa geológico del sur–poniente del valle de México. Experiencias Geotérmicas en la zona poniente del Valle de México: Sociedad Mexicana de Mecánica de Suelos, 1–6 p. 4

[5] DEERE, D. U., & MILLER, R. P. Engineering classification and index properties for intact rock. Illinois Univ. At Urbana Dept. Of Civil Engineering, 1966. 5

[6] BIENIAWSKI, Z. T. Engineering rock mass classifications: a complete manual for engineers and geologists in mining, civil, and petroleum engineering. John Wiley & Sons, 1989. 6.

[7] BARTON N. Some new Q-value correlations to assist in site characterisation and tunnel design. International journal of rock mechanics and mining sciences. 2002. Feb 1; 39 (2):185-216. 7

[8] HOEK, E., CARRANZA-TORRES, C.T., and CORKUM, B. (2002): Hoek-Brown failure criterion, edition. Proc. North American Rock Mechanics Society, 2002. 8

[9] MORELLLI, G. L. Alternative Quantification of the Geological Strength Index Chart for Jointed Rocks, Springer International Publishing AG 2017. 9

[10] KALENDER, A.; SONMEZ, H.; MEDLEY, E.; TUNUSLUOGLU, C.; KASAPOGLU K.E. An approach to predicting the overall strengths of unwelded bimrocks and bimsoil, Hacettepe University, Department of Geological Engineering, Applied Geology, Division, Oakland, CA, USA, 2014. 10

[11] ISRM .Suggested Methods for the Quantitative Description of Discontinuities in Rock Masses. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts. 1978, 15, 319-368. 11

[12] MILLER, R.P. Engineering classification and index properties for intact rock. Tesis de Doctorado, University of Illinois. 1965. 12

[13] BARTON, N. & CHOUBEY, V. The shear strength of rock joints in theory and practice. Rock Mechanics 1/2:1-54, 1977. 13

[14] BARTON N. Modelling rock joint behaviour from in situ block tests: implications form nuclear waste repository design. Office of Nuclear Waste Isolation, Columbus, Ohio, ONWI-260. 1982. 14

[15] HOEK, E., CARTER, T.G., DIEDERICHS. Quantification of the Geological Strength Index Chart. 47th US Rock Mechanics / Geomechanics Symposium, 2013, San Francisco, CA, USA. 15

[16] BIENIAWSKI Z. T. Rock mass classification in rock engineering applications. Proceedings of a Symposium on Exploration for Rock Engineering, 1976 Vol. 12, pp. 97-106. 16

[17] HOEK, E., DIEDERICHS, MS. (2006), Empirical estimation of rock mass modulus", International Journal of Rock Mechanics and Mining Sciences, 43(2), 203-215. 17

[18] SONMEZ H, KASAPOGLU KE, COSKUN A, TUNUSLUOGLU C, MEDLEY EW, ZIMMERMAN RW. A conceptual empirical approach for the overall strength of unwelded bimrocks. ISRM Regional Symp. Rock Engineering in Difficult Ground Conditions, Soft Rocks and Karst, 2009 (pp. 357-360). 18

[19] GRIMSTAD E, KANKES K, BHASIN R, MAGNUSSEN AW, KAYNIA A. Rock mass quality Q used in designing reinforced ribs of sprayed concrete and energy absorption. Report, Norwegian Geotechnical Institute. 2002. 19.