ESTABLISHING NEW CORRELATIONS FOR ROCK MASS DEFORMABILITY DETERMINATION

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Summary: *As a part of geotechnical research at several locations in Republika Srpska and Federation of Bosnia and Herzegovina, detailed geotechnical investigations of rock masses were carried out. On the abovementioned exploration sites, terrain is composed of different rock masses (Cretaceous limestone, Palaeozoic gneiss, Mesozoic peridotite and serpentinite). This paper presents an overview of correlation between uniaxial strength, elastic wave velocity and rock mass quality, on one side and in situ obtained results of rock mass deformability, on the other side. Modification of the correlation between deformation modulus and rock mass quality in a form of correctives for each of the equations by Galera, Alvarez and Bieniawski, was also presented. All deformability tests were carried out by the Institute for the Development of Water Resources „Jaroslav Černi" Belgrade.*

Keywords: *rock mass, deformability, correlations.*

1. INTRODUCTION

Knowing the rock mass deformability characteristics is of great importance for stress - deformation analysis of engineering objects built in rock masses.

The best way to determine rock mass deformability characteristics is *in situ* testing: hydraulic flat jack, plate loading test and dilatometer test [1,2]. Other approaches are indirect methods based on statistical modelling.

There are many papers dealing with the definition of correlations between the deformation modulus on one side and RMR, wave velocity and uniaxial strength on the other side [3] - [9].

This paper presents an overview of the correlation between results of RMR, wave velocity and uniaxial strength and *in situ* obtained results of rock mass deformability based on detailed geotechnical investigations of rock mass at the dam "Bočac", dam "Jelašnica", as well as at the nine barriers on the Ibar river [10]. A new modification of

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the correlation between the deformability modulus (D) and rock mass quality (RMR) in a form of correctives of equations is presented below.
As a part of geotechnical rock mass investigations, a direct, *in situ* testing of rock mass deformability under pressure was carried out. The deformability dilatometer tests in the boreholes gave the values of static deformability characteristics of rock mass, that is, of the deformation modulus. Geophysical tests along the boreholes at dilatometer testing locations and detailed engineering geological mapping of the core were performed. In addition, samples were taken out for uniaxial strength tests.
By applying these testing procedures, it was possible to define rock mass characteristics at the sites of dilatometer experiments: velocity of seismic waves (V_p [km/s]), classification parameters (RMR), geological strength index (GSI) and uniaxial strength of intact rock (σ_{ci}) and to establish the correlation between the obtained values of deformation modulus (D) and the abovementioned characteristics of rock mass.

2. ROCK MASS TESTING LOCATIONS

Dilatometer tests covered different types of rock masses. Limestone was examined at the “Bočac 2” dam. This rock mass was mostly moderately fractured, and to a lesser extent it was compact, with small fracture density. The site of “Jelašnica” dam was built from gneiss. The gneiss rock mass was highly fractured and intensely changed. The barriers on the Ibar river are located in the peridotite rock mass, represented dominantly by serpentinite, dunite and harzburgite. One barrier site is partly built of andesite, and one is completely located in granite and granodiorite. The peridotite was fractured and changed in varying degrees; andesite was less fractured, while granites and granodiorite were moderately fractured.
A total of 90 dilatometer experiments were performed and compared. The most experiments were done in serpentinite (39), and least in granite - granodiorite, gneiss and dunite - harzburgite (9 each).

3. DETERMINATION OF DEFORMATION MODULUS USING DILATOMETER

Figure 1. Dilatometer prepared for testing

Testing with dilatometer (Figure 1.) produced by “Telemac”, which measures volume changes, was performed in a borehole with a diameter of 76.0 mm and maximum depth

of 35.0 m. The cylindrical dilatometer probe was lowered into the borehole to the specified depth at which the rock mass was loaded in pressure by hydraulic jack, after which measurement of volume change was recorded.
Figure 2. illustrates typical stress - volume diagram from deformability test using the dilatometer method.

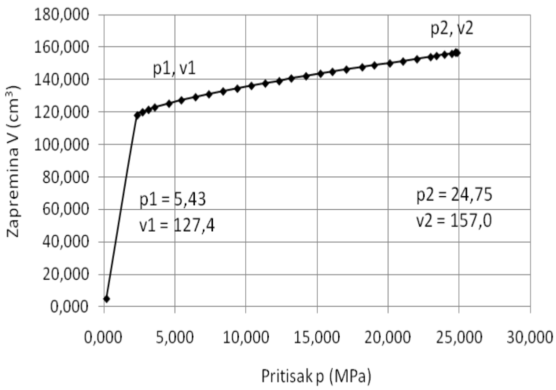

Figure 2. Stress - volume diagram

4. OVERVIEW OF PROPOSED CORRELATIONS FOR DEFORMATION MODULUS CALCULATION

By increasing uniaxial strength, velocity of elastic waves and RMR class, the deformation modulus is also increased. However, there are rheological phenomena that compromise these relationships to a certain extent.
Due to the size effect, the ratio of uniaxial strength - deformability has reduced reliability. Also, velocity of elastic waves is defined along a profile with a length of several hundred meters, and on this length, local occurrences of fractured, low-velocity rock masses are possible within highly monolithic and high-velocity rock masses. Also, RMR values are of subjective character (they describe the fracture state).
The proposed correlation presented in [10] has three variables. The first depends on RMR, the second one on velocity of elastic waves, and the third on uniaxial strength. However, each member has a coefficient (a, b, and c) whose value depends on the size of the corresponding parameter and they correct the influence of each variable on the final result. The final correlation for defining the deformation modulus is:

$$D = e^{\frac{RMR-100}{a}} \cdot b \cdot \sqrt{\frac{V_p}{100}} \cdot e^{\frac{\sigma_{ci}}{c}} \quad [\text{GPa}] \tag{1}$$

The coefficient values a, b and c are obtained depending on the variable values. Coefficient a is obtained based on the expression (2) or (3), coefficient b based on the expression (4), and coefficient c based on the expression (5).

$$a = 2 \cdot RMR - 80 \quad (RMR \geq 45)$$
$$a = 20 \quad (RMR < 45) \tag{2}$$

$$a = logRMR \cdot RMR - 10 \cdot \sqrt{RMR} + 5 \quad (RMR \geq 37)$$
$$a = 20 \quad (RMR < 37) \tag{3}$$

$$b = \ln V_p[\frac{km}{s}] - 0.30 \tag{4}$$

$$c = 210 - \sigma_{ci} \tag{5}$$

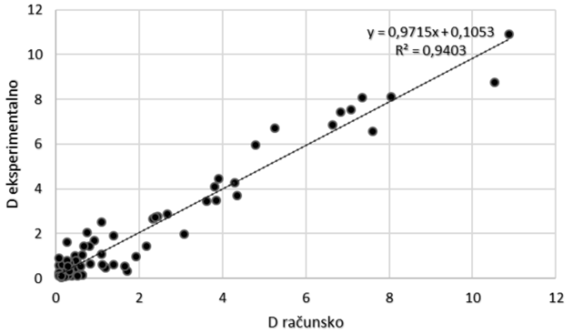

Figure 3. Pearson correlation coefficient of the analytical model according to the expression (1)

Correlations show a good agreement between analytical and experimental values. The accuracy of the model was verified by calculating the mean squared error RMSE (6), the mean absolute error MAE (7) and Pearson coefficient (8).

$$RMSE = \sqrt{\frac{1}{N} \cdot \sum_{i=1}^{N} (y_{mi} - y_i)^2} \tag{6}$$

$$MAE = \frac{1}{N} \cdot \sum_{i=1}^{N} |y_{mi} - y_i| \tag{7}$$

$$r = \frac{\sum_{i=1}^{N} (y_{mi} - \bar{y}_m)(y_i - y)}{\sqrt{\sum_{i=1}^{N} (y_{mi} - \bar{y}_m)^2 \sum_{k=4}^{N} (y_i - y)^2}} \tag{8}$$

Table 1 gives accuracy parameters calculated for certain models according to other authors listed in the literature.

No.	Model according to	Model accuracy parameters		
		RMSE	MAE	r
1	**(1)**	**0.637**	**0.485**	**0.9697**
2	[4]	12.088	9.615	0.905
3	[11]	3.265	2.138	0.591
4	[12]	12.302	9.766	0.930
5	[13]	15.001	10.850	0.931

Table 1. Overview of accuracy parameters for different models

The accuracy parameters of the model defined in the expression (1) are given in the first row of Table 1. In rows 2-5, the accuracy parameters of the models described in [4, 11, 12, 13] are given. They are calculated using the same set of data obtained from exploratory boreholes.
The proposed correlation in the expression (1) gives more realistic values of the deformation modulus than the correlations of other authors, since it takes into account three variables (RMR, V_p, σ_{ci}). In the study presented in [11], one variable (V_p) was used. Also, one variable (RMR) was used in the researches presented in [12, 13], while two variables (RMR, σ_{ci}) were used in the study presented in [4].
In terms of accuracy, models defining the deformation modulus with one variable [11, 12, 13] have significantly higher values of mean squared (6) and mean absolute errors (7) than the proposed model with three variables (1). The model with two variables [4] is better than the models presented in [12] and [13], but it is worse than the model (1) previously suggested by the authors of this paper.

5. SUGGESTION OF NEW CORRELATIONS FOR DEFORMATION MODULUS CALCULATIO

In order to better correlate RMR and the deformation modulus, in this paper, a modification of the equation [4] has been proposed, and it has given significantly better results of the deformation modulus. The proposed modified expression is as follows:

$$D = \frac{1}{8} \cdot \sqrt{\frac{\sigma_{ci}}{100}} \cdot 10^{\frac{RMR-10}{40}} \quad \text{[MPa]} \qquad (9)$$

Furthermore, a modification of the equation [13] was performed, which also gave very good results. The authors suggested two different equations depending on the quality of rock mass, so two different corrections for each equation are given:

$$D = \frac{0.0876 \cdot \mathrm{RMR}}{\sqrt{2 \cdot \mathrm{RMR} - 10}} \text{ [GPa] za RMR<50} \tag{10}$$

$$D = \frac{(0.0876 \cdot \mathrm{RMR} + 1.056 \cdot (\mathrm{RMR}-50) + 0.015 \cdot (\mathrm{RMR}-50)^2)}{\sqrt[3]{10 \cdot \mathrm{RMR} - 1}} \text{ [GPa] za RMR>50} \tag{11}$$

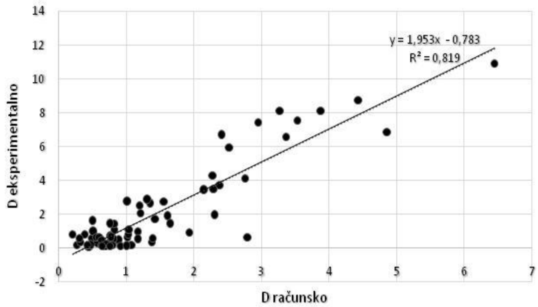

Figure 4. Pearson correlation coefficient of the analytical model according to the expression (9)

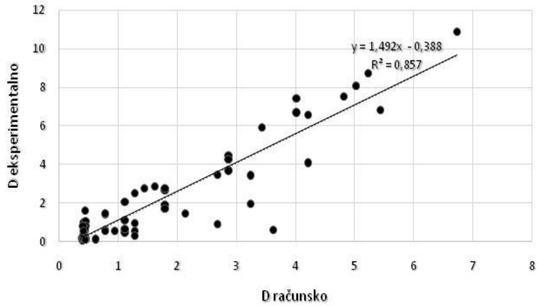

Figure 5. Pearson correlation coefficient of the analytical model according to the expressions (10) and (11)

Correlations show a relatively good agreement between analytical and experimental values. which can be seen from the data presented in Table 2. For these modified and original models, the mean squared error RMSE (6), the mean absolute error MAE (7), and Pearson coefficient (8) are given. They are calculated using the same set of data obtained from exploratory boreholes.

No.	Model according to	Model accuracy parameters		
		RMSE	MAE	r
1	**(9)**	**1.700**	**1.122**	**0.905**
2	[4]	12.088	9.615	0.905
3	**(10, 11)**	**1.323**	**0.882**	**0.926**
4	[13]	15.001	10.850	0.931

Table 2. Overview of accuracy parameters for different models

Based on the data presented in Table 2, the suggested correlations in expressions (9), (10) and (11) give more realistic values of the deformation modulus than the original expressions [4] and [13].

6. CONCLUSION

In engineering practice, prediction of the deformation modulus is most often based on one of the determined rock mass characteristics that is directly related to fracture state (RMR, Q, RMI) or on velocity of elastic waves. A smaller number of correlations takes into account the uniaxial strength.
The reliability of these correlations is influenced by the size effect as well as heterogeneity and anisotropy of rock mass. In addition, rock mass can be exposed to intense endogenous and exogenous forces in certain areas. These forces can, to some extent, altere the intact state of the rock mass in terms of decrease in quality. Because of the above it is impossibile to rely with certainty on the correlations given by different authors for defining the deformation modulus in everyday engineering practice.
The proposed equations for defining the deformation modulus are influenced by each of the three essential characteristics of rock mass (RMR, V_p, σ_{ci}) or the fracture state, and the developed models showed a good accuracy in comparison to the models of other authors.
In accordance with the previous discussion, correction of the output result is performed in case that any of the characteristics, which has an influence on defining the deformation modulus, for some reason does not give an objective result.

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УТВРЂИВАЊЕ НОВИХ ЗАВИСНОСТИ ПРИ ОДРЕЂИВАЊУ ДЕФОРМАБИЛНОСТИ СТЕНЕ

Резиме: *У оквиру геотехничких истраживања на неколико места у Републици Србији и Босни и Херцеговини извршена су детаљна геотехничка испитивања стенске масе. На наведеним истражним локацијама терен граде различите стенске масе (кредни кречњаци, палеозојски гнајсеви, мезозојски перидотити и серпентинити). У раду је приказан осврт на повезивање резултата једноаксијалне чврстоће, брзине еластичних таласа и квалитета стенске масе са добијеним резултатима испитивања деформабилсности стене на терену. Представљена је и модификација корелације између модула деформабилности и квалитета стенске масе у виду коректива за сваку од једначина чији су аутори Galera, Alvarez и Bieniawski. Сва наведена испитивања деформабилности извршена су од стране Института за водопривреду „Јарослав Черни“из Београда.*

Кључне речи: *стенска маса, деформабилност, корелације.*