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Deformation modulus determination from pressuremeter and dilatometer tests for crystalline rock

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Abstract. The deformation modulus is an important characteristic of the mechanical behaviour of rock mass. The deformation parameters of rock mass may be obtained by execution of in-situ tests. In situ testing comprises the most reliable and comprehensive methods to describe the mechanical behaviour of the rock mass. Results of pressuremeter and dilatometer tests for crystalline rocks and their interpretation are presented in the paper. Comparison of two types of in-situ geotechnical tests results was analysed based on ground investigation for new expressway in Slovakia. In the evaluated section, an extensive part of the expressway is situated on bridges. During geological investigation, 161 of dilatometer and 150 of pressuremeter tests were carried out to determine rock parameters. Logging measurements were conducted in each borehole in advance of geotechnical testing to select the best testing section of the borehole. Consequently, the pressuremeter and/or dilatometer tests were performed in selected boreholes. It was observed that the difference between deformation modulus determined by dilatometer and pressuremeter tests are significant especially for intact rock with high value of Rock Quality Designation (RQD). Correlations for estimating rock deformation parameters were derived based on analysis of the results from dilatometer and pressuremeter in-situ testing of crystalline rocks.

1. Introduction

Design engineering geological and hydrogeological investigation for a new expressway R2 – Kriváň – Lovinovaňa – Tomášovce was carried out mainly for new bridges foundations. Investigation boreholes were drilled to determine geotechnical properties of rock massif (deformation and strength). Geotechnical tests included pressuremeter and dilatometer tests, complemented by laboratory tests of rock mechanics and borehole logging. These complex in-situ tests allow to obtain comprehensive information about geological conditions and to create a ground model. Investigation boreholes and geotechnical tests were performed to develop relations between the value of Rock Quality Designation (or macroscopically estimated degree of faulting) and in-situ determined deformational parameters. Such relation would allow to estimate a deformation parameter of rocks in places where it is not possible to perform a testing borehole and only an investigation pit without the possibility to conduct an in-situ geotechnical test.

It is almost unreal to simulate the real geological situation prevailing on testing site by laboratory testing. Therefore, the laboratory tests were conducted only on such rock samples which have saved their geomechanical properties after in-situ sampling, transportation, and preparation in laboratory. In the investigated area, the samples included mainly homogenous and fresh rocks with minimal disruption. On the contrary, it was not possible to take samples from others rock types, mainly strongly weathered,



altered, and tectonically disrupted rocks, or the samples were not representative. These types of rocks were characterised only on the base of in-situ geotechnical tests.

The deformation modulus is an important characteristic of mechanical behaviour of rock mass. The deformation parameters of rock mass may be obtained by execution of in-situ tests. In situ testing is considered to be the most reliable and comprehensive methods to describe mechanical behaviour of rock mass [1-4]. Complex in-situ tests allow obtaining comprehensive information about geological conditions. Results from geotechnical tests which included pressuremeter and dilatometer tests complemented by laboratory tests of rock and borehole logging are analysed in this paper.

The indirect methods for deformation parameters determination can be divided into empirical correlation methods and the equivalent continuum approach [5, 6]. In this paper, simple expressions are derived for estimating the deformation modulus using rock quality designation (RQD) and degree of faulting.

2. Model locality description

The expressway R2 Kriváň – Lovinobaňa – Tomášovce is situated in southern part of Slovakia and passes through Slovenské stredohorie mountains. Route of motorway follows roughly the line of Kriváňský Potok River between Kriváň and Lovinobaňa. The route changes the side of valley several times and leads mainly in the cuts and on the bridges.

The area is formed by crystalline rocks of southern Veporicum and metamorphic crystalline rocks of Revúca group (perm). In situ tests were performed mainly in this area. The route of the highway continues south of this region and touches the Mesozoic carbonate massive (dolomites, see Figure 1) close to Divín, where some of dilatometer and pressuremeter tests were done. In the southern part of the route, the geotechnical tests were conducted also in Neogene basaltic body near Podrečany.

Palaeozoic crystalline massif of this area consists of wide varying types of granitoids, such as granite, tonalite, granodiorite, diorite, migmatite with bodies of paragneisses or amphibolites. Palaeozoic metamorphic complex consists of slightly metamorphosed sandstones and volcanoclastic sediments, or of phyletic schists, phyllites, thin layers of volcanogenic material, and very sporadic intrusive bodies of acid rhyolite metavolcanoclastics. All these sediments are recrystallized due to regional metamorphose and schistose. In addition, breccias occur in the area of Mesozoic dolomites.

Neogenous sediments consist of gravels and sands, which continuously change to silts and clays [7]. Sand and gravel layers are characterized by relatively good strength properties, but what influences the construction activity negatively is the fact that they constitute an artesian aquifer [8]. In some parts of the region, neogenesis rocks occur – basalts and volcanoclastic sediments. Geotechnical tests were conducted in these rocks as well. Realised detailed engineering-geological investigation for the expressway R2 Kriváň - Lovinobaňa – Tomášovce is a good example of using two types of in-situ geotechnical tests. In the evaluated section, an extensive part of the expressway is situated on bridges. The basic demand of the contractor was a design investigation and a ground model for each single bridge pillar as well as the determination of foundation type. For these purposes, a double-barrel core borehole with water flush was used. Moreover, logging measurements were conducted in each borehole in advance of geotechnical testing to choose the best testing section of the borehole. Consequently, the pressuremeter and/or dilatometer tests were conducted in selected boreholes.

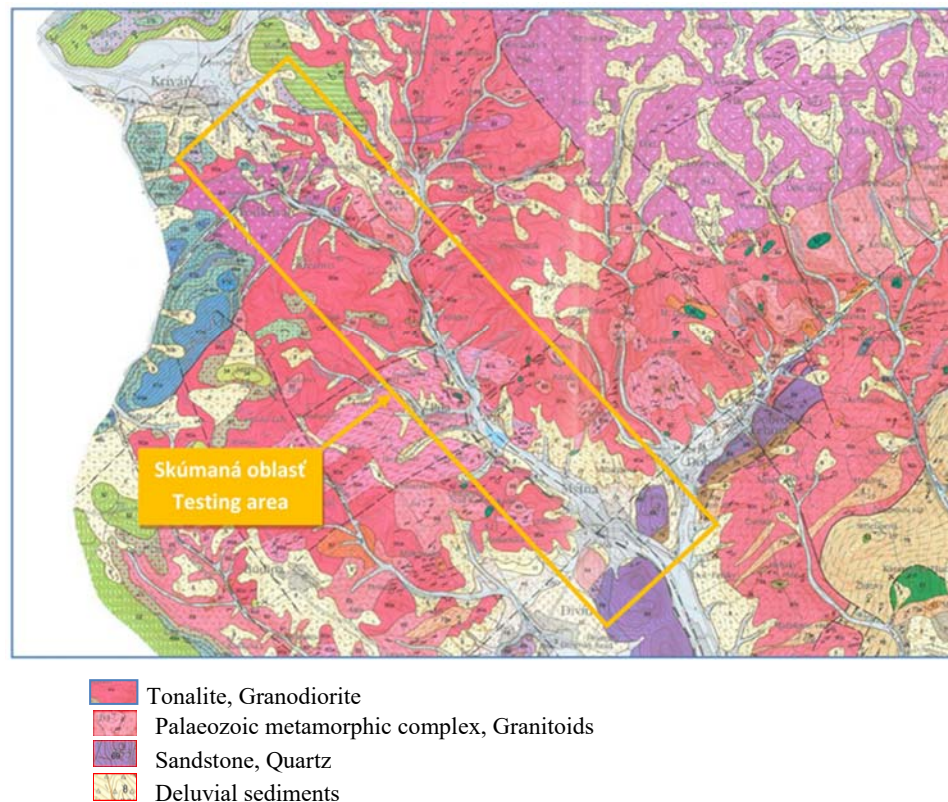


Figure 1. Geological map of tested area in scale M 1: 50 000, [9]

During geological investigation, 161 of dilatometer and 139 of pressuremeter tests were done in total and 145 dilatometer tests and 139 pressuremeter tests were performed for the same rock type (see table 1). Such number of tests represents an extensive and representative set of results suitable for further statistical processing.

Table 1. Overview of realised field tests

Lithological type	Number of dilatometer tests	Number of pressuremeter tests
Granodiorite	73	47
Diorite	10	5
Migmatite	17	8
Gneiss	35	62
Dolomite	5	8
Basalt	5	9
All tests	145	139

3. Results and discussions

3.1. Pressuremeter and dilatometer tests evaluation

For dilatometer and pressuremeter tests in similar rock environment, values of deformation modulus were derived. Modulus of deformation $E_{\text{def PR}}$ was derived in lower load range from dilatometer tests. This lower load range corresponds with common load range of pressuremeter tests and with maximum reached limit pressure (within the meaning of pseudolinear behaviour during pressuremeter test). An example of a dilatometer test evaluation is shown in Figure 2, where load ranges used for deformation

modulus calculation are displayed – red range shows a maximum used limit pressure (dilatometer test), blue range shows a maximum load range in the case of pressuremeter test.

The relation between values of E_{def} (modulus of deformation from dilatometer test) and $E_{\text{def PR}}$ (modulus of deformation from dilatometer test for lower load range) for 91 realised dilatometer tests were graphically plotted in semi-logarithmic scale (see Figure 3). By applying a regress analysis on data, it is possible to deduce a mutual relation between variables – in this case it appears to be a logarithmic curve. As shown in Figure 3, the variation of derived values $E_{\text{def PR}}$ for lower load range is highly significant at high values of E_{def} . The plotted points are widely scattered in the range 30 000 MPa to 100 000 MPa. It is likely that at low load pressures and in the case of compact rocks, the pseudolinear relation state between load pressure and volumetric deformation of rock is not reached.

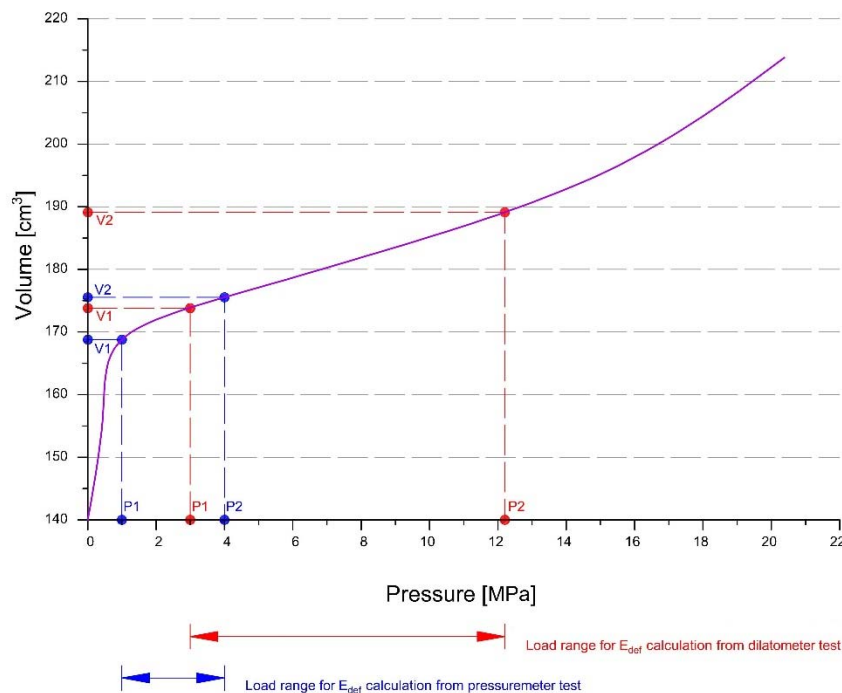


Figure 2. Typical course of dilatometer test with different load range

During the execution of dilatometer and pressuremeter tests, further parameters of rock environment were collected in the field. In addition to detailed geological description of rocks, the macroscopical description and the degree of weathering or faulting was determined. If a proper drilling method is applied, it is also possible to determine a value of RQD . This parameter is one of the most important for evaluation of rock massif quality, which is also the basic parameter for geotechnical design. Relationship between RQD value and the results of field tests were analysed. In the two following graphs, the relations between RQD value and calculated deformation modulus E_{def} from dilatometer tests (Figure 4) and pressuremeter modulus E_p from pressuremeter test (Figure 5) are shown. These figures show that values E_{def} or E_p respectively vary around the regression curve (exponential function), whereas they do not depend on rock lithological type with the exception of tectonically totally degraded rocks (tectonites) with $RQD = 0$. It can be seen that in $RQD = 0$, a lot of different values of deformation modulus E_{def} /pressuremeter modulus E_p are cumulated, whereas dispersion of values reaches more than 3 orders (1000 times). In these Figures, it is indicated that in the case of the highest quality rock types with high RQD values, the pressuremeter tests are not able to provide representative information about deformational properties of rocks. Pressuremeter modulus values significantly deviate from deformation modulus

(extreme value more than 100 times). Relation between E_{def} and RQD from dilatometer tests for lower load range is presented in Figure 6.

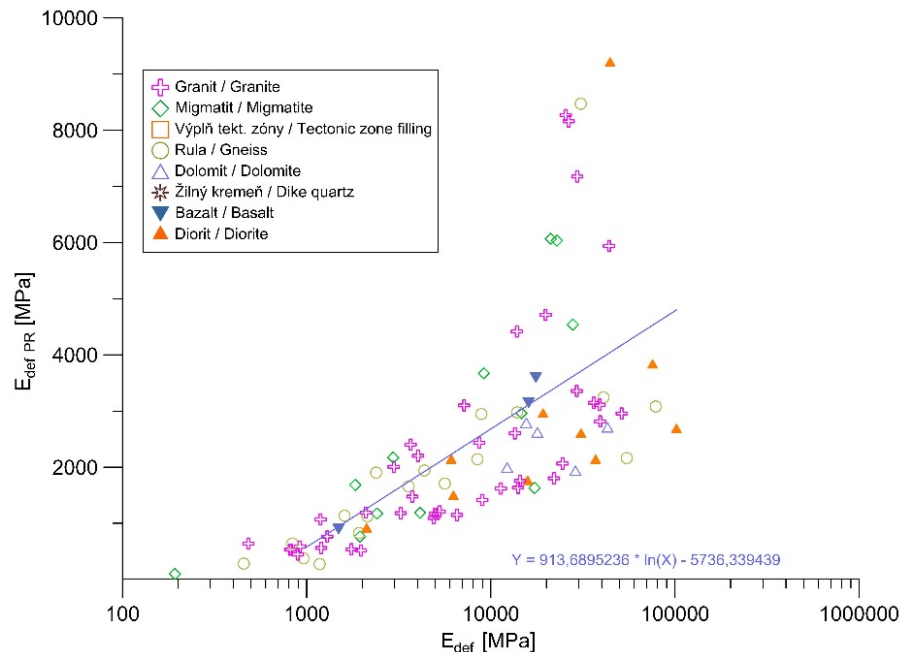


Figure 3. Relation between E_{def} a $E_{\text{def PR}}$ for 91 realised dilatometer tests

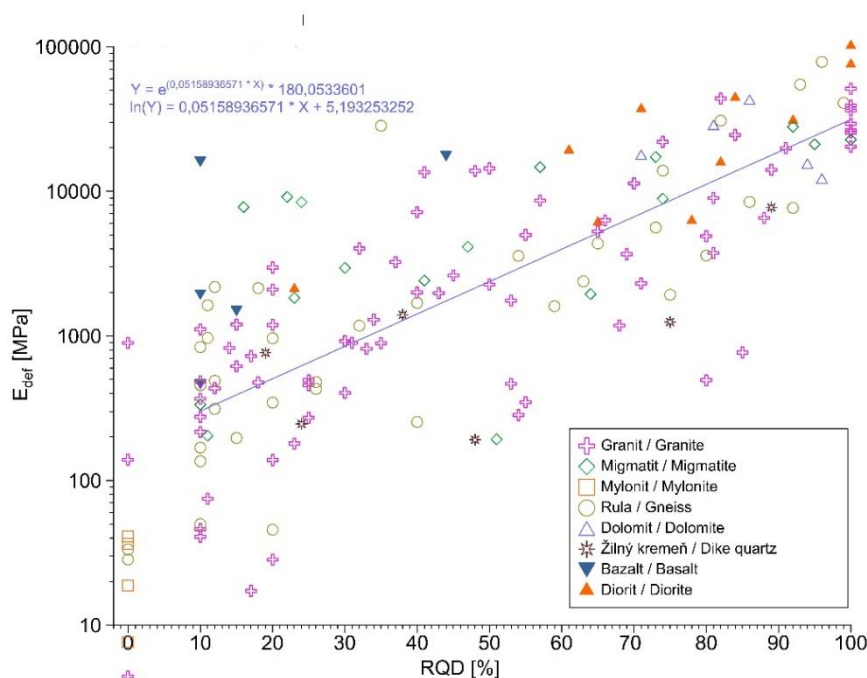


Figure 4. Relation between E_{def} and RQD from dilatometer tests

3.2. Statistical processing of in-situ test results

Analysis of the relationship between degree of faulting or value RQD and deformation modulus can be a very useful tool for estimating deformation modulus E_{def} or pressuremeter modulus E_p in the field.

Determined values of RQD can be classified into groups according to its value. In this analysis, five groups have been created with ranges 0 – 25%, 25 – 50%, 50 – 75%, 75 – 90%, and 90 – 100%. Intervals are not of the same size. Similarly, a classification for macroscopic estimation of faulting degree was created, where the degrees are defined as follows:

- 1 – Intact undisturbed rock,
- 2 – Slightly jointed rock,
- 3 – Strongly jointed rock,
- 4 – Foliateous or very dense jointed rock, breccia
- 5 – Tectonically crushes rock (cataclastic, soil-like).

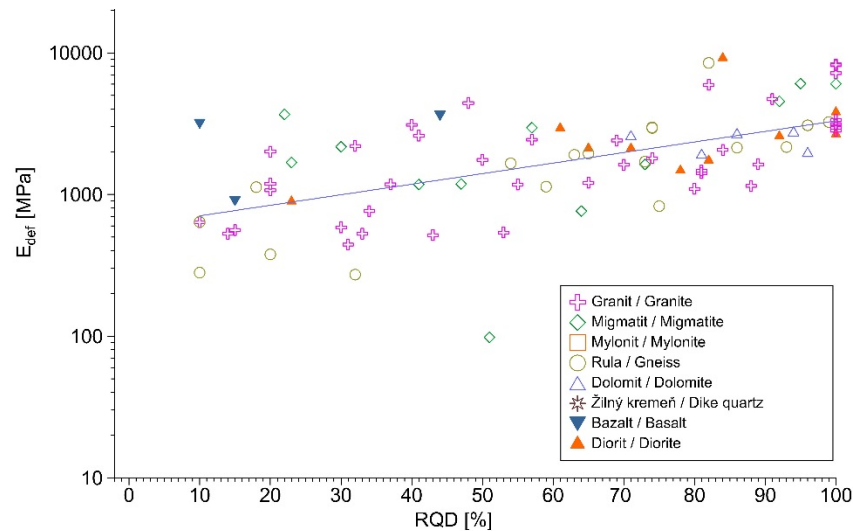


Figure 5. Relation between E_p and RQD from pressuremeter tests

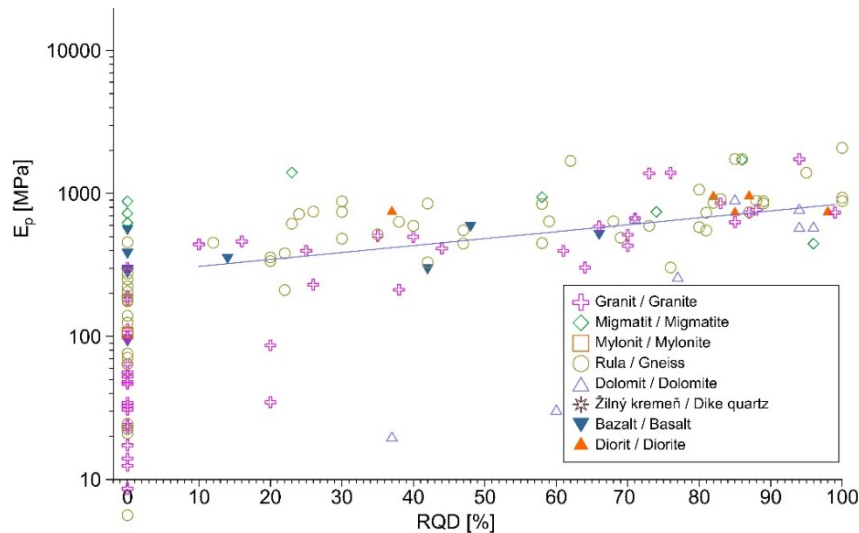


Figure 6. Relation between E_{def} and RQD from dilatometer tests for lower load range

For this evaluation of relation, the analysed samples in the data set of pressuremeter or deformation modulus were only from crystalline rocks, i.e. all tests in volcanic rocks have been excluded. Crystalline rocks are represented by granites, diorites, gneiss, migmatites and their mutual interchanges in different degrees of weathering and faulting. Such population consists of 150 dilatometer test results and data set of pressuremeter tests consists of 121 test results. The relationship between deformation modulus and

group values RQD was analysed as well as the relation between deformation modulus and macroscopically evaluated degrees of faulting, both for pressuremeter and dilatometer tests. The relation between the value of pressuremeter modulus E_p and group values RQD is shown on the left side of Figure 7. The relation between E_p and macroscopically evaluated degrees of faulting (jointing) is presented in the Figure 7 on the right side. An increase of the value dispersion for pressuremeter modulus E_p can be seen (in the range 3 – 1401 MPa or 3 – 624 MPa, respectively) in the most faulted rocks. In the case of less jointed rocks, the variation of E_p values is not significant. It is likely that this fact is caused by a very wide definition of the last group of rock jointing. Small-debris jointed rock with uneven surface and locked edges together with weak and soft rock (clay with debris) are included in this group.

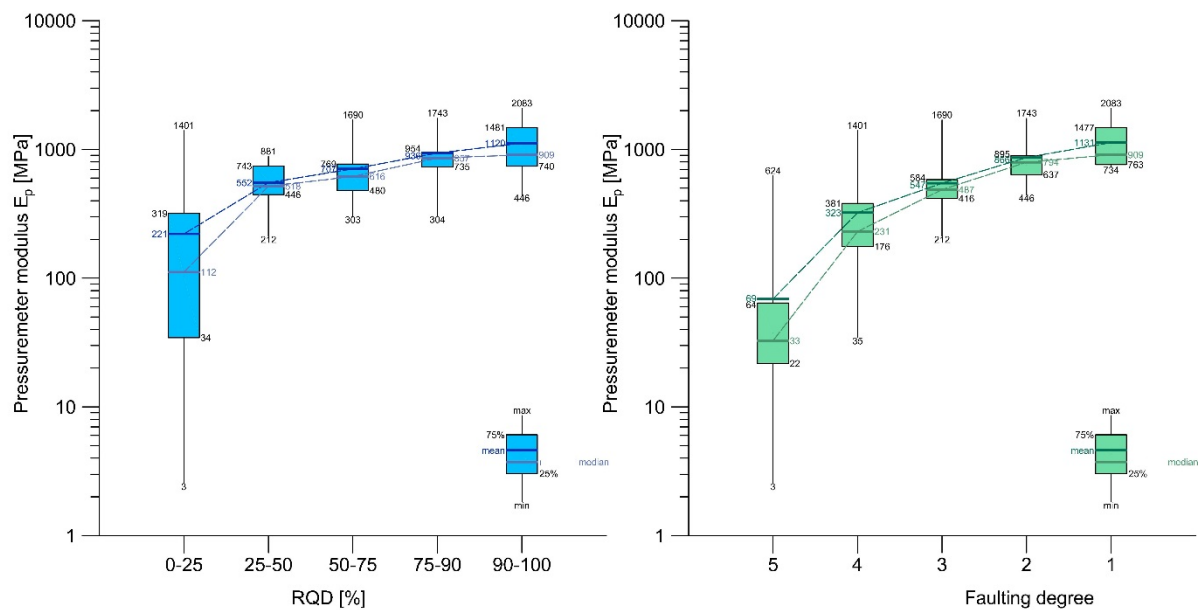


Figure 7. Variation of pressuremeter modulus E_p according to RQD (left) or macroscopically estimated degree of faulting (right)

If the regression curve is put over median course, there will be polynomial curve of the 2nd degree defined for the relation between RQD group and median E_p by the following equation:

$$E_p = -260.674 + 435.6651429 \cdot RQD - 40.36785714 \cdot RQD^2 \quad (1)$$

In the case of relation between degree of faulting and median E_p it is possible to define a regression polynomial curve of 2nd degree (Figure 7) by the following equation:

$$E_p = 1128.308 - 182.3809286 \cdot x - 8.218928571 \cdot x^2 \quad (2)$$

where x is the macroscopically estimated degree of faulting (jointing), the value is from 1 to 5.

The mean value (for evaluation according to macroscopic degree of faulting) is even out of second and third quartile for the most faulted (jointed) rocks.

If the regression fit curve is put over median course (Figure 8), there will be an exponential curve defined for relation between RQD group and median E_{def} by the following equation:

$$E_{def} = 175.73 \cdot e^{1.023 \cdot RQD} \quad (3)$$

For E_{def} determination based on *faulting degree* following equation could be used:

$$E_{\text{def}} = 153692 * e^{-1.688 * x} \quad (4)$$

where x is the macroscopically estimated degree of faulting (jointing), the value is from 1 to 5.

The mean values deviate significantly from median and even from the second and third quartile. At low population, the mean value of test results responds to extreme values very sensitively, i.e. to minimum and maximum values in the data set. For further analysis, it would be desirable to extend the input data sets and to eliminate extremes. In this case, all measured tests results were used.

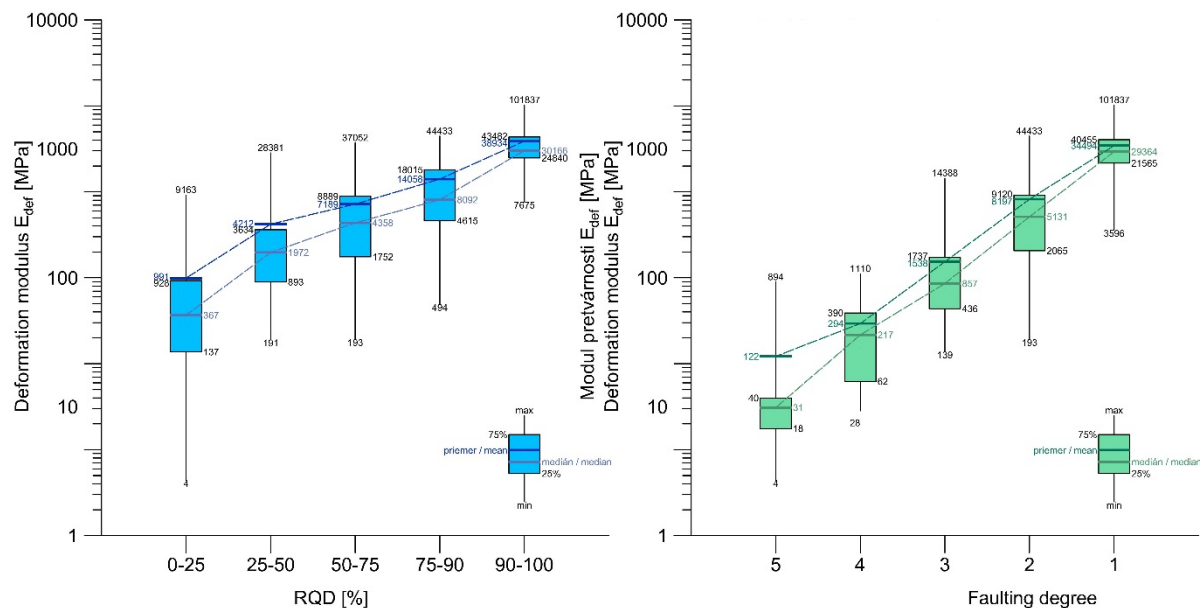


Figure 8. Variation of deformation modulus E_{def} according to RQD (left) or macroscopically estimated degree of faulting (right)

4. Conclusions

The geomechanical properties of rock masses can be measured through direct or indirect investigations. The direct methods include laboratory tests on rock specimens and in-situ tests on field rock masses. Since laboratory tests on small specimens are often inadequate to predict the deformability of rock masses, in situ tests are necessary. Results of two in situ testing methods were compared in the paper. It was observed that the difference between deformation modulus determined by dilatometer and pressuremeter tests could be significant especially for intact rock with high RQD. In this case, a derived value of deformation modulus from pressuremeter tests could not be a representative value and the value of modulus was more than 100 times lower.

A helpful correlation for estimating rock deformation parameters can be derived from the equations based on analysis of the results from dilatometer and pressuremeter in-situ testing of crystalline rocks. Although various empirical methods have been developed, they come in many forms and are scattered in different sources as presented by Zhang [10]. Presented correlations are based on RQD or macroscopically evaluated degrees of faulting. This could be used in inaccessible places, where no drilling rig can be installed, therefore no field testing can be provided. Further analysis of a wider range of rock types in various degrees of jointing and weathering would contribute to a better understanding of the relation between different deformation parameters such as E_p and E_{def} . Such correlation would allow estimating deformation parameters of rocks on sites where it is not possible to perform a testing borehole or where ground investigation does not include any in-situ geotechnical test. Empirical equations for indirect estimation of the deformation modulus are simple and may be cost-effective in many engineering applications.

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