Evaluation of the deformation modulus of rock masses using RMR. Comparison with dilatometer tests.

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ABSTRACT: This paper presents the result of comparisons between the modulus of deformation obtained from dilatometer tests and the geomechanical quality of the rock mass using the RMR classification and the basic intact rock properties such as the uniaxial compressive strength and Young's modulus.

The first step was to compare the dilatometer modulus with RQD and RMR. Subsequently, it has been decided to use the RMR without considering the lithology, as the differences where found insignificant.

The second step was to scrutinize the data, excluding those with the following limitations: Weathering grade ≥ IV and dilatometer modulus ≤ 0.5 GPa. Also in those cases in which Em ≤ 10 GPa, 15 points were added to the value of RMR because an undrained modulus was being considered.

Excluding any data with anomalous ratios, the final database consists of 436 cases in which known values of Em, RMR, σ^i_c and E' are considered reliable.

With this database several correlations were investigated to estimate rock mass deformability improving on the existing criteria of Bieniawski (1978), Serafin-Pereira (1983), Nicholson-Bieniawski (1990) and Hoek (1995). The results were presented at ISP5 Int. Symp. (Galera et al, 2005). A new relation between RMR and E_m/E^i is recommended:

$$E_m = E_i \cdot e^{(RMR-100)/36}$$

representing a useful tool for the estimation of rock mass deformation modulus.

Finally in the paper, the new relations are proven using data from two main civil works.

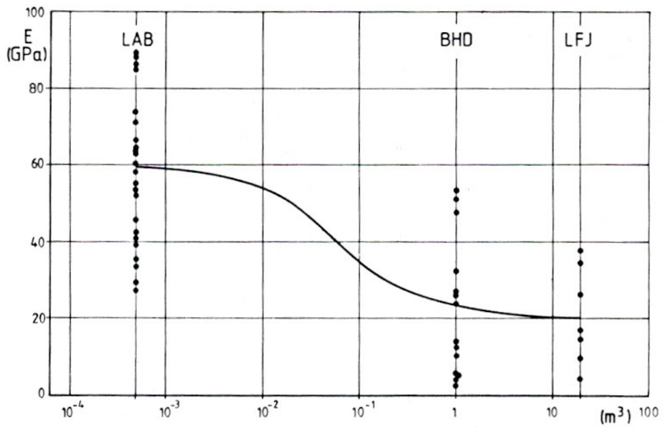
1 INTRODUCTION

The main purpose of this paper is to present a state of the art evaluation of the rock mass deformability and to present the results of comparisons between the modulus of deformation obtained from dilatometer and pressuremeter tests and the geomechanical quality of the rock mass, using the RMR classification. In addition, intact rock properties such as uniaxial compressive strength and Young's modulus are discussed.

2 SOME CONSIDERATIONS OF THE SCALE EFFECTS IN ROCK MASSES

One of the considerations of scale effects in rock masses was by Hoek and Brown (1980) where the strength of the rock mass was estimated by means of the value of the RMR.

Also, the ISRM organized a work group for the investigation of the scale effects in rock masses concerning strength, deformability, joint properties, permeability, and even in situ stresses. The results of these studies were presented in two Workshops, at Loen (1990) and Lisbon (1993).
In particular, concerning the scale effect in rock mass deformability, Pinto de Cunha and Muralha (1990) showed the effect of the volume involved in the test of the deformation modulus measured.
Figure 1 shows this phenomenon, where LAB are laboratory tests, BHD are Borehole Dilatometer Tests and LFJ are Large Flat Jack Tests. Two different ideas can be derived from this figure. One is that the bigger the volume involved in the test, the lower the modulus. The second is that the bigger the volume, the smaller the variability of the results.



"Figure 1 Deformability modulus vs. tested volume (Pinto da Cunha & Muralha, 1990)".

3 EMPIRICAL EVALUATION FROM GEOMECHANICAL CLASSIFICATIONS

It is clear that in situ methods are the best approach to predict deformability of rock masses. However, in situ tests are relatively expensive and not always provide reliable results due to several reasons.
Rock mass deformation modulus estimation by correlations with geomechanical classifications appeared as a traditional tool in rock mechanics since Bieniawski (1978) and his RMR index.
Subsequent correlations have included RQD (Gardner, 1987; Kayabasi et al., 2003; and Zhang and Einstein, 2004), Q system (Barton, 1983; Grimstad and Barton, 1993), and RMR (Serafim and Pereira, 1983; Nicholson and Bieniawski, 1990; and more recently, Hoek et al., 1995).
Currently, three different correlations using Q, RQD and RMR are used:

a) Q and rock mass deformation modulus

Barton (1983) and Grimstad and Barton (1993) provided a study with several geophysical borehole measurements obtaining the following relations:

$Q = 10(V_p - 3.5)$ with Vp in km/s, and concluding

$$E(GPa) = 25 \, LogQ \qquad (1)$$

although in other projects $E = 10 \, LogQ$ was found more suitable.

b) RQD and rock mass deformation modulus

Gardner (1987) proposed the following expression,

$$E_m = \alpha_E \cdot E_i \qquad (2)$$

where α_E = 0.0231·RQD-1.32 (≥0.15). This method was used by the AASHTO (American Association of State Highway and Transportation Officials).
More recently Zhang and Einstein (2004) recommended the following relations:

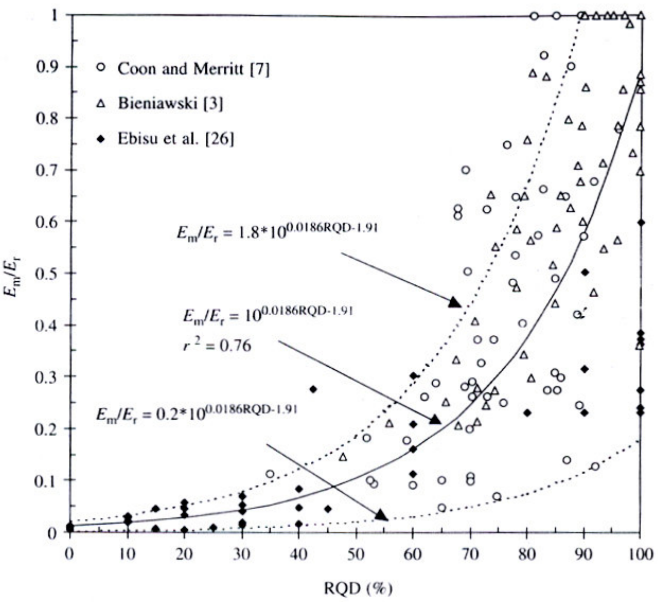
$E_m/E^i = 0.2 \cdot 10^{0.0186RQD-1.91}$ (Lower bound)
$E_m/E^i = 1.8 \cdot 10^{0.0186RQD-1.91}$ (Upper bound)
$E_m/E^i = 10^{0.0186RQD-1.91}$ (Mean)

These expressions are shown in Figure 2. Note the large scatter.

c) RMR and rock mass deformation modulus

The first correlation between RMR and rock mass deformation modulus was proposed by Bieniawski (1978), as

$$E_m(GPa) = 2 \cdot RMR - 100 \text{ (For RMR≥50)} \qquad (3)$$

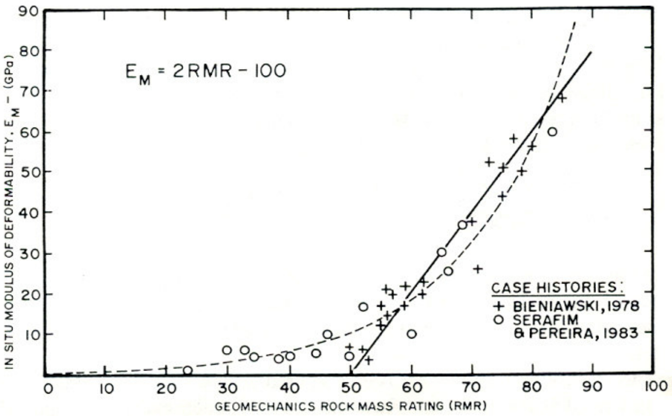


"Figure 2. Relationships between RQD and Em/Er (Zhang and Einstein; 2004)".

Later, Serafim-Pereira (1983) proposed the more known expression,

$$E_m(GPa) = 10^{\frac{(RMR-10)}{40}} \qquad (4)$$

Figure 3 shows graphically both expressions and their comparison.



"Figure 3 Correlation between the in-situ modulus of deformation and RMR (Bieniawski, 1989)".

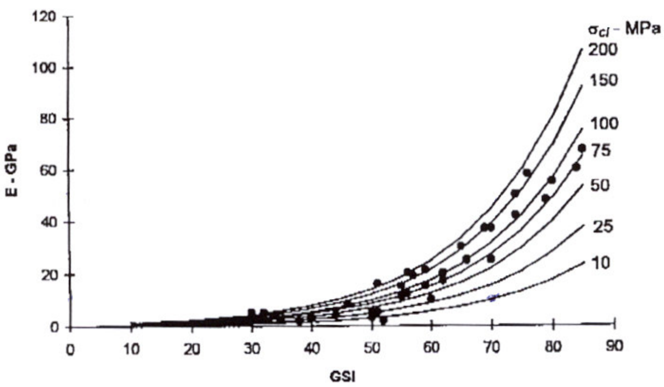
Nicholson and Bieniawski (1990) derived the following relation considering not only RMR but also the Young's modulus of the intact rock E_i:

$$\frac{E_m}{E_i} = \frac{1}{100} \cdot \left(0.0028 \cdot RMR^2 + 0.9^{\frac{RMR}{22.82}}\right) \tag{5}$$

More recently Hoek et al. (1995) suggested a correction to the Serafim-Pereira expression, using a factor of $\sqrt{\frac{\sigma_c^i(MPa)}{100}}$, and interchanging GSI (Geological Strength Index) with RMR, as follows

$$E_m(GPa) = \sqrt{\frac{\sigma_c^i(MPa)}{100}} \cdot 10^{\frac{(GSI-10)}{40}} \tag{6}$$

Figure 4 shows graphically this Hoek et al. (1995) relation.



"Figure 4 Proposed relationships between GSI or RMR with the intact rock strength (σci) and in situ modulus of deformation Em (Hoek et al., 1995)".

Finally, Hoek and Diecrich (2006) suggested the following equation:

$$E_m = (MPa) = 100.000\left(\frac{1 - D/2}{1 + e^{((75+25D-GSi)/11)}}\right) \tag{7}$$

and also.

$$Em(MPa) = Ei\left(0{,}02 + \frac{1-D/2}{1+e((75+25D-GSi)/11)}\right) \tag{8}$$

considering the value of the intact modulus.

The use of RMR and not GSI is strongly recommended because GSI introduces more empirism in a classification that itself is empirical, as was stated in a recent review by Palmström (2003) who warned as follows *"Visual determination of GSI parameters represents the return to quality descriptions instead of advancing quantitative input data as in RMR, Q and RMi systems. GSI was found mainly useful for weaker rock masses with RMR<20.*
As GSI is used for estimating input parameters (strength), is is only an empirical relation and has nothing to do with rock engineering classification".

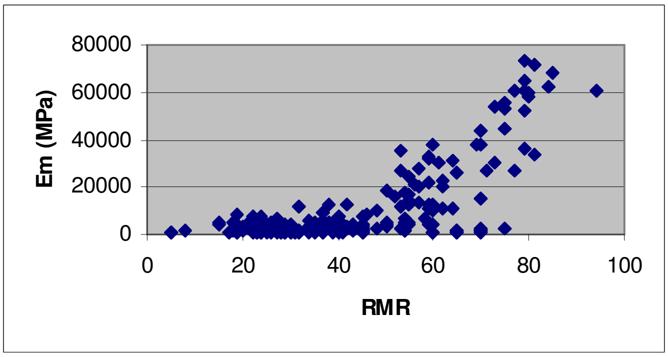
4 NEW CORRELATIONS BETWEEN RMR AND ROCK MASS DEFORMATION MODULUS

4.1 *Database*

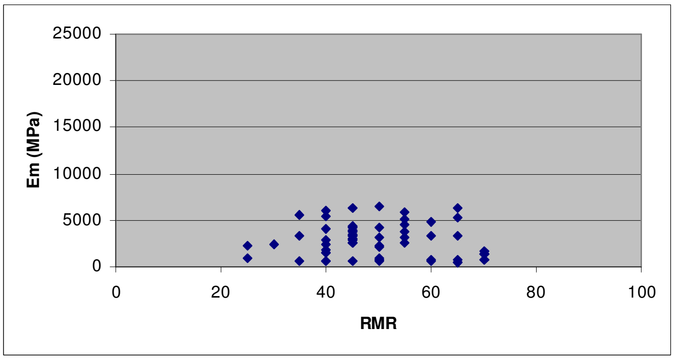
The information presented here is derived partially from bibliography (Bieniawski, 1978; Serafim-Pereira, 1983; and Labrie et al. (2004)) but mainly from pressuremeter and dilatometers measurements made by Geocontrol during the last decade.
The amount of available data classified by its lithology is the following:

- igneous rocks: 270
- metamorphic rocks: 108
- detritic sedimentary rocks: 175
- carbonate sedimentary rocks: 101
- bibliography: 48

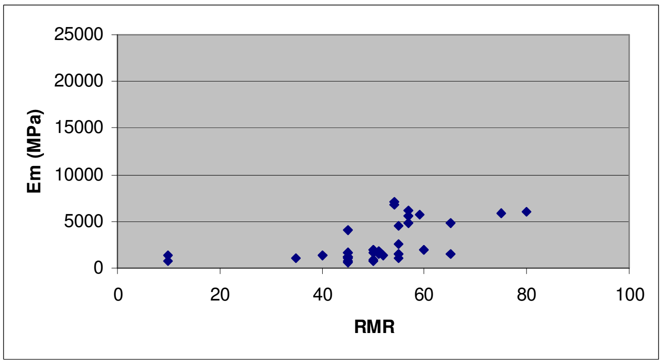
This represents 702 data in which the E_m from in situ tests, RMR and RQD are known.
In 123 of these data also the uniaxial compressive strength (σ_c^i) and Young's modulus of the intact rock (E_i) are also known.
Figures 5a, b, c and d show the available data classified by the lithology. This classification is based on the ISRM and Goodman lithological classifications of rock masses.



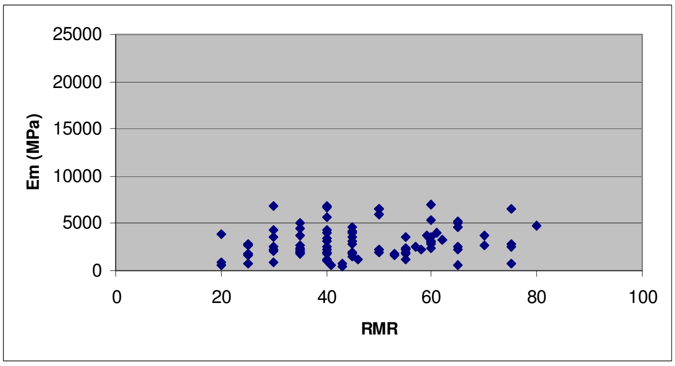
“Figure 5a Igneous rocks”



“Figure 5b Metamorphic rocks”.



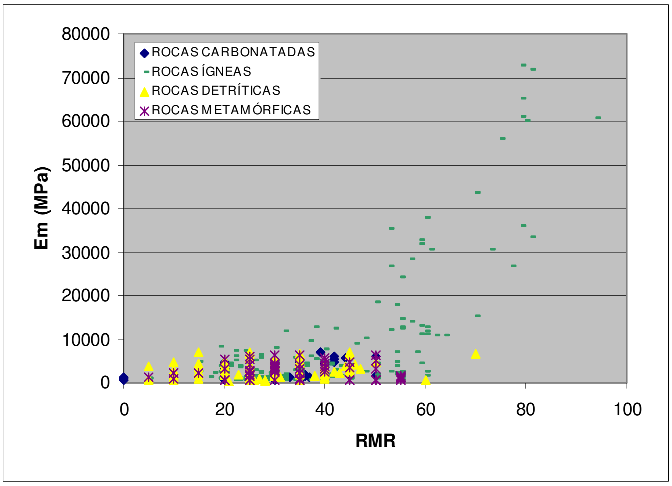
“Figure 5c Sedimentary carbonate rocks”



“Figure 5d Sedimentary detritic rocks”.

“Figure 5. Database according to the lithology”.

Figure 6 shows all the data jointed in the same graph and it can be observed that the differences due to the lithology are insignificant.



“Figure 6 Relation Em (MPa) vs.RMR according to the lithologies”.

The first objective has been to compare the pressuremeter and dilatometer results, which represents the rock mass modulus Em, with RQD and RMR. In Figure 7 a and b both comparison are shown.

It is evident that RMR provides a better trend of the data, since RQD is only one of the five major components of the RMR classification.

This figure clearly shows that RMR is more reliable to estimate the deformation modulus than RQD alone by providing a lesser scatter of data.

4.2 *Analysis of the data*

The second step has been to scrutinize the data, excluding those with the following limitations:

- Weathering grade bigger or equal than IV.
- Pressuremeter or Dilatometer modulus lesser or equal than 0.5 GPa.

The reason for this filter is to remove data with a “soil behaviour” in which the application of RMR classification is inappropiate as not constituting a “conventional” rock mass.

Also in those cases in which $E_m \leq 10$ GPa, 15 points were added to the value of RMR because a drained modulus was considered.

Celada et al. (1995) analyzed the relation between drained and undrained modulus as:

$$\frac{E_u}{E} = \frac{3(1-\nu)Kw + E \cdot n}{2(1+\nu)(1-2\nu)Kw + E \cdot n} \tag{9}$$

where Kw is the balk modulus of the water and n is the porosity. From this relation the following can be concluded:

- If E is bigger than 10 GPa, $E_u/E \simeq 1$ and no significant difference exists between both modulus.
- If E is smaller than 10 GPa and with a drained Poisson’s ratio of 0.3, $E_u/E \simeq 1.15$, so the undrained modulus is around 15% higher than drained modulus.

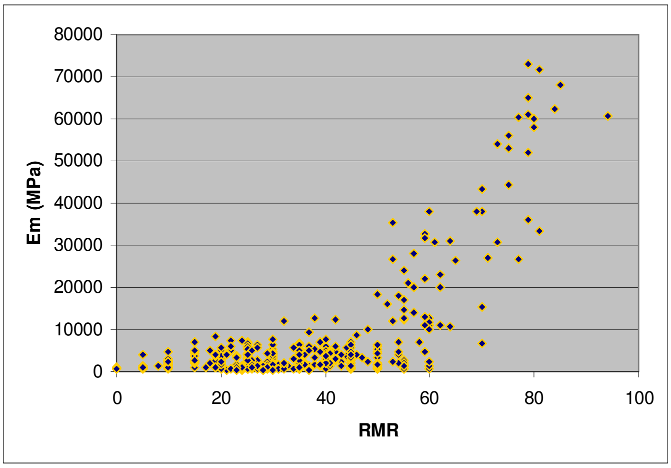


Figure 7a Modulus of deformation vs. RMR.

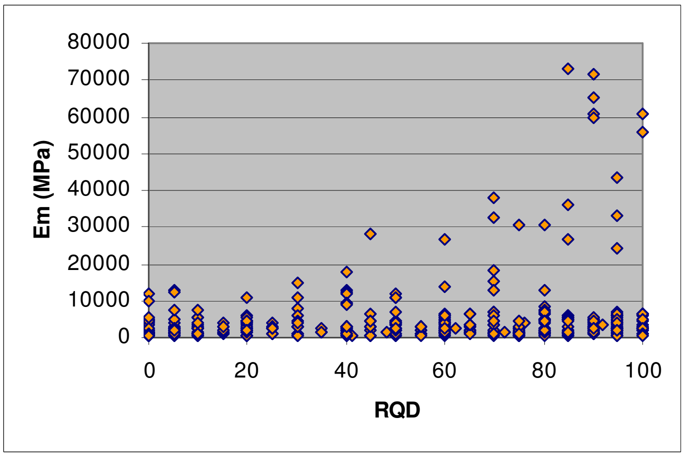


Figure 7b Modulus of deformation vs. RQD.

Finally, the third step has been to perform a sensitivity and quality analysis of data, using the following criteria:

- comparison E_i vs. σ_c^i
- comparison E_i vs. E_m, and
- comparison E_m/E_i vs. RMR.

Excluding any data with anomalous ratios, the final database consists of:

- 427 cases in which E_m and RMR are considered reliable.
- 98 cases in which E_m, E_i, σ_c^i and RMR are considered reliable.

4.3 *Discussion*

With these data, several correlations have been investigated to estimate rock mass deformability by improving on the existing relationships described in section 3.

Experience shows that with the current correlation usually the deformation modulus Em estimated is higher than the modulus measured by means of borehole expansion tests such as pressuremeters and dilatometers.

Two new different types of relations are proposed:

- without considering Ei values
- including E_i values

In the first case also the values of σ_c^i are included using this expression:

$$\sigma_m = \sigma_c^i \cdot e^{(RMR-100)/24}$$ (Kalamaras and Bieniawski, 1995) (10)

In all the cases the coefficient of regression r^2 has been calculated as follows:

$$r^2 = 1 - \frac{\sum (y_i - y_i')}{\sum (y_i - \bar{y})^2} \quad (11)$$

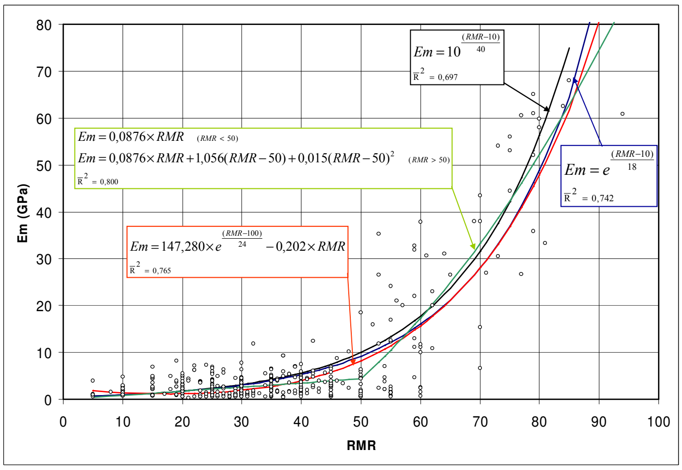
where y_i is the value of E_m, $\bar{y}$ is the mean and y_i' are the adjusted values.

a) New correlations between RMR and rock mass deformation modulus

Figure 8 shows all the new correlations considered and also the Serafim-Pereira expression.

i. considering $\sigma_m = \sigma_c^i \cdot e^{(RMR-100)/24}$ it is derived:

$$E_m(GPa) = 147.28\frac{\sigma_m}{\sigma_c^i} - 0.202 \cdot RMR \quad (12)$$



"Figure 8. New correlations between RMR and rock mass deformation modulus E_m".

The coefficient of regression, r^2, obtained is 0.765, that is higher than the one obtained in the regression of the data following Serafim-Pereira, namely, a r^2 = 0.697.

ii. The second relation is an improvement of Serafim-Pereira, as follows:

$$E_m = e^{(RMR-10)/18} \quad (13)$$

The coefficient of regression r^2 = 0.742, that improves by 10% the estimation of E_m.

iii. Finally, following the original estimation, a threshold of RMR = 50 is derived:

$$E_m(GPa) = 0.0876 \cdot RMR \quad \text{for } RMR \leq 50 \tag{14}$$

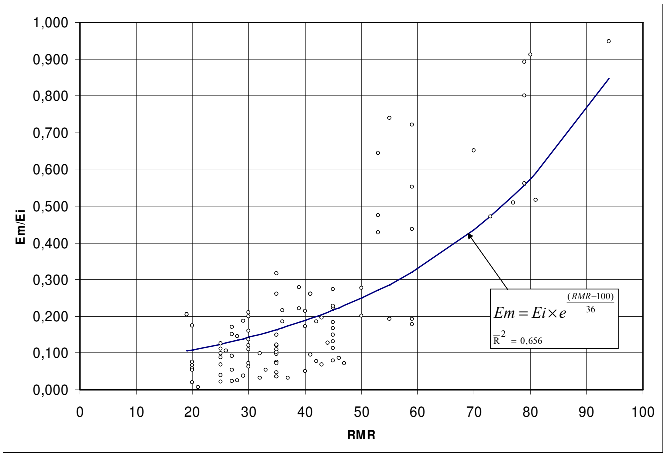
$$E_m(GPa) = 0.0876 \cdot RMR + 1.056(RMR - 50) + 0.015(RMR - 50)^2 \quad \text{for } RMR > 50 \tag{15}$$

This above correlation gives a coefficient of regression $r^2 = 0.8$, that improves by more than 15% the estimation of Serafim-Pereira.

b) New correlation between RMR and rock mass deformation modulus including Ei

Figure 9 shows the relation $E_m = E_i \cdot e^{(RMR-100)/36}$.

The coefficient of regression, r^2, is 0.656 which is smaller than that given by the previous correlations but it makes a more reliable estimation as Ei is considered and improves by almost 40% the estimation due to Nicholson and Bieniawski (1990) which gives r^2=0.472.



"Figure 9 Correlation between RMR and rock mass deformation modulus ratio including E_i".

5 SUMMARY AND CONCLUSIONS

(1) The Borehole Expansion Tests, mostly Flexible dilatometers, were found to be the best in situ test for the determination of the rock mass deformation modulus.
(2) The empirical Em – RMR correlations present a smaller scatter than the previous correlations Em – RQD.
(3) Several empirical correlations have been studied to estimate rock mass deformation modulus Em. Most of them provide an overestimation of the value Em.
(4) Considering 427 data collected from the published literature and our own data, the best coefficient of regression is obtained considering a threshold of RMR = 50. A linear regression is suggested for values smaller or equal to 50, while a polynomial expression is recommended for values of RMR bigger than 50.
(5) A new relation between RMR and Em/Ei is recommended, considering 98 data. This expression is

$$E_m = E_i \cdot e^{(RMR-100)/36} \tag{16}$$

representing a useful tool for estimation of the rock mass deformation modulus.

Considering that rock mass strength $\sigma_m = \sigma_c^i \cdot e^{(RMR-100)/24}$ and equation (14), it results in the following expression:

$$\frac{E_m}{E_i} = \left(\frac{\sigma_m}{\sigma_c^i}\right)^{2/3} \tag{17}$$

providing another useful relationship for rock mass characterization.
(6) Nevertheless, the presented correlations should be used realizing that some factors are ignored such as directional effect of jointing.

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