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Estimation of the rock mass deformation modulus using a rock classification system

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It is often difficult to directly obtain specific design parameters of interest. In these situations, estimation based on empirical correlations is an alternative. The deformation modulus of a rock mass, which is important to know for engineering projects, is measured by in situ tests, such as plate bearing, flat jack, pressure chamber, borehole jacking and dilatometer tests. Nevertheless, these in situ tests are expensive, time consuming and sometimes even impossible. Many attempts have been made to estimate the E modulus using easy-to-obtain parameters of a rock mass. This paper reviews previous studies and the equations that have been developed. In addition, this study presents a new relation developed using a database of 82 dilatometer test results gathered from two dam sites and a tunnel site. Statistical analyses were performed to correlate accessible rock parameters with measured E modulus values from in situ tests. Knowing that discontinuity characteristics and the strength of rock materials are the most important contributors to rock deformability, the focus was on identifying parameters that are affected by the mentioned properties. Among the tested parameters, RMR (Rock Mass Rating) showed the best correlation with the E modulus. Statistical analyses resulted in a new empirical equation that has an acceptable estimation ability.

Keywords: E modulus; rock mass; dilatometer

1. Introduction

It is often difficult for rock engineers to directly obtain the specific design parameters of interest. As an alternative, they use typical values or empirical correlations for similar rocks to indirectly estimate the specific parameters of interest (Zhang 2008).

An example of this practice is the determination of the deformability of a rock mass. Deformability means the capacity of rock to strain under applied loads or in response to unloading upon excavation (Goodman 1989). Rock masses usually contain discontinuities that affect the behaviour of rock materials. To obtain realistic values of the rock mass deformation modulus, in situ tests, such as plate bearing, flat jack, pressure chamber, borehole jacking and dilatometer tests, need to be conducted. However, in situ tests are time-consuming, expensive and, in some cases, even impossible to carry out. Therefore, the deformation modulus of a rock mass is often estimated indirectly from correlations with classification indices such as the RQD (Rock Quality Designation), RMR (Rock Mass Rating), Q (Q-System) and GSI (Geological Strength Index).

Some empirical relations between the deformation modulus and the rock mass properties have been developed for the indirect estimation of the deformation modulus by some researchers (Kayabasi *et al*. 2003, after Mitri *et al*. 1994). In some cases, the estimated deformability has been compared with extensometer measurements from actual sites (Justo *et al*. 2008).

Empirical relations are applicable in the initial stages of projects, especially in the site selection process, for which the data are limited. Some relations provide background knowledge about site conditions based only on engineering geological information that was gathered by surface studies and simple tests. As an example, a rock mass can be classified with a geological study and Schmidt hammer test results, and this information could be used in an empirical relation.

Although the empirical equations used for the indirect estimation of the deformation modulus are simple and cost-effective, the equations include some uncertainties related to the limited data availability, the variability of the rock type and the heterogeneous nature of the rock masses. For this reason, application of some existing empirical equations and evaluation of the obtained results are of significant importance, both for rock engineering projects and the future development of these equations (Kayabasi *et al*. 2003). This study attempts; a) to produce empirical relations for different rock types using an in situ dilatometer test and rock mass properties, b) to study the properties of a rock mass that could be used to estimate the E modulus of the rock mass, c) to compare established equations

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with existing ones and d) to estimate whether different rock types with specific rock mass conditions obey the same equations. To accomplish these goals, we gathered 82 dilatometer test data points, rock mass properties, such as joint study and classification, and experimental test data, such as UCS results, from three dam sites in Iran.

2. Materials and methods

2.1 *Rock mass and intact rock properties*

The data used in this study were collected from two dam sites in western and northern Iran and one tunnel site located in the central part of Iran, which are identified as site 1, site 2 and site 3, respectively, in this paper. The positions of these sites are shown in Figure 1. Site 1 is mainly covered by grey-green schist and phyllite. According to the classification recommended by the (ISRM, 1978) (International Society for Rock Mechanics), the discontinuity spacing is generally moderate and wide, while the apertures are tight or partly open. Apertures include infilling material, such as quartz and, rarely, pyrite. Discontinuity surfaces are generally rough and slightly weathered. Dark grey to black limestone with calcite veins extend over the dam site 2 area, accompanied by grey to dark sandstone. The discontinuity spacing of this unit is generally moderate and wide. The apertures are also tight and partly open, while the discontinuity surfaces are slightly weathered and rough to slightly planar. The tunnel site (site 3) is covered by limy dolomite, the spacing of discontinuities is moderate, and apertures are tight, while the discontinuity surfaces are dominantly planar to rough. The unit is slightly weathered. All data used in this study were collected from the geotechnical boreholes at the dam and tunnel sites mentioned above. In addition to the field observations, 82 dilatometer tests were performed. The boreholes have a 76 mm diameter. A dilatometer test is a borehole expansion experiment conducted with a rubber sleeve. The expansion of the borehole is measured by the oil or gas flow into the sleeve as the pressure is increased or by potentiometers or by linear or variable differential transformers built inside the sleeve (Goodman 1989). An assessment of the geomechanical properties and rock mass classifications (RMR) of the three sites are demonstrated in Table 1.

2.2 *Review of the existing relations and attempts to find a more correlative parameter*

The aim of the study is to identify the parameters of a rock mass that could be used in E modulus estimation and then to select a limited number of these parameters. The second step is to correlate the selected parameters with the E modulus obtained from field tests to discover the parameters that have the best relationship with the E modulus. To conduct this study, the existing empirical equations were first reviewed.

As suggested by Clerici (1993) (cited in Kayabasi *et al.* 2003), it is appropriate to select an empirical equation for the estimation of the deformation modulus according to the following criteria: (a) the equations must be based on parameters that can be acquired easily and at low cost and (b) the equations must be widely mentioned in the literature.

As mentioned above, different equations could be used to estimate the deformation modulus from different parameters; for example, Gardner (1987), (cited in Zhang 2008) proposed Equation (1) for estimating the rock mass deformation modulus

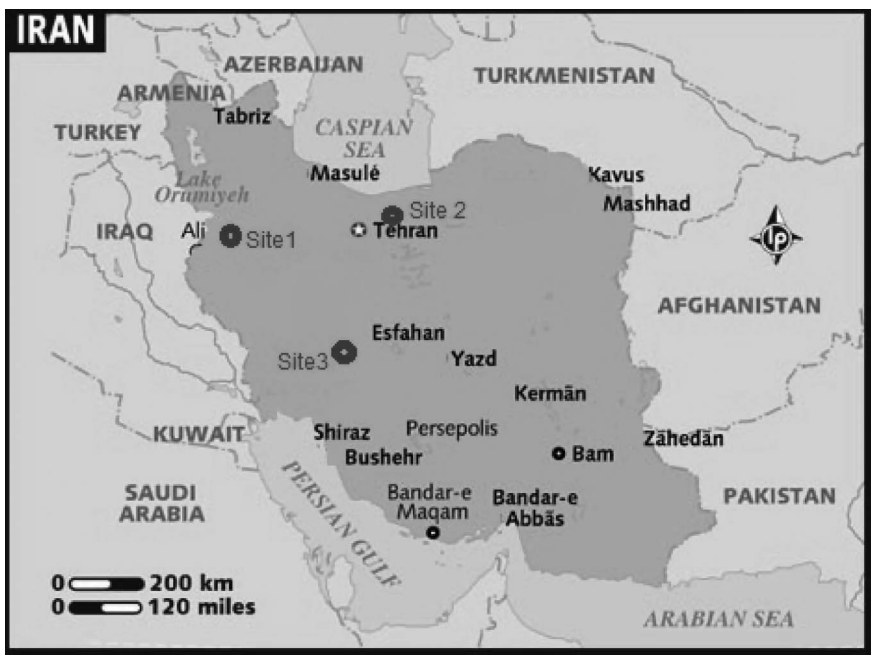

Figure 1. Position of studied Sites.

Table 1. Summary of the geotechnical and rock mass properties of the rock employed in the study

	Site 1			Site 2			Site 3		
property	Min	Max	Avg.	Min	Max	Avg.	Min	Max	Avg.
Uniaxial compressive strength (MPa)	15	131	63	66	146	106			82
Modulus of deformation of rock mass (GPa) from UCS test	1.76	5.01	3.05	1	13.4	5.1	13.4	54.5	31.5
Spacing (mm)	60	300	180	60	170	115	20	60	40
RQD (%)	30	85	63	18	75	46	47	100	75
RMR	39	56	48	39	68	54	63	87	75
Weathering degree	slightly weathered and occasionally highly weathered			faintly weathered to slightly weathered			generally slightly weathered		
Aperture (mm)	generally 1–2 mm to tight			generally <5mm			generally <1mm to tight		
Infilling	quartz and pyrite			calcite and quartz			Fe		
Roughness	generally rough			slightly rough to rough			generally rough		
Persistency							> 20m		
Groundwater conditions	dry			dry			dry		

(E_m) from the intact rock modulus E_r by using a reduction factor α_E that accounts for the frequency of discontinuities using the RQD:

$$E_m = \alpha_E E_r \tag{1}$$

$$\alpha_E = 0.0231(\mathrm{RQD}) - 132 \geq 0.15$$

Kayabasi *et al*. (2003) derived Equation (2) based on the RQD, the weathering degree of discontinuity and the intact rock deformability:

$$E_m = 0.1423\left[\frac{E_m = (1 + 0.01RQD)}{WD}\right]^{1.1747} \tag{2}$$

Gokceoglu *et al*. (2003) changed Equation (2) to Equation (3) and added more data to the equation:

$$E_m = 0.001\left[\frac{(E_r/\delta_c)(1 + 0.01\mathrm{RQD})}{\mathrm{WD}}\right]^{1.5528} \tag{3}$$

Zhang and Einstein (2004) proposed the relations cited in Equation (4) between the rock mass deformation modulus and the RQD:

Upper band

$$\frac{E_m}{E_r} = 1.81 \times 10^{0.0186RQD - 1.91} \tag{4}$$

Lower band

$$\frac{E_m}{E_r} = 0.2 \times 10^{0.0186RQD - 1.91}$$

Mean

$$\frac{E_m}{E_r} = 10^{0.0186RQD - 1.91}$$

Barton (2002) presented the following correlation seismic P-wave velocity (ν_p) (v_p is in km/s):

$$E_m = 10 \times 10^{\frac{\nu_p - 3.5}{3}}(Gpa) \tag{5}$$

Based on the UCS, a relation was developed by Rowe and Armitage (1984):

$$E_m(Mpa) = 215\sqrt{\delta_c} \tag{6}$$

In addition to the above-mentioned equations, there are many other relations between different geotechnical parameters of rocks and the rock mass deformation modulus, but as was noted, simplicity and accessibility are inherent elements of a user-friendly empirical equation with an emphasis on correlation. Most of the recent studies focused on this fact to develop relations between rock classification systems and the rock mass deformation modulus, and thus, they seem more realistic than other relations. This is mainly because it is possible to take into consideration more characteristics of the rock mass, which could affect the deformability of the rock. Many attempts have been made in this field by researchers, which resulted in the empirical equations that are summarized in Table 2.

There are many suggested empirical equations, some of which are used widely in practice, but there are also some limitations (Zhang 2008).

(1) The anisotropy of the rock mass caused by discontinuities is not considered.
(2) Different empirical relations often give very different deformation modulus values of rock masses at the same site.

Despite these limitations, the search for accurate relations continues.

Table 2. Summary of Empirical equations suggested by different researchers between E modulus and rock mass properties

Empirical equation	Required parameters	Limitations	Equations
Bieniawski	RMR	RMR > 50	$E_m = 2RMR - 100$
Serafim and Pereira	RMR	RMR ≤ 50	$E_m = 100^{(RMR-10)/40}$
Nicholoson and Bieniawski	E_i and RMR	–	$E_m = E_i[0.0028RMR^2 + 0.9\exp\left(\frac{RMR}{22.82}\right)$
Mitri et al.	E_i and RMR	–	$E_m = E_i\left[0.5\left(1 - \left(\cos\left(\pi * \frac{RMR}{100}\right)\right)\right)\right]$
Hoek and Brown	GSI and UCS	UCS ≤ 100Mpa	$E_m = \sqrt{UCS/100}10^{(GSI-10)/40}$
Barton	Q		$E_m = 10Q_c^{1/3}, Q_c = UCS/100$
Palmstrom and Singh	RMi	–	$RM_i > 0.1, E_m = 5.6RM_i^{0.375}$ $301 > RM_i > 0.1, E_m = 7RM_i^{0.4}$
Kayabasi et al.	E_i, RQD and WD	–	$E_{mi} = 0.135\left[\frac{E_i\left(1+\frac{RQD}{100}\right)}{WD}\right]^{1.1811}$
Sonmez et al. (2005)	E_i	–	$E_{rm} = E_i 10\left[\left(\frac{(RMR-100)(100-RMR)}{4000\exp\left(-\frac{RMR}{100}\right)}\right)\right]$
Mohammadi and Rahmannejad	RMR	–	$E_m = 0.0003RMR^3 - 0.0193RMR^2 + 0.315RMR + 3.4064$
Galera et al.	RMR and E_i	–	$E_m = E_i.e^{(RMR-100)/36}$
Sonmez et al. (2004)	GSI	–	$E_m = E_i(s^\alpha)^{0.4}$

3. Empirical relation

As mentioned in the introduction, this study tries to examine the reliability of existing E modulus relations using information from three sites for which field and lab test data are available. For this purpose, selected parameters correlations are tested in one of the sites, Site 3. The main reason for choosing this site was because the authors were present for the field and lab tests and thus have access to detailed and accurate information. After finding the parameter with the best correlation, the data from all three sites were collected, and analyses were performed on them to derive the best correlation between the E modulus and the selected parameter. First, pure parameters were compared with the E modulus to identify the parameter that had the best correlation. A brief summary of the information available for Site 1 is given in Table 3.

The correlation between the E modulus as a dependent parameter and other properties as independent variables is studied using the SPSS statistical software and its various regression models. The output of the software involves tables that include statistical analysis results, such as r^2 (r squared). The adjusted r^2 is also used in studies such as ours in which not much data are available. The term "Significant" (sig.), which expresses the reliability of the regression, is another necessary statistical parameter that is given in the output tables of the ANOVA test results.

Three parameters have meaningful relationships with the E modulus. Among them, the RMR correlation with E is the best correlation, as shown by $r^2 = 0.9$ in the exponential curve estimation. So most appropriate parameter is the RMR, which shows the best correlation with the E modulus and is able to predict E value in a rock mass.

Based on the above results, all 82 accessible data points from the three sites were used to perform the mentioned statistical procedure to obtain the best estimation curve and produce an equation to predict the E modulus in a rock mass. The results of this statistical research are summarized in Table 4 and are also depicted in Figure 2. This diagram demonstrates the measured

Table 3. Site 1 rock mass geomechanical

Properties employed in study						
No	BH	RMR	RQD (%)	UCS (Mpa)	ν_p (km/s)	E (Gpa) (calculated from Dilatometre test)
1	CHR2	46	45	89	5.37	2.35
2	CHR2	42	49	16	3.36	1.76
3	CHR4	56	80	86	5.20	5.01
4	CHR4	51	80	66	5.73	3.43
5	CHR4	47	60	85	6.02	2.54
6	CHR5	47	70	45	5.09	2.54
7	CHR5	39	30	39	4.74	2.15
8	CHR5	44	70	3	4.94	2.02
9	CHR5	55	70	131	5.57	4.64
10	CHR5	54	85	72	5.48	4.10

Table 4. Statistical models summary

Model	R Square	Adjusted R Square	Std. Error of the Estimate
Linear	.859	.857	2.481
Power	.891	.889	.273
Exponential	.875	.874	.292

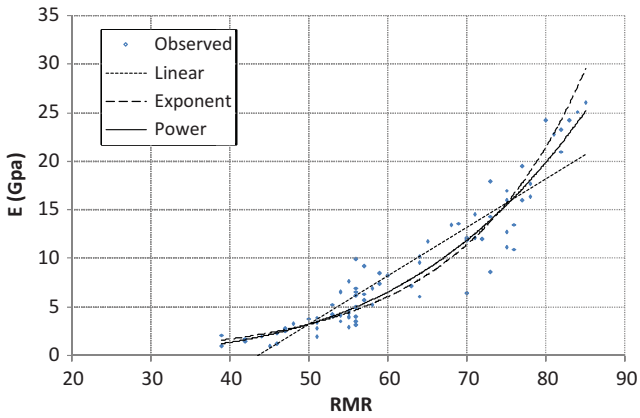

Figure 2. Relationship between measured E modulus and calculated RMR for equivalent depths in under study sites.

E and the calculated RMR for equivalent parts. As given in Table 4, the power curve model has a greater r-squared value than the linear or the exponential model.

An empirical relation based on the statistical analyses (power model regression, $r^2 = 0.89$) was selected and is given in Equation (7).

$$E_m = 9E - 7RMR^{3.868} \tag{7}$$

As will be shown in the Discussion, the relation is evaluated by comparing the estimated E modulus with the experimental value and the estimated E modulus from similar empirical equations. The comparison shows that the new relation is somewhat more conservative but closer to the experimental values.

4. Discussion

As mentioned in the introduction, several empirical approaches have been proposed in the rock mechanics literature for predicting the deformation modulus of a rock mass (Table 2). Nevertheless, only some of the empirical equations given in Table 2 are considered in this study, but whenever possible, we have tried to compare the new equation with them. For example, Equation (8), presented by Gokceoglu *et al.* (2003), which is an empirical relation like Equation (7), employs only the RMR.

$$E = 0.0736e^{0.0755RMR} \tag{8}$$

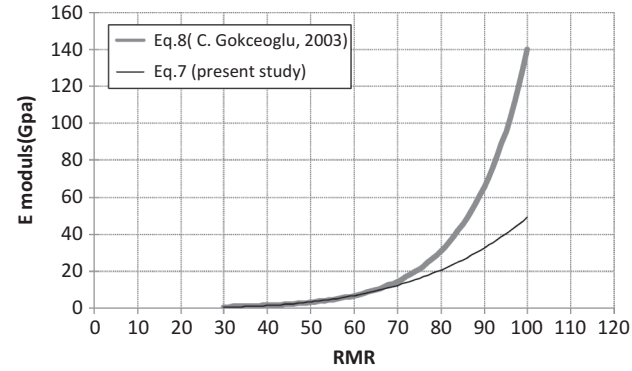

Figure 3. Estimated E modulus using Equations (7) and (8).

Equation (8) was selected for compression because it is newly derived and also because of its similarity to Equation (7), which uses only the RMR as a determining factor.

As a comparison, the estimated E modulus based on Equations (7) and (8) determined using the three sites' RMR quantities are plotted in Figure 3.

This diagram demonstrates that both equations have similar results. They are correlative at a high level. Nonetheless, after a certain point, Equation (8) predicts larger values for E. Both relations could be used as estimation tools, even in a conservative treatment, for RMRs less than 60. For higher RMR quantities, Equation (7) seems more appropriate.

However, there are still some limitations to using both equations when the reliability of E modulus quantities is checked. As illustrated in Figure 3, the predictions from the two equations deviate from each other for RMR > 80.

To investigate this issue further, calculated quantities for the E modulus from both equations in the mentioned range are presented in Table 5.

As indicated in Table 5, for an RMR range greater than 86, Equation (8) resulted in an E modulus between 50 and 140,

Table 5. E modulus calculated from empirical equations

RMR	E modulus calculated from Equation (7)	E modulus calculated from Equation (8)
84	25	42
85	26	45
86	27	49
87	29	52
88	30	57
89	31	61
90	33	66
91	34	71
92	35	76
93	37	82
94	39	89
95	40	96
96	42	103
97	44	112
98	45	120
99	47	130
100	49	140

Table 6. Typical values of Elastic modulus of intact rocks (after ASSHTO 1989)

Rock type	No. of values	No. of rock Types	Elastic modulus (Gpa) Max	Min	Mean	Standard Dev.
Granite	26	26	100	6.41	52.7	24.5
Diorite	3	3	112	17.1	51.4	42.7
Gabbro	3	3	84.1	67.6	75.8	6.69
Diabase	7	7	104	69	88.3	12.3
Basalt	12	12	84.1	29	56.1	17.9
Quartzite	7	7	88.3	36.5	66.1	16
Marble	14	13	73.8	4	42.6	17.2
Gneiss	13	13	82.1	28.5	61.1	15.9
Slate	11	2	26.1	2.41	9.58	6.62
Schist	13	12	69	5.93	34.3	21.9
Phyllite	3	3	17.3	8.62	11.8	3.93
Sandstone	27	19	39.2	0.62	14.7	8.21
Siltstone	5	5	32.8	2.62	16.5	11.4
Shale	30	14	38.6	0.007	9.79	10
Limestone	30	30	89.6	4.48	39.3	25.7
Dolostone	17	16	78.6	5.72	29.1	23.7

but according to Table 6, the E modulus averages are generally not this high. Additionally, the E quantities calculated using Equation (7) with max = 50 remain in the correct range and seem less risky. It should not be forgotten that these formulations are for hard rocks; soft rocks demand their own estimation relations, such as the search conducted by Nihat *et al*. (2008) who studied deformability using pressure meter results on soft rocks.

5. Conclusion

Measurement of the deformation modulus of rock masses by in situ tests is time-consuming, expensive and, in some cases, even impossible to carry out. Therefore, this parameter sometimes is estimated indirectly using correlations with various rock properties, such as the UCS, and with various rock classification indices, such as the RQD (Rock Quality Designation), RMR (Rock Mass Rating), Q (Q-System) and GSI (Geological Strength Index). Different empirical relations have been derived by researchers, and some of the equations have a good estimation ability. In this study, we investigated the various rock mass E modulus relations by employing approximately 82 dilatometer test results from three sites. The correlations showed that the UCS, RQD and RMR are correlated well with the E modulus of a rock mass. RMR was found to be the best choice for estimating the E modulus. Based on the review of the existing relations, the data were used to make these relations more accurate if possible. A simple relation that is similar to the equation suggested by Gokceoglu *et al.* (2003) but that is more conservative and presents more acceptable results for the recorded range of the E modulus was chosen.

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