Evaluation of the Deformation Modulus of the Algeciras Flysch Unit by Means of Pressuremeter Tests: Correlation with RMR

Évaluation du module de déformation de l'Unité du Flysch d'Algéciras au moyen d'essais pressiométriques : Corrélation avec l'indice RMR.

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ABSTRACT : Due to the difficulty in measuring the deformation modulus of a rock mass, it is very common to estimate this parameter, very important for geotechnical design, by means of empirical correlations based on geomechanical parameters that can be easily measured in the field. For this purpose, in the framework of the project of a future tunnel under the Strait of Gibraltar between Europe and Africa, the Geotechnical Laboratory of the Centre for Studies and Experimentation on Public Works (Centro de Estudios y Experimentación de Obras Públicas, CEDEX) in Spain, has carried out an in situ testing survey program. In this paper the deformability parameters measured by pressuremeter testing have been analysed, and some correlations between rock mass deformability and Rock Mass Rating (RMR) index are proposed. These correlations have been compared with some others published by different authors.

RÉSUMÉ : Le module de déformation d'un massif rocheux, très important pour le projet géotechnique, comporte une grande difficulté de mesure. Par conséquent ce paramètre est usuellement estimé grâce à des corrélations empiriques basées sur des paramètres géomécaniques assez faciles à obtenir à partir d'essais in situ. A cet effet, et dans le cadre du futur Projet du tunnel sous le Détroit de Gibraltar entre l'Europe et l'Afrique, le Laboratoire de Géotechnique du Centre d'Études et d'Expérimentation des Travaux Publics (Centro de Estudios y Experimentación de Obras Públicas, CEDEX), en Espagne, a développé une campagne de reconnaissance sur le terrain avec des essais pressiométriques. Ce document analyse les paramètres de déformation obtenus au moyen de ces essais pressiométriques, et certaines corrélations entre la déformabilité et la classification des massifs rocheux (avec l'indice RMR) ont été proposées. Ces corrélations ont également été comparées avec celles d'autres études publiées par des auteurs reconnus.

KEYWORDS : Rock mass deformation, RMR, Pressuremeter, Strait of Gibraltar tunnel, Correlation.

MOTS CLÉS : déformation d'un massif rocheux, RMR, pressiomètre, tunnel du Détroit de Gibraltar, corrélation.

1 INTRODUCTION

Rock mass deformation modulus is one of the most important parameters to consider in any geotechnical engineering project. Its determination is not a fully solved theoretical problem (Serrano, 2002; Romana, 2002).

Discontinuities play an important role in the deformability of a rock mass, and the scale factor is very relevant. To define the rock mass properties properly, the representative elementary volume (REV) is, in most cases, too large to be tested in laboratory. Therefore, nowadays, the only method that can provide a reasonable estimation of the deformability of a rock mass is the use of large scale *in situ* tests (Deere, 1967).

Large scale tests (flat jack, radial jack, pressure chamber tests, plate-bearing tests, or *in situ* triaxial tests) are difficult to carry out and very expensive. They are only feasible for major projects and limited number of tests. Other type of in situ tests is the pressuremeter (or dilatometer). These tests are realized inside a borehole, what allows studying the deep zones of the rock mass at relatively low costs.

Many papers have been published with different methods to estimate the deformability of a rock mass in an indirect way, by means of the correlation between the deformation modulus and any easily measured massif parameter, as propagation velocity of elastic waves, or different parameters of the intact rock, as unconfined compressive strength, combined with a fracturing degree of the rock mass.

This paper presents the study of the deformability of different lithological flysch groups from the Algeciras Unit, by means of the empirical correlations between the deformation moduli, measured with pressuremeter tests, and the geomechanical properties of the rock mass, represented by the Rock Mass Rating (RMR).

Algeciras Unit is one of the geological formations that will be crossed by the future tunnel between Europe and Africa through the Strait of Gibraltar.

The project of this tunnel is coordinated, from the Spanish government, by *Sociedad Estatal para el Estudio de la Comunicación Fija Europa - África a través del Estrecho de Gibraltar* (SECEG).

2 EXPERIMENTAL PROGRAM

For the study of the geotechnical properties of the Algeciras Unit three testing zones were chosen. These zones are located, each one of them, in three different lithological formations, all of them belonging, nevertheless, to this main Unit.

The three zones are situated inside an experimental gallery, property of SECEG. This gallery, 3.8 m in diameter and 572 m long, was tunnelled in the 1990's near the town of Tarifa

(Spain) in order to characterize the geotechnical properties of the different materials involved in the future tunnel under the Strait of Gibraltar. Different geotechnical investigation campaigns have been carried out in this gallery for this purpose.

In this last campaign, the field investigation in each zone consisted of the drilling of four boreholes, between 15 and 20 metres deep, taking undisturbed samples and performing in situ geotechnical study based on pressuremeter and geophysical tests.

In this paper the pressuremeter test results are used to determinate the stiffness parameters of the Algeciras Unit. A total of 35 pressuremeter tests were carried out. The probe used in this work was the pre-boring OYO Elastmeter-200.

In addition, the Rock Mass Rating (RMR) was measured along the bore holes to determinate the quality of the rock mass where each pressuremeter test was carried out.

3 ROCK UNITS STUDIED

The Algeciras Unit (Upper Cretaceous – Oligocene) is part of the Campo de Gibraltar Complex, in the tectonic region of the Betic Mountain range of the Iberian Peninsula. This Unit outcrops at different locations in the province of Cadiz, in Southern Spain, as well as at the sea bed of the Strait of Gibraltar. These materials would be crossed along the major section of the future tunnel.

The present study is focused on three flysch lithologies that form part of the Algeciras Unit: I) Micaceous Sandstones and Marls Flysch (Oligocene-Aquitanian); II) Red Pellitic Succession (Lower Oligocene); and III) Calcareous Flysch (Eocene).

3.1 *Zone 1. Micaceous Sandstones and Marls Flysch*

The Micaceous Sandstones and Marls Flysch (MF) are formed by grey silty claystone strata interlayered by calcareous sandstones and argillaceous siltstones. In all the area studied these strata are dipping almost vertically (See Fig. 1).

The intact rock shows low strength (Perucho et al., 2012), in the range of weak rocks (5–25 MPa) according to the criteria of ISRM (1981).

Most discontinuities are related to stratification and parallel lamination. These planes are slickensided, slightly stepped, unweathered, and closed. The measured RQD is in the range between 55 and 100%, and the mean value is about 85%.

The RMR measured varies between 47 and 66 in this area. This factor allows classifying this rock mass as Fair - Good (Bieniawski, 1989).

Figure 1. Drill cores form a borehole in Zone 1.

3.2 *Zone 2. Red Pellitic Succession*

The Red Pellitic Succession (RM) is composed of unweathered red argillite strata interlayered by fine grained, grey calcareous sandstone (see Fig. 2).

The intact rock strength is low. Using the data from the laboratory investigation, these rocks are classified as Weak Rock (Perucho et al., 2012).

In the studied area, the massif is lightly jointed with RQD higher than 70 % in all cases. Discontinuity surfaces are unweathered, closed, and smooth-slickensided. These planes correspond, most of them, to stratification and parallel sedimentary lamination, and their dip angle is close to 90º.

The RMR is very homogeneous in the whole zone, with a range between 51 and 61 which corresponds to a Fair rock mass (Bieniawski, 1989).

Figure 2. Drill cores form a borehole in Zone 2.

3.3 *Zone 3. Calcareous Flysch*

The Calcareous Flysch (CF) consists, mainly, of grey calcareous sandstones with interlayers of marls and argillites (see Fig. 3).

The uniaxial compressive strength measured for the intact rock classifies it, generally, as Medium Strong (Perucho et al., 2012).

The studied outcrop has low geotechnical quality. Zones of fault or fracturing are common. Fractures are fresh to slightly weathered and closed to tight. Occasionally some clay or sand fills appear. RQD has a great variation; having a range from 0 to 90%.

The dip angle of the stratification is close to vertical.

The RMR varies between 26 and 51, corresponding to a Poor to Fair rock mass (Bieniawski, 1989).

Figure 3. Drill cores form a borehole in Zone 3.

4 THE PRESSUREMETER TEST

The pressuremeter test is, in essence, an in situ loading test, that is carried out by means of a cylindrical probe coated by an elastic membrane. These tests are executed inside a rock mass (or a soil) by means of a drilling.

The test consists of placing the cylindrical probe in a borehole in the ground and expanding it to pressurize the rock mass horizontally by means of a radial pressure and measuring the relative increase in the cavity radius (r). Therefore this test provides an in situ stress-strain curve for the rock mass (see Fig.4).

From the pressuremeter curve, among other parameters, a deformation modulus can be calculated. This modulus is denominated as Pressuremeter Modulus (E_M).

The pressuremeter modulus (E_M) is calculated from the slope of the straight portion of the pressuremeter curve (see Eq. 1), where the material shows a "pseudo elastic" behaviour. A lineal elastic, isotropic, and homogeneous material is supposed.

$$E_M = (1+\nu)\cdot\Delta P \frac{r_m}{\Delta r} \quad (1)$$

where ν is the Poisson's ratio, P is the pressure, r is the radius of the cavity, and r_m is the mean radius of the cavity in the linear part of the pressuremeter curve.

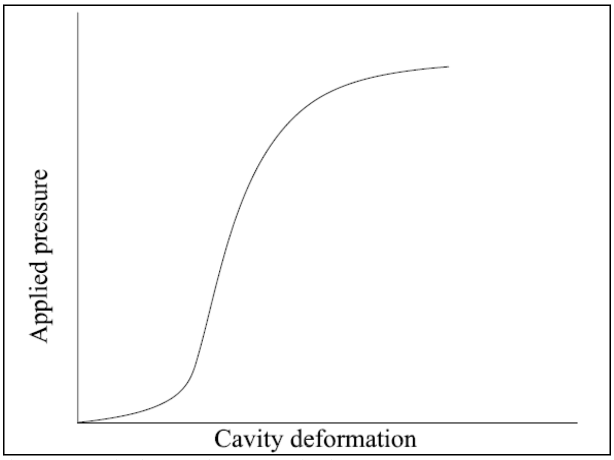

Figure 4. Typical curve form a Pre-boring pressuremeter test.

Ménard (1975) proposed an empirical correlation (see Eq. 2) to obtain the deformation modulus of a rock mass (E_r) from the pressuremeter modulus (E_M):

$$E_r = \frac{E_M}{\alpha} \quad (2)$$

where α is the rheological factor that takes into account the influence of the strain increment path and the difference between the modulus in tension an the modulus in compression of the rock mass (Leblanc, 1982; Briaud, 1992).

Ménard (1975) gave different values for α based on the soil type or on the fracturing degree of a rock mass (see Table 1).

Table 1. Rheological factor α for rocks. Ménard (1975)

Rocks	Extremely fractured	Other	Slightly fractured or extremely weathered
α	1/3	1/2	2/3

In each of the tests carried out, several unload-reload cycles have been performed. From each cycle, a modulus has been calculated that, theoretically, represents the elastic response of the rock mass. These elastic moduli do not take into account the plastic deformations produced in the joints and, therefore their relationship with the geomechanical indexes (RMR, Q or GSI) is poor. Furthermore, for most geotechnical problems deformation modulus is a more relevant factor than the pure elastic modulus. Consequently, this study has not been focused on the cyclic moduli.

5 DATABASE ANALYSED IN THIS STUDY

A total of 35 pressuremeter tests have been realized in the three zones to obtain the rock mass deformation moduli. As mentioned above, RMR has been measured at each test point. A summary of these data are listed in Table 2 and Table 3.

Table 2. Rock Mass Deformation Moduli (E_r) obtained by means of pressuremeter tests

	Num. of data	Mean	Max	Min	Standard deviation
Zone 1 (MF)	13	3.78	8.00	1.09	2.18
Zone 2 (PR)	11	3.17	5.21	1.64	1.07
Zone 3 (CF)	11	2.13	7.00	0.57	1.81
Total	**35**	**3.07**	**8.00**	**0.57**	**1.86**

E_M is expressed in GPa.

Table 3. Rock Mass Ratting values measured.

	Num. of data	Mean	Max	Min	Standard deviation
Zone 1 (MF)	13	57	66	47	6.09
Zone 2 (PR)	11	55	61	48	3.64
Zone 3 (CF)	11	38	51	26	8.81
Total	**35**	**50**	**66**	**26**	**10.55**

Stiffness data show some differences between the three zones of study. Zone 1 (MF) is the stiffest one whilst Zone 3 (RP) is the most deformable. This result is coherent with the geomechanical properties measured for each zone.

6 REGRESSION ANALYSES

6.1 *Introduction*

As mentioned above, due to the great difficulty (or impossibility) in measuring directly the deformation modulus of a rock mass, it is necessary to look for indirect ways to estimate the stiffness of a massif. For that reason, many authors have proposed several mathematical expressions, mostly empirical, that estimate the deformability of a rock mass by means of different geomechanical indexes such as RMR.

In table 4 some of the most widespread expressions are listed, for illustrative purposes. Note that the correlation of Galera et al. (2005) was developed, exclusively, on the basis of pressuremeter tests.

6.2 *Relationship between deformation modulus and RMR*

Values of the rock mass deformation moduli (E_r) calculated by the pressuremeter tests (see Eq.2), have been compared with the RMR values measured at each testing point. From this comparison, linear, power, exponential and logarithmic functions were separately considered. The results from these regression analyses are shown in Table 4.

The three geological materials involved in this study have been gathered as one. This procedure allows analysing a greater range of RMR values and a greater dataset; consequently the use and the reliability of an empirical correlation will be increased. In addition, the use of a single equation for all materials involved in the project greatly simplifies the collecting of data in the first steps of the tunnel design.

Of the 35 pressuremeter tests carried out, three of them (204, 301, and 302) have not been used for the correlation analysis because the results were far different from those obtained from the rest of the data. The origin of theses anomalies could be attributed to a wrong interpretation of the geomechanical data due to the difficulties in the drilling and the deficient quality of the rock cores. The data from these discarded tests are also represented in Figure 5, surrounded with a dot line, but they have not been included in the regression analysis nor in the error study.

Table 4. List of some empirical equations suggested for estimating the modulus of deformation of a rock mass. E_r and E_I (Young's modulus of intact rock) are expressed in GPa in all equations.

Author	Expression
Bieniawski (1978)	$E_r = 2 \cdot RMR - 100$
Serafim & Pereira (1983)	$E_r = 10^{\frac{RMR-10}{40}}$
Nicholson & Bieniawski (1990)	$E_r = \frac{E_I}{100} \cdot \left(0.0028 (RMR)^2 + 0.9\, e^{\frac{RMR}{22.82}} \right)$
Mitri et al. (1994)	$E_r = \frac{E_I}{2} \cdot \left(1 - \cos\left(\frac{\pi \cdot RMR}{100} \right) \right)$
Gockceoglu et al. (2003)	$E_r = 0.0736 \cdot e^{0.0755 \cdot RMR}$
Galera et al. (2005)	$E_r = E_I \cdot e^{\frac{RMR-100}{36}}$
Barton (1983)	$E_r = 10\, Q^{1/3}$
Singh & Bhasin (1996)	$E_r = 1.5 \cdot Q^{0.6} \cdot E_I^{0.14}$
Palmströn & Singh (2001)	$E_r = 8 \cdot Q^{0.4}$
Coon & Merrit (1970)	$E_r = E_I (0.0231 \cdot RQD - 1{,}32)$

For each equation, the coefficient of correlation (R^2) has been calculated. This coefficient sets the accuracy of the adjustment between experimental data and the mathematical equation. In Table 5 the different types of calculated expressions, and their corresponding R^2, are shown.

The equation having the highest coefficient of regression between the rock mass deformation modulus (E_r) and RMR was the exponential (see Table 5).

Table 5. Correlation between the modulus of deformation of the rock mass (E_r) and the RMR obtained from the database of this study. E_r is expressed in GPa in all equations.

Type	Equation	Coefficient of regression, R^2
Linear	$E_r = 0.13 \cdot RMR - 3.95$	0.56
Power	$E_r = 2.59 \cdot 10^{-4} \cdot RMR^{2.33}$	0.47
Logarithmic	$E_r = 5.37 \cdot Ln(RMR) - 18.127$	0.68
Exponential	$E_r = 0.14 \cdot e^{0.06 \cdot RMR}$	0.73

The exponential equation has been simplified as shown bellow (Eq. 3) where the unit of E_r is GPa:

$$E_r = e^{\frac{RMR-35}{18}} \qquad (3)$$

In figure 5 the correlation between the rock mass deformation moduli obtained from the experimental data and the RMR measured in each point is showed. The regression curve corresponds to the equation shown above (See Eq. 3).

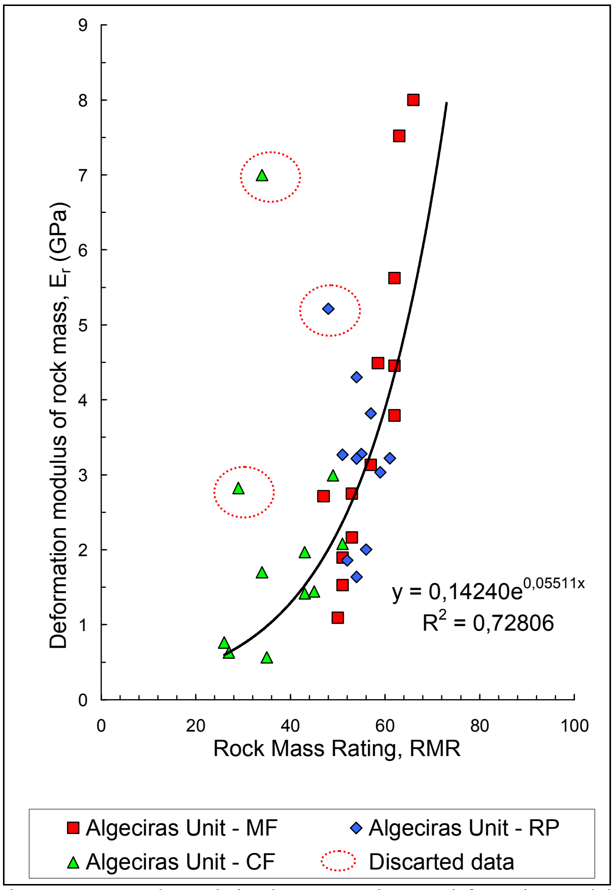

Figure 5. Proposed correlation between rock mass deformation moduli of Algeciras Unit and RMR

6.3 *Prediction performance of the proposed empirical correlation. Comparison with existing relations*

As previously mentioned, there are many empirical correlations, published by different authors, trying to estimate the deformation modulus of a rock mass by means of geomechanical indexes and other parameters easily measured in situ.

In Figure 6 the expressions of the correlations based in RMR that offer a better adjustment to the data studied in this work are represented. This Figure highlights that the equation presented in this paper has certain similarity with the equations of other authors in a range of RMR medium to low. This similarity is in accordance with the range of RMR analysed in this work (25<RMR<65).

The Root Mean Square Error (RMSE) is a good tool to compare different correlations and to select the equation that produces the less mean error; in other words, the correlation with a higher prediction performance. The lower the RMSE is, the greater the prediction performance. The RMSE takes into account equally the errors of overestimation and the errors of underestimation (see Eq. 4).

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (E_r - E_r')^2} \qquad (4)$$

In Eq. 4, E_r is the measured rock mass deformation modulus, E_r' is the predicted deformation modulus, and N is the number of data analysed.

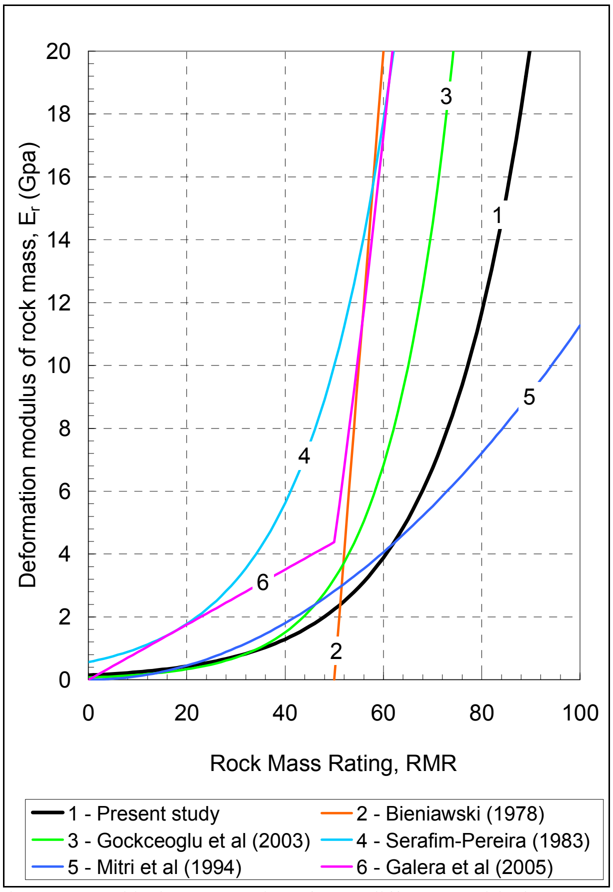

Figure 6. Graphical representation of some different empirical correlations between rock mass modulus of deformation and RMR

Table 6 shows the Root Mean Square Error (RMSE) and the coefficient of regression (R^2) between the rock mass moduli measured by means of pressuremeter tests (see Eq. 2) and the moduli of deformation calculated from different empirical correlations with the RMR.

The calculated values of the R^2 coefficient for each equation are high in all cases (>0.60), but the Root Mean Square Error for the empirical equation proposed in this paper (see Eq. 3) is clearly the lowest.

Table 6. RMSE and R^2 calculated for different empirical equations with the database of the present study

Equation	R^2	RMSE
Proposed in this study	**0.72**	**1.45**
Mitri et al. (1994)	0.63	1.70
Galera et al. (2005)	0.73	11.77
Gockceoglu et al. (2003)	0.75	2.82
Serafim y Pereira (1983)	0.72	15.72
Bieniawski (1978)	0.64	28.46

On the other hand, the prediction error is a good indicator of the accuracy of an equation of correlation (see Eq. 5):

$$Prediction\ error\ (\%) = \frac{E_r - E_r'}{E_r} \cdot 100 \qquad (5)$$

where E_r is the measured rock mass deformation modulus and E_r' is the predicted rock mass deformation modulus.

Figure 7 shows the cumulated prediction error for the dataset analysed in this study using the empirical equation proposed earlier (see Eq. 3), as well as using some equations presented for other authors.

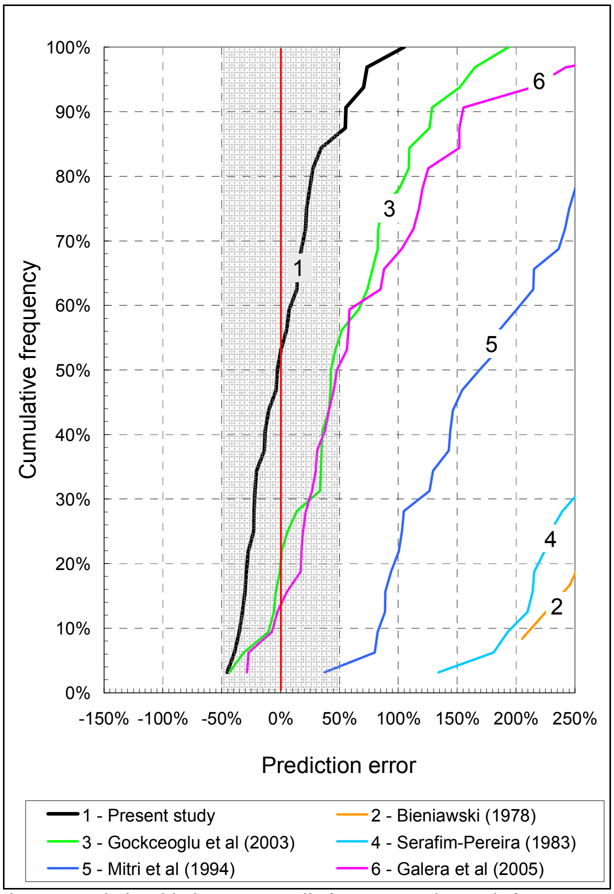

Figure 7. Relationship between prediction error and cumulative frequency for different empirical correlations

If the empirical equation proposed above is used, for more than 80 % of the analysed data points the error is lower than ± 50 %, and for all of them the error between the measured E_r and the calculated E_r' is lower than 100 %. This error has been considered as acceptable by other authors (Gockceoglu et al., 2003), hence the empirical equation proposed above could be regarded as helpful for the prediction of the deformation moduli of the studied geological formation (see Fig. 7).

The prediction errors calculated for the empirical equations proposed by other authors are greater than the calculated for the equation proposed in this study (Fig. 7). Excluding the equation proposed here, the equation given by Gockeoglu et al. (2003) and by Galera et al. (2005) presents the lowest prediction error for this rock mass.

7 SUMARY AND CONCLUSIONS

A total of 35 pressuremeter tests, carried out in Algeciras Unit, have been analysed.

The moduli of deformation of the rock mass ($E_r=E_M/\alpha$) from these tests have been compared with the Rock Mass Rating (RMR) measured at the location point of each test.

An empirical correlation between the deformation moduli and RMR has been proposed.

The correlation proposed has a high predictive capability for this study data. The prediction error is less than those obtained from other published empirical equations.

The analysed dataset has a RMR between 26 and 66 (26<RMR<66), so the proposed correlation must be used with precaution for RMR values out of this range.

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