Engineering geological and geotechnical study of potencial host rock environments for radioactive waste disposal in Slovakia

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Abstract: Deep geological repositories are the best way to high-level radioactive waste and spent nuclear fuel disposal, which involves the safety and security aspects and the requirements of providing passive protection for future periods after their closure. The aim of this study is to present knowledge about host rock engineering geological and geotechnical properties obtained from preliminary engineering geological investigation on two the most perspective sites for the construction of the deep geological repository in Slovakia. In the crystalline environment, it is the central part of Tribeč Mts.; in the sedimentary environment, it is the southern part of Slovakia (area between Rimavská kotlina basin and Cerová vrchovina Upland). The use of several different testing methods proves to be necessary for the reliable characterization of the host rock environment. Results of laboratory tests on determination of key characteristics are presented and compared with results of field tests realised in comparable rock environments. Since laboratory tests on small specimens are often less reliable to predict the deformability of rock masses, in situ tests are necessary. Dilatometer and pressuremeter testing in comparable crystalline rock environments are analysed, focused on the deformation modulus determination. Statistical analysis to develop relations between the in-situ detected value of Rock Quality Designation or macroscopically estimated degree of faulting in the borehole and deformation parameters is presented. However, dilatometer field tests are universal for various geological conditions and these test methods can be consistently applied to later site investigation stages process.

Key words: deep geological repository, high-level radioactive waste, geological barrier, host rock environment, geotechnical parameters, laboratory and field tests

1. INTRODUCTION

Every waste-producing country must have its national programme for the managing a radioactive waste of each type. Based on existing European documents (e.g. European Directive 2011/70/EURATOM of 19 July 2011), it is necessary to consider the construction of a deep geological repository (DGR). However, European legislation assumes that radioactive waste will be disposed of in the Member State where it was produced.

The isolation of radioactive waste from the environment and the long-term safety of a repository is assured by a combination of multiple engineered and natural barriers (so-called multi-barrier system). A suitable host geological environment provides the natural barrier. The essential requirement for DGR is to ensure the long-term stability, safety, durability, and isolation of radioactive waste from people and the environment. Therefore, the issue of design and construction a safe repository for high-level radioactive waste (HLW) and spent nuclear fuel (SNF) is a long-term task that involves, among other things, knowledge of the rock environment, waste disposal strategy, feasibility studies, design of technical solutions, and safety analyses (Matejovič et al., 2006; Rozsypal, 2007; Slaninka et al., 2007; IAEA Safety Standards, 2011; Dupray et al., 2013; Wang et al., 2018).

DGR typically consists of a network of underground tunnels and placement gallery rooms or boreholes for a radioactive waste constructed several hundred meters below the surface. Due to the demanding time, financial and technological requirements associated with the construction of the repository and the high demands on the safety and quality of knowledge of natural conditions, the research needs to use the knowledge and methodological procedures of several scientific and technical disciplines.

Finding a suitable stable geological structure for the permanent and safe disposal of HLW and SNF in DGR is a technically demanding and long-term process accompanied by extensive research. The site must meet highly demanding requirements and criteria regarding natural, technical, or technological parameters (Witherspoon & Bodvarsson, 2006; Slaninka et al., 2007; Kordík et al., 2008). The evaluation process for selecting a suitable site includes an engineering geological and geotechnical assessment of the host rock's basic physical and technical properties. The geological selection criteria represent only part of the conditions and factors leading to the final decision. The most important and crucial condition for the final selection of a site is its acceptability to the local population and the municipalities concerned (Witherspoon & Bodvarsson, 2006; Auffermann et al., 2015).

Granitoids as crystalline igneous rocks represent one of two rock environments for constructing a DGR in Slovakia. The advantage of this geological environment, in general, is the relatively sufficient areal and depth extent of individual granitoid massifs in the Western Carpathians, long-term stability, and satisfactory engineering geological, thermal, and technical properties of the rocks, low geothermal gradient and rare occurrence of mineral deposits (Kováčik & Lukaj, 2002). On the other hand, lithological and structural inhomogeneity, tectonic faulting, high

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hydraulic anisotropy (along fissures), and poor knowledge of the environment at depths more than 500 m are less favourable.

The second potentially suitable rock environment for a DGR in Slovakia is Neogene molasse sediments in the Juhoslovenská kotlina basin or Cerová vrchovina Upland. However, only some lithologically relatively monotonous clayey and silty sediments are being considered, located outside areas with potential groundwater, geothermal energy, and mineral reserves. The claystone strata with numerous sandstone layers cannot be used for this purpose. Neogene sediments of this basin are of sufficient thickness, high homogeneity, low hydraulic conductivity, and their tectonic disturbance is insignificant (Slaninka et al., 2012). However, disadvantages are low strength, high porosity and deformability, and other less favourable geotechnical and thermal properties.

The presented paper provides additional knowledge to previously published research on a host environment selection for the DGR in Slovakia (Slaninka et al., 2007; Frankovská et al., 2008; Kordík et al., 2008; Adamcová et al., 2009). It includes the knowledge from the crystalline and sedimentary rock environment based on selected engineering geological and geotechnical characteristics determined by field tests, laboratory research and application of comparable experiences. Furthermore, due to the limited geological survey in the first stages of the site selection process, the presented research shows how knowledge found in comparable rock environments on other sites can be used.

2. SITE SELECTION PROCESS FOR DGR IN SLOVAKIA

The selection of potencial sites for a DGR in Slovakia from geological aspects was dealt with by the State Geological Institute of Dionýz Štúr within the framework of two projects in period 1996 –1997 and 1998 –2000 (Kováčik et al., 1999; Kováčik et al., 2001). The second framework project was focused on a geophysical survey of prospective areas, neotectonic and geomorphological analysis and on preliminary design and evaluation of study sites. First selection of suitable sites was also based on the desk study and regional geological research, including mapping. As a result of the assessment process, the number of areas of interest was reduced from twelf initially proposed to six (Fig. 1).

A preliminary engineering geological investigation on six proposed sites included the drilling and sampling, field work and experimental laboratory testing. In the first stages, the determination of rock massifs characteristics was only focused on a crystalline rock environment. The boreholes up to depths of 200 – 250 m (RAO-1, RAO-2, RAO-3 and RAO-4) have been drilled on the selected sites. Core samples taken from different depth horizons were tested in the laboratory to determine of fundamental physical parameters. In the following stages, completed in 2001, the geological survey continued in the sedimentary rock environment by drilling the deep borehole RAO-5 in the Juhoslovenská panva basin. An overview of boreholes that were realised in the framework of engineering geological survey to select DGR sites is summarised in Tab. 1.

Based on the preliminary geological investigation results, it was recommended to continue the further exploration work and to carry out detailed geophysical, field and laboratory investigation at five sites, three of which are located in crystalline and two in sedimentary rock environments (Kováčik et al., 2001). The Žiar Mts. site was evaluated as the least suitable of the assessed territories and was therefore excluded from further assessment (Frankovská et al., 2008).

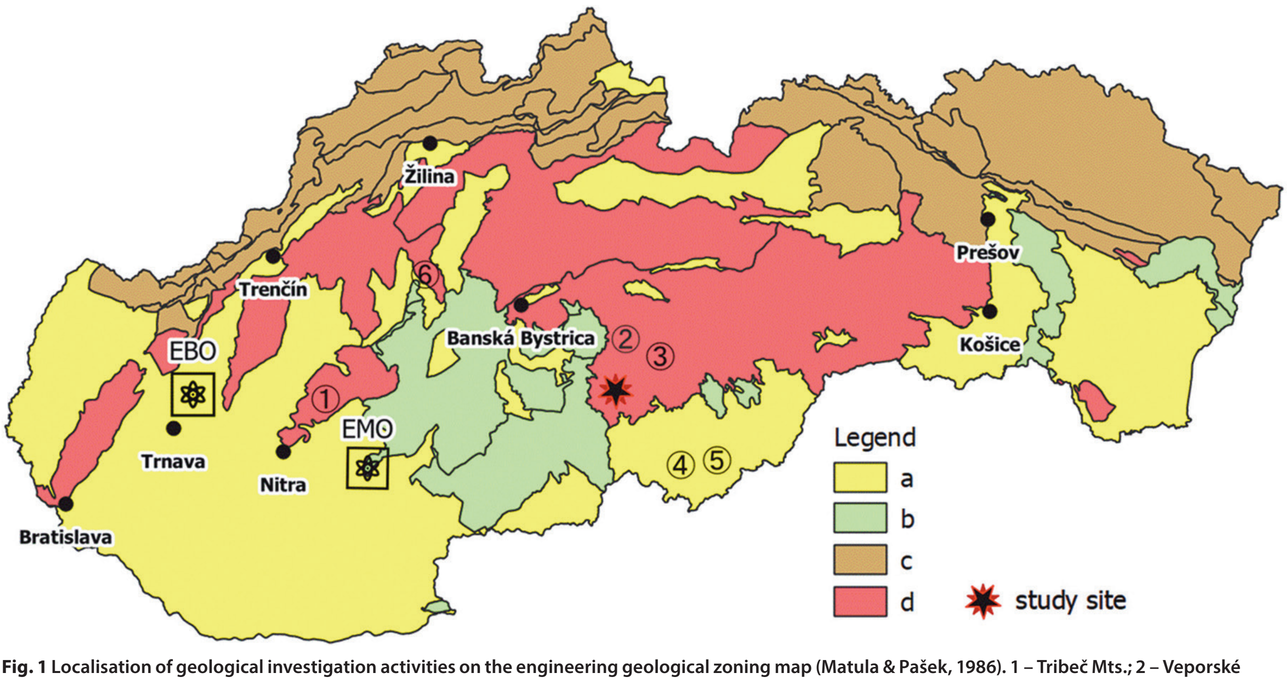

Fig. 1 Localisation of geological investigation activities on the engineering geological zoning map (Matula & Pašek, 1986). 1 – Tribeč Mts.; 2 – Veporské vrchy Mts.; 3 – Stolické vrchy Mts.; 4 – Rimavská kotlina Basin; 5 – Cerová vrchovina Upland; 6 – Žiar Mts.; a – region of Neogene tectonic depressions; b – region of Neogene volcanic mountains; c – region of Carpathian flysch; d – region of crystalline core mountains;, EBO – Jaslovské Bohunice nuclear power plant; EMO – Mochovce nuclear power plant; ∗site of field tests (Kriváň village in Veporské vrchy Mts.).

Tab. 1 Realized exploratory boreholes in the site selection process in Slovakia

Borehole	Depth (m)	Potential site	Rock environment type	Investigation period
RAO-1	201	Fabova hoľa Veporské vrchy Mts.	crystalline (granodiorites to tonalites)	1998–1999
RAO-2	200	Sihla area Veporské vrchy Mts.	crystalline (granodiorites to quartz diorites)	1998–1999
RAO-3	200	Kostoľany pod Tribečom Tribeč Mts.	crystalline (granodiorites to tonalites)	2000–2001
RAO-4	250	Budiš Žiar Mts.	crystalline (granites to granodiorites)	2000–2001
RAO-5	250	Gemerček Rimavská kotlina Cerová vrchovina	sedimentary (calcareous siltstones) Szecseny Schlier	2000–2001
GOR-1	100	Gortva Rimavská kotlina Cerová vrchovina	sedimentary (calcareous siltstones) Szecseny Schlier	2009–2012

Further information for the site selection process and characterisation of the host rock environment was provided by the solution of the geological task commissioned by the Ministry of Environment of the Slovak Republic (Slaninka et al., 2012), in which aspects of the suitability of the sedimentary rock environment were addressed. In the framework of this project, the GOR-1 borehole was drilled to a depth of 100 m, and research methodologies were verified to obtain the required quality and reliability characteristics of the rock environment.

It is expected to reduce the number of prospective sites to two in the following selecting process. One site will represent a sedimentary, and the second will be crystalline geological environment. Therefore, the paper presents the results of surveys from both geological environments and those locations that appear to be the most prospective for the DGR construction in Slovakia.

3. SCOPE AND METHODOLOGY OF EXPERIMENTAL RESEARCH

The core samples were tested in the laboratory to determine their basic physical properties depending on the type of rock (moisture content, specific gravity, bulk density, porosity, consistency limits, grain size distribution), strength properties (unconfined compressive strength, tensile strength, point load strength), deformation characteristics (modulus of elasticity, modulus of deformation, Poisson's number) and water contact properties (water absorption, hydraulic conductivity, swelling and swelling pressure). The properties were determined in a standard way according to the methodology specified in relevant technical standards or laboratory manuals (Head, 1994; EN 1997-2).

Test specimens were prepared from drill cores in the slenderness ratio (i.e., the ratio of the diameter and height of the sample) of 1:1 and 1:2 to perform laboratory tests on the determination of strength and deformation properties of rocks. The deformations of the specimens during the uniaxial load test were measured by resistance strain gauges (tenzometers). Properties of rocks in contact with water are essential in the design of various geotechnical structures, whether for landfill, underground or water management structures. The permeability of a rock environment, expressed for geotechnical purposes by the coefficient of hydraulic conductivity k_f (m/s), depends mainly on the mineral composition and on the content of smectites. The value of hydraulic conductivity can be indicated indirectly by basic physical parameters such as liquid limit, plasticity index or specific surface area. Hydraulic conductivity was determined under laboratory conditions by the constant flow test in a triaxial cell with back-pressure saturation (Head, 1994).

Rock Quality Designation *RQD* according to Deere (1967) is a characteristic of rock core quality taken from a borehole. *RQD* signifies the degree of jointing or fracture in a rock mass measured in percentage, where *RQD* of 75 % or more shows good-quality hard rock and *RQD* less than 50 % shows low-quality weathered rocks. *RQD* is used to evaluate the quality of rocks, such as degree and depth of weathering, zones of rock weakness and fracturing. This characteristic is a part of rock classification, such as the Rock Mass Rating system (Bieniawski, 1978) or Q-system (Barton et al., 1974). The relation between deformation modulus and values of *RQD* is analysed in the paper. In addition, the classification of rock cores according to the macroscopic estimation of faulting and jointing proposed by Kuvik et al. (2018) was used instead of parameter *RQD*. Macroscopic degree of faulting (*MDF*) has five grades as follows: 1 – Intact undisturbed rock; 2 – Slightly jointed rock; 3 – Strongly jointed rock; 4 – Foliaceous or very dense jointed rock, breccia; 5 – Tectonically crushes rock (cataclastic, soil-like rock).

The strength and deformation parameters of rock mass may also be obtained by field tests. In situ testing is considered the most reliable and comprehensive method to describe the mechanical behaviour of rock mass (Bieniawski, 1978; Goodman, 1989; Hoek & Brown, 1997). Complex in-situ tests allow to obtain comprehensive information about geological conditions. The most common and widely used in-situ tests in rock environments are pressuremeter and dilatometer tests in boreholes (Schnaid, 2009). Dilatometer and pressuremeter testing in comparable rock environments was analysed, focused on the deformation modulus E_{def} determination. These tests were performed in the region of crystalline core mountains in Slovakia, close to the village Kriváň in Veporské vrchy Mts. (Fig. 1). Dilatometer tests were carried out by PROBEX dilatometer probe, which consists of the robust expandable membrane with the length 475 mm, hydraulic and electrical circuit and electronic datalogger (Fig. 2). Hydraulic system can reach load up to 30 MPa. The maximum depth range is about 500 m. Pressuremeter tests were conducted with standard equipment for Ménard pressuremeter, with an inflatable membrane of 10 cm in length and two expandable protection cells. The theoretical load capacity of this probe is 10 MPa, and the maximum depth range is up to 30 m.

Fig. 2 Equipment necessary for the performing of dilatometer tests in boreholes.

4. RESULTS

4.1 Crystalline igneous rock environment

The borehole RAO-3 drilled in the central part of Tribeč Mts. indicated a homogeneous rock environment from a mineral and petrological point of view. Only one intermediate rock type – granodiorite to tonalite was identified in all borehole lengths. However, in some depths of the massif, the rock varied by grain sizes and structural-textural features: to a depth of 50 m, fine to medium-grained granodiorite to tonalite was identified, deeper up to 100 m, medium- to coarse-grained and strongly anisotropic granodiorite has occurred. From 100 m to 200 m, the rock was isotropic and medium to coarse-grained. The basic physical properties of rock material are presented in Tab. 2. The bulk density values of the samples range from 2.67 to 2.77 g/cm^3, the average total porosity is less than 1 %, and the water absorption does not exceed 0.3 %. The average unconfined compressive strength *UCS* value of the specimens taken from the RAO-3 borehole is 171 MPa for the rock sections deeper than 100 m. The Point Load strength values of the RAO-3 set samples range from 6.1 MPa to 10.6 MPa and confirm the results of UCS tests (considering the correlation coefficient of $K = 22$, suggested by EN 1926). Additional strength characteristics of the tested rock, such as the splitting tensile strength determined by the Brazilian test, are presented in Tab. 2. In the set of samples from the borehole RAO-3, a higher degree of alteration and different grain sizes of the rock were identified reflected by lower values of strength parameters. However, the geological environment represented by the samples from this borehole can be characterised as an environment of fresh rocks. Therefore, the rock was classified as strong according to EN ISO 14 689, with *UCS* in the range from 100 to 250 MPa.

The deformation characteristics presented in Tab. 3 provide additional information to characterise the mechanical behaviour of the rock environment. These parameter values will become important in the context of the excavation method for the construction of a DGR.

Due to limited drilling exploration at the potential locality of Tribeč Mts., field tests performed in a comparable rock environment – granodiorites near the Kriváň village were also evaluated (Fig. 1). The maximum depth of the boreholes in this locality reached 30 m. This fact is reflected in more dilatometer or pressuremeter tests realised in rock environments with a lower value of *RQD*. The relation between deformation modulus (pressuremeter modulus respectively) and values *RQD* has been analysed, as the relationship between the deformation modulus and *MDF*, both for pressiometer and dilatometer tests. Kuvik & Frankovská (2019) observed that the difference between deformation modulus determined by dilatometer and pressuremeter field tests could be significant, especially for a intact rock with high *RQD* (75–100 %). The relation between the deformation modulus from pressuremeter tests E_p and the parameter *RQD* is presented in Fig. 3 and relevant statistical data characteristics are listed in Tab. 4.

To identify the relationship between the value of *RQD* (or *MDF* respectively) and the pressuremeter modulus E_p, after

Tab. 2 Physical properties of rocks from the RAO-3 borehole

Borehole	Depth of sampling (m)		Bulk density (g/cm^3)	Total porosity (%)	Water absorption (%)	Point load index (MPa)	UCS (MPa)	Splitting tensile strength (MPa)
RAO-3	32–52	Mean value	2.681	0.6	0.24	8.7	127	11.1
		Standard deviation	0.007	0.14	0.03	–	2.05	0.42
	98–197	Mean value	2.762	0.5	0.25	9.2	171	12.2
		Standard deviation	0.007	0.3	0.02	2.1	45.5	2.6

Tab. 3 Deformation properties of granitoid rocks from the RAO-3 borehole based on laboratory tests

Borehole	Depth of sampling (m)	Deformation modulus (MPa)	Young's modulus (MPa)	Poisson´s ratio
RAO-3	187–188	56 899	59 782	0.198
RAO-3	196–197	58 407	60 008	0.205

Tab. 4 Basic statistical characteristics of pressuremeter tests results at the locality Kriváň according to RQD

Crystalline rock complex								
RQD (%)	**Min E_p (MPa)**	**Max E_p (MPa)**	**mean**	**median**	**25 % quantile**	**75 % quantile**	**s**	**N**
0–25	3	452	14	98	32	208	133	51
25–50	212	881	552	518	446	743	198	17
50–75	303	945	589	591	459	662	177	14
75–90	56	1063	806	849	734	890	138	17
90–100	446	2083	1120	909	740	1481	563	8

RQD – Rock Quality Designation, E_p – deformation modulus obtained from pressuremeter tests, s – standard deviation, N – count

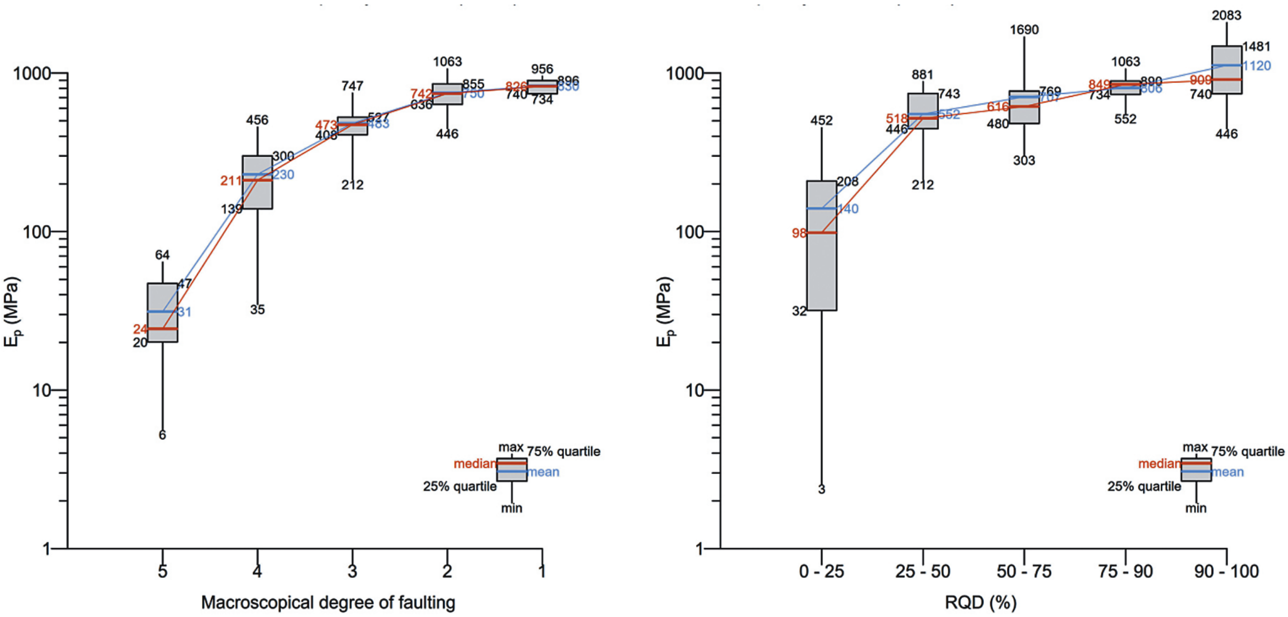

Fig. 3 Hi-Lo graphs for the results of pressuremeter tests, conducted in crystalline rock complex at the locality Kriváň.

adjusting the statistical input file (removal of outliers), a graph of the dependence between the indicated values was constructed with regression curves (Fig. 4). A simple regression shows the relationship between the *RQD* value and the pressuremeter modulus E_p at the maximum possible load range. The following regression relationships were considered:

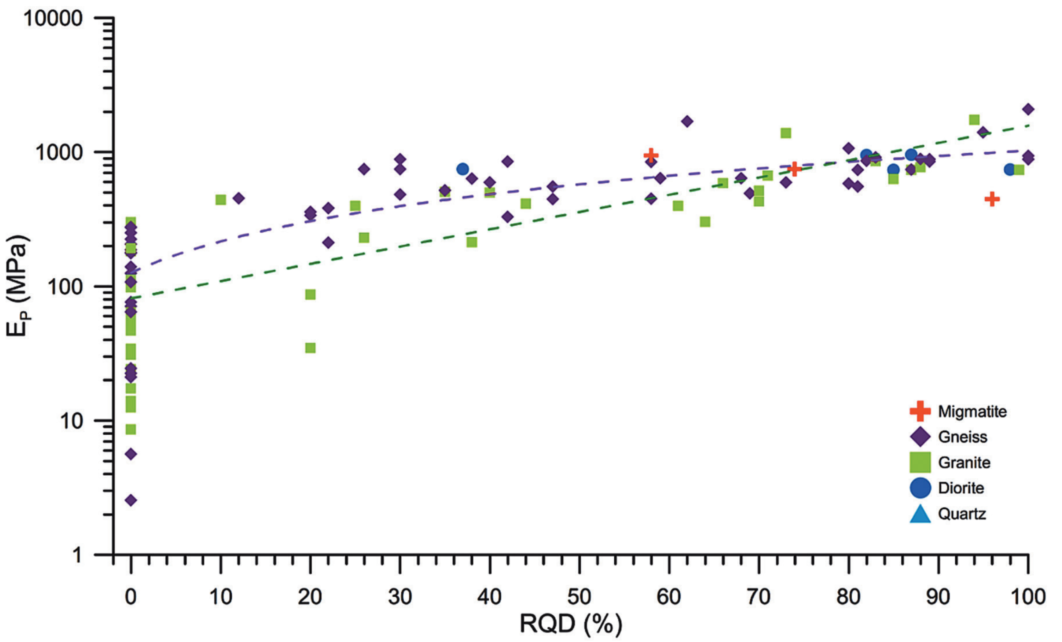

Fig. 4 The relation between E_p and RQD, with the most relevant regression curves – linear (purple - - -) and exponential (green - - -).

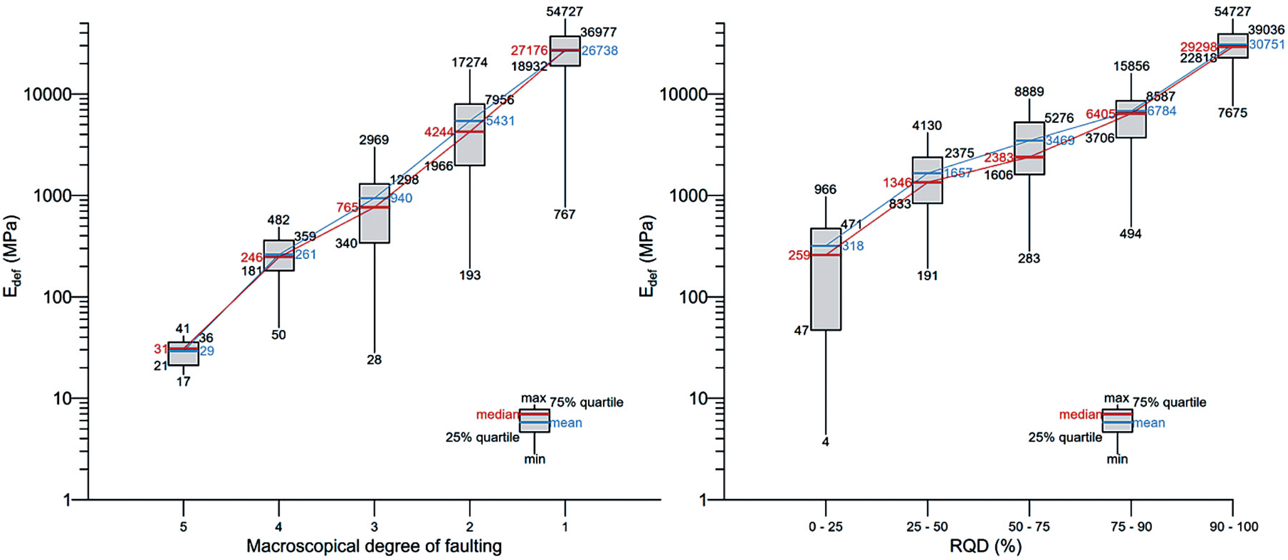

Fig. 5 Hi-Lo graphs for the results of dilatometer tests, conducted in crystalline rock complex at the locality Kriváň.

- Linear regression

$E_p = RQD \times 9.110 + 118.137 \quad (R^2 = 0.638) \quad (1)$

- Exponential regression

$E_p = e^{RQD \times 0.031} \times 73.625 \quad (R^2 = 0.600) \quad (2)$

Similarly, during dilatometer tests, a set of values of deformation modulus E_{def} was obtained. The range of deformation modulus E_{def} for crystalline igneous rock based on *RQD* and *MDF* is shown in Fig. 5, and the statistical characteristics of data are presented in Tab. 5.

On the Fig. 6 the results of dilatometer tests (values of E_{def}) are shown in relation with *RQD* value. Two regression curves were translated to describe this relation. The following regression relationships were considered:

- Power regression

$E_{def} = RQD^{1.851} \times 1.926 \quad (R^2 = 0.649) \quad (3)$

- Exponential regression

$E_{def} = e^{RQD \times 0.055} \times 94.949 \quad (R^2 = 0.747) \quad (4)$

Deformation modulus E_{def} could be estimated from the actual value of *RQD* for crystalline rock using equations (1) and (2), as it is shown in Tab. 6. The deformation modulus E_{def} determined from the dilatometer test for the crystalline rock complex was found to be in the range from 4 MPa to 54727 MPa. These ranges represent statistically cleaned values.

Based on the adequate value of *RQD* and the regression equations shown before, the relation between pressuremeter and deformation modulus was derived as follows:

$$E_{def} = e^{E_p \times 0.006} \times 46.531 \quad (5)$$

$$E_{def} = 134.263 - 2.881 \times E_p + 0.015 * E_p^2 - 3.819.10^{-6} \times E_p^3 + 1.077.10^{-9} \times E_p^4 \quad (6)$$

The relations are graphically expressed on the Fig. 7. The orange curve was obtained by calculation of E_{def} values from pressuremeter modulus E_p in the crystalline rock environment using of coefficients α and β (Ménard in Matys et al., 1990; Head, 1994; EN ISO 22 476-1). From this figure can be seen

Tab. 5 Basic statistical characteristics of dilatometer tests results on the locality Kriváň according to RQD

Crystalline rock complex								
RQD (%)	**Min E_{def} (MPa)**	**Max E_{def} (MPa)**	**mean**	**median**	**25% quantile**	**75% quantile**	**s**	**N**
0–25	4	966	318	259	47	471	285	46
25–50	191	4130	1657	1346	833	2375	1184	22
50–75	283	8889	3469	2383	1606	5276	2596	21
75–90	494	15856	6784	6405	3706	8587	4698	12
90–100	7675	54727	30751	29298	22818	39036	1	17

RQD – Rock Quality Designation, E_{def} – deformation modulus, s – standard deviation, N – count

Tab. 6 Indicative values of deformation modulus E_{def} based on RQD for the crystalline rock environment

RQD (%)	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
$E_{def} = e^{RQD \times 0.055} \times 94.949$ (MPa)	95	165	285	494	857	1485	2574	4462	7734	13404	23233
$E_{def} = RQD^{1.851} \times 1.926$ (MPa)	0	137	493	1044	1779	2688	3767	5011	6416	7979	9697

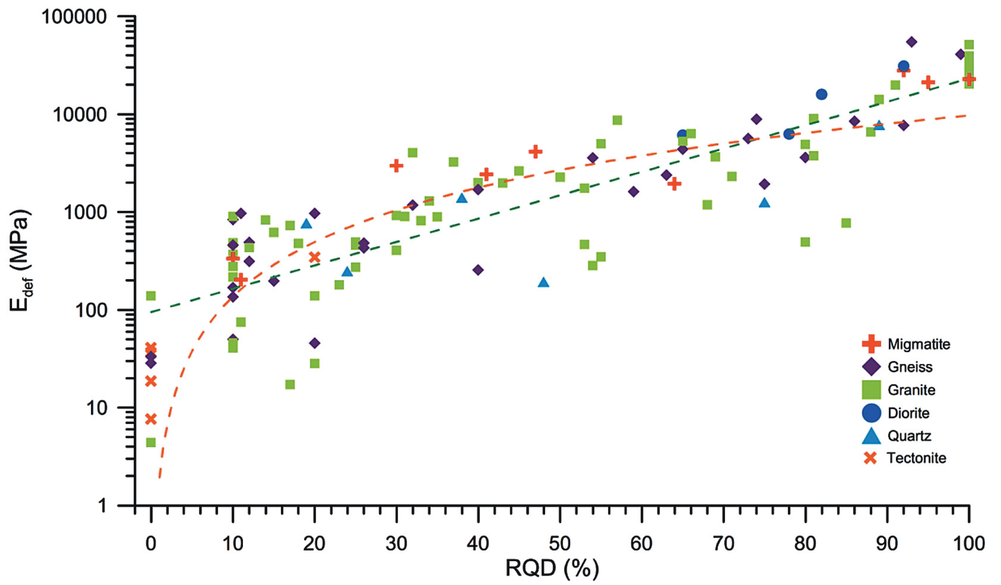

Fig. 6 The relation between E_{def} and RQD, with the most relevant regression curves – power (orange - - -) and exponential (green - - -).

that – especially in higher values of pressuremeter modulus E_p – the derived equations give better values of calculated E_{def}, which is more comparable with the field test results of dilatometer tests than the values obtained by common way via coefficients α and β. The higher values of E_p and E_{def} respectivelly reflect also the less disrupted rock environment with higher *RQD*. Equations (5) and (6) seem to describe better the conversion from E_p to E_{def} for rocks with *RQD* higher than 30 than the E_{def} conversion using the coefficients alpha (conversion of E_p to E_{oed}) and beta (conversion of E_{oed} to E_{def}), which are commonly used in Slovak practice to express E_{def} from the presiometric test (Fig. 7). The polynomic relationship is not reliable for small values of E_p. Therefore the exponential relationship appears to be the more appropriate.

Various empirical methods have been developed based on the rock quality designation (*RQD*), rock mass rating *(RMR)*, unconfined compressive strength *(UCS)* or macroscopically evaluated degrees of faulting *(MDF)*. A simple equation based on *UCS* by Palmstrom & Singh (2001) can be used for the deformation modulus of granitoid rocks from the borehole RAO-3 in Tribeč Mts:

$$E_{def} = 200\ \mathrm{UCS\ (MPa)} \tag{7}$$

Applying the equation (7), the average deformation modulus of rock in the borehole RAO-3 is 34 GPa. The value corresponds with the deformation modulus range in Slovakia's crystalline rock environment determined by dilatometer field tests for *RQD* equal to 90–100 % (Kuvik et al., 2018). Deformation modulus in the crystalline rock environment determined by pressiometer field tests for *RQD* 90–100 % were significantly smaller with the mean value of 2 GPa. The laboratory determination of deformation modulus was 60 GPa for the borehole RAO-3 (Tab. 3).

4.2 Sedimentary rock environment

Two boreholes have been drilled in the sedimentary rock environment, RAO-5 to a depth of 250 m and GOR-1 to a depth of 100 m. From a geomorphological point of view, both boreholes

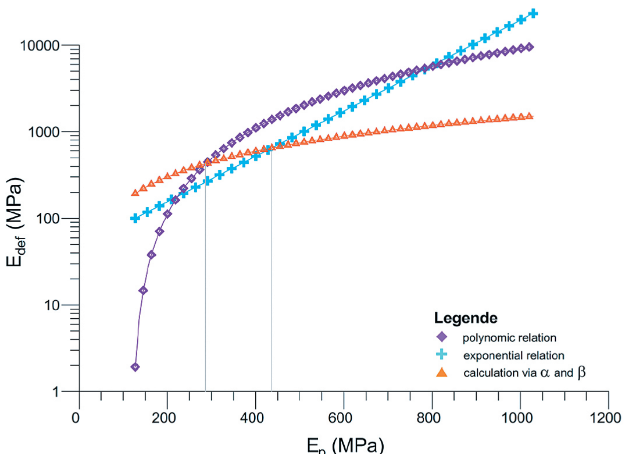

Fig. 7 Relation between E_p a E_{def} for crystalline rock environment on the study locality near Kriváň village.

are situated in the southern part of Slovakia in the peripheral part of Cerová vrchovina Upland. Geologically, the territory is formed by Lučenec formation; its dominant member is the so-called Szecseny schlier. The maximum thickness of the formation verified by the boreholes is about 700 m (Vass et al., 1988 in Kordík et al., 2008). The age of the formation is Late Oligocene – Early Miocene boundary (egerian). Szecseny schlier is partially consolidated sedimentary rock, calcareous silt (siltstone) and clay (claystone) with fine-grained sand layers. The colour of the sediments is light grey or bluish grey. Based on the macroscopic evaluation, the rock material taken from all 13 tested sampling locations of the borehole RAO-5 appeared relatively uniform (Frankovská et al., 2008). However, despite the visual homogeneity, minor differences were evident in the values of the determined physical properties, probably due to the alternation of layers with different percentages of silty and sandy fractions in the siltstone and claystone, respectively, as well as due to the more strongly consolidation of the material with the depth. Laboratory results of samples from the RAO-5 borehole are also analysed in the paper by Adamcová et al. (2009). Therefore, more attention is paid to the knowledge gained from the borehole GOR-1.

Through the selected method of the borehole, GOR-1 realisation was tested with the appropriate drilling technique and sampling of undisturbed cores (Slaninka et al., 2012). GOR-1 borehole was sampled by rotary core drilling using a triple tube according to the requirements of the international standard for sampling EN ISO 22 475-1 to obtain the samples of the highest quality. The diameter of the borehole for continuous sampling by drilling was 146 mm, and the diameter of the samples was 100 mm. The rock core was obtained in all planned lengths, from 0.2 m to 100 m. Using an additional third plastic tube inside the inner tube improved the recovery of the rock core, formed a package, and protected the sample during transport. Parameter *RQD* of rock core from the borehole was 98.4 % and *RQD* from the depth 13.5 m was 100 %.

Values of strength parameters and the behaviour in contact with water of all tested samples collected from RAO-5 and GOR-1 boreholes corresponded to the criteria for soft rocks. It should be noted the relatively high porosity of this rock material (from 15 % to 21 %), as well as the fact that it is a rock very sensitive to contact with water (see Tab. 7). The values of the rock *UCS* ranged from 18 to 30 MPa and, together with the results of the other strength tests, indicate the relative mechanical homogeneity of this rock environment. The low deformation characteristic values indicate rocks' plastic behaviour in the sedimentary environment (see Tab. 8).

Consistency (Atterberg) limits were also determined on grounds of core samples had disintegrated entirely in water to soil (Fig. 8). The average value of the liquid limit w_L for the samples from the RAO-5 borehole was 39.2 %, and the plasticity limit w_p was 24.4 %. In the case of the GOR-1 borehole was found that the value of the liquid limit w_L increases with increasing depth. At a depth of 21.2 m, it reached a value of 35 %, and at a depth of 98.6 m, it reached a value of 51.3 %. The plasticity index I_p indicated a rock with medium to high plasticity and indirectly indicated the possible presence of smectites ($I_p = 30$ %).

The mineral composition of the fine fraction of samples from both boreholes is the same (Slaninka et al., 2012). The Szecseny schlier is composed mainly of a complex mixture of clay minerals like smectite, illite, chlorite and kaolinite, quartz, plagioclase, calcite and dolomite. Other minerals as pyrite and sericite, were also identified. A combination of X-ray diffraction methods and chemical analysis calculation determined the quantitative mineralogical composition. Clay minerals were determined to be less than 15 % of the sample. X-ray diffraction analyses confirmed the presence of smectites in the samples (Fig. 9). The content of the smectite was calculated at about 9–11 %.

Laboratory permeability determinations were carried out on two samples from the RAO-5 borehole, 161.5 m and 209.5 m depths. These measurements confirmed the assumed low permeability of this rock environment (Frankovská et al., 2008).

Tab. 7 **Physical properties of sedimentary rocks obtained from the boreholes RAO-5 and GOR-1**

Borehole	Depth of sampling (m)		Bulk density (g/cm^3)	Total porosity (%)	Water absorption (%)	Point load index (MPa)	UCS (MPa)	Splitting Tensile strength (MPa)
RAO-5	21–248	Mean value	2.204	17.6	-	0.94	23.7	1.9
		Standard deviation	0.032	1.6	-	0.44	3.5	0.41
GOR-1	21–100	Mean value	2.198	21.9	-	0.47	25.7	–
		Standard deviation	0.074	2.16	-	0.5	7.94	–

Tab. 8 **Deformation characteristics of samples obtained from the boreholes RAO-5 and GOR-1**

Borehole	Depth of sampling (m)	Deformation modulus (MPa)	Young's modulus (MPa)	Poisson´s ratio
RAO-5	176	2 263	2 939	0.12
RAO-5	231	3 290	4 600	0.12
GOR-1	34	1 478	2 071	0.14
GOR-1	48	2 745	3 986	0.16
GOR-1	69	2 968	4 148	0.10
GOR-1	99	3 449	4 459	0.13

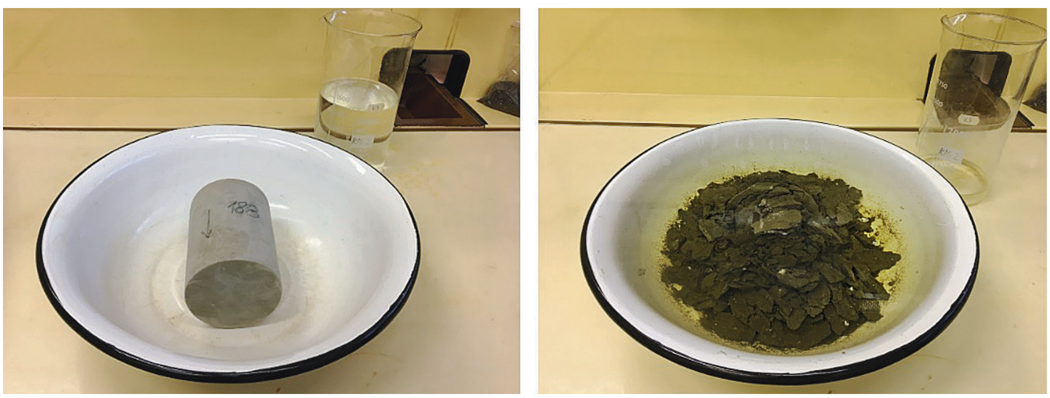

Fig. 8 **Rock sample from the borehole RAO-5 (depth of 188 m) completely disintegrated in water.**

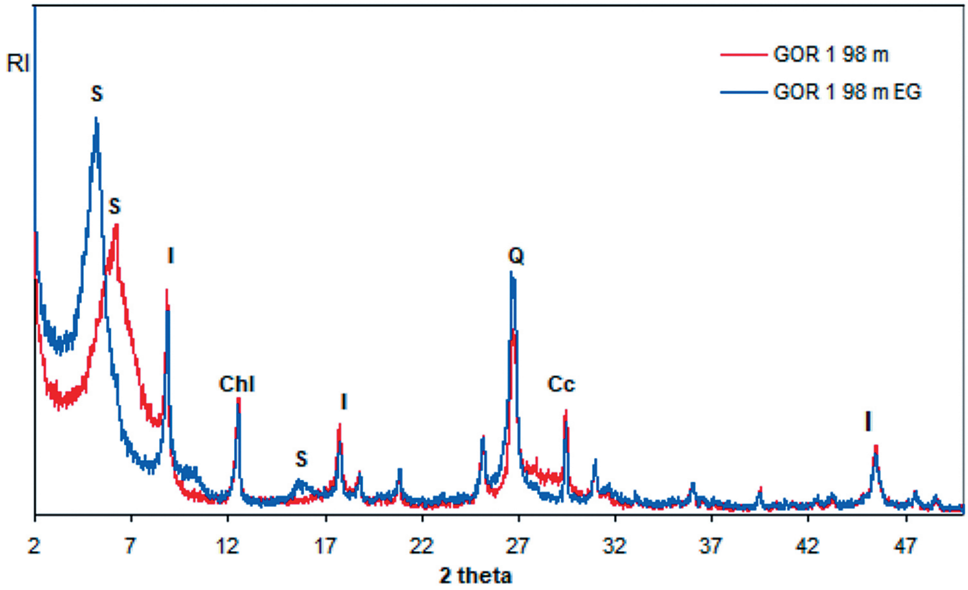

Fig. 9 X-ray diffraction analysis of the clayey fraction of samples from the borehole GOR-1, depth of 98 m. Samples were analysed after air-drying (air-dry) and after saturation with ethylene glycol (EG). RI – relative intensity; S – smectite; Chl – chlorite; I – illite; Q – quartz; Cc – calcite.

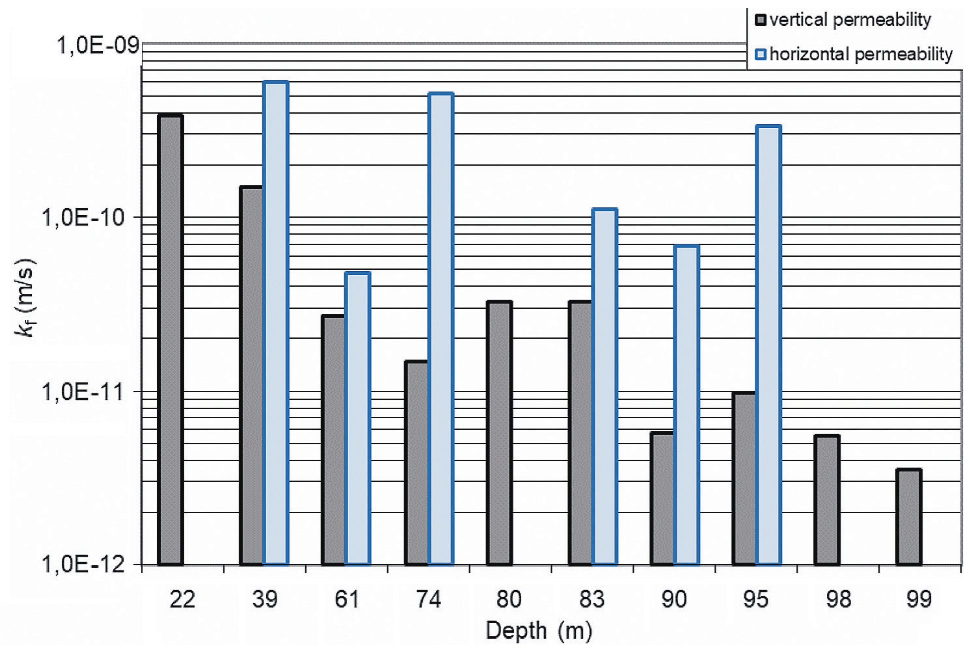

Fig. 10 Permeability of rock samples from the borehole GOR- 1 with the depth measured in the horizontal and vertical direction.

In the case of rock samples from the borehole GOR-1, hydraulic conductivity was analysed for ten samples from depths of 21 to 99 m in vertical and six samples in horizontal directions. A graphical presentation of the permeability test results is shown in Fig. 10. The values of the hydraulic conductivity in the vertical direction range from $3.55.10^{-12}$ m/s to $3.87.10^{-10}$ m/s, with an average value of $7.05.10^{-11}$ m/s. The trend of decrease in coefficients of hydraulic conductivity with depth is significant. The hydraulic conductivity values in the horizontal direction range from $4.75.10^{-11}$ m/s to $6.05.10^{-10}$ m/s. The average value is $2.94.10^{-10}$ m/s. These laboratory determined values need to be verified by hydrodynamic field tests. The hydraulic conductivity in the borehole RAO-5 ranged from $8.45.10^{-11}$ m/s to $2.89.10^{-10}$ m/s (Frankovská et al., 2008, Kordík et al., 2008). It is expected that at a depth of 500 m, the hydraulic conductivity will be even lower due to the lower porosity of the rocks.

Values of deformation modulus of the samples from the borehole RAO-5 and GOR-1 determined by laboratory methods, ranged from 1.5 to 3.5 GPa (see Tab. 8).

5. DISCUSSION

The construction of engineering works, especially at the preliminary design stage, requires reliable knowledge of the geotechnical parameters of the rock environment in which the structure will be located. These properties and their reliability are crucial for the correct design of the geotechnical system and the access tunnel or a credible simulation of the interaction of the DGR with the surrounding rock environment. Furthermore, strength and deformation parameters are among the most important quantities that allow describing the mechanical behaviour of the rock environment under different conditions (stress, climate, geometry, etc.). It should be emphasized that the presented results characterize the properties of the rock material (not rock mass) and are thus idealized compared to the natural properties of a structurally and lithologically heterogeneous rock mass. Nevertheless, these data provide basic information on the physical-mechanical properties of individual rock environments at different depth horizons and greater depths of the massif, with presumably less structural heterogeneity. Therefore, they should approximate the state properties of the rock mass.

Evaluation of rock mass deformability is challenging for the geological repository since rock masses are discontinued (Bieniawski, 1978; Hoek & Brown, 1997; Jade & Sitharam, 2003; Zhang & Einstein, 2004; Zhang, 2017). A comparison of the values determined by field and laboratory testing confirmed that the scale and size of samples significantly influence the strength and stiffness of rock masses properties. Although, according to Heuze (1980), the field strength values are generally several times smaller than laboratory values, the difference between the values of deformation modulus based on the testing method could be from 20 to 60 %. In the boreholes drilling and sampling processes to determine the parameter *RQD* is necessary of the reason its high informative value. In this context, the results of presiometer and dilatometer tests realised in comparable granitoid rock on other locality in Slovakia are presented and on them are documented relationships between the deformation parameters and parameter *RQD* (or *MDF*) as shown in Fig. 3 and Fig. 5. Good correlation was founded predominantly in high quality rock environments with high value of *RQD*. And precisely such geological condition is expected in deeper zones of massifs. In comparison of presiometer and dilatometer tests results, dilatometer tests standed better. As it is presented in the clause 4.1 of the paper, the presiometric test is not able to provide a representative picture of the deformation properties of the rock, or the presiometer modulus differs significantly from the modulus of deformation, in extremes by as much as two orders of magnitude.

Crystalline rocks are well known for their high strength in a fresh and intact state, which is also reflected in the values of deformation parameters. Nevertheless, the maximum values of the modules by dilatometer tests from greater depths of the rock massif could be even higher. At the study locality near Kriváň village, tests were carried out in boreholes up to a depth of 30 m, where the subsurface zone of rock loosening and weathering is still evident. In the future, it would be possible, with a sufficiently large statistical set, to distinguish individual lithological types of crystalline rocks or to consider structural anisotropy. It is expected that similar or more extensive field investigations to be carried out on Cerová vrchovina Upland in a sedimentary rock environment.

6. CONCLUSION

The geological surveys carried out so far at selected locations in Slovakia and the knowledge gained from them about rocks as a host environment for the DGR can be considered as an initial stage in solving this problem. The paper presents the determined engineering geological and geotechnical characteristics of the host environment in two the most perspective territories and complements the previous knowledge. The locality Tribeč Mts., represented by the borehole RAO-3 seems to be the most suitable among the evaluated areas in a crystalline rock environment. Boreholes RAO-5 and GOR-1 drilled in a sedimentary rock environment in southern part of Slovakia confirmed the homogeneity of the rock massif. Differences in engineering geological and geotechnical properties of the boreholes samples were minimum. This is evidence of a significant monotonicity of sediment evolution (marine evolution, a shallow sea without turbidity flows, etc.). Laboratory measurements confirmed relatively low permeability of the sediments and the trend of its decreasing with the depth. On the based the current knowledge it can be stated that the sedimentary Szecseny schlier, together with its subjacent Číž Formation, has favourable properties for the design and construction of the DGR in Slovakia.

In Slovakia, it is necessary to continue the ground investigation and conduct geophysical, field and laboratory research at sites in both granitoid and sedimentary rock environments. While drilling next boreholes, it will be essential to determine a value of *RQD*. This parameter is one of the most important for an evaluating rock massif quality, which also enters into many geotechnical calculations. In carrying out the relevant number of investigation boreholes, it is possible to do statistical analysis to develop relations between the in-situ detected value of *RQD* (or macroscopically estimated degree of faulting) and deformation parameters. Since laboratory tests on small specimens are often inadequate to predict the deformability of rock masses, in situ tests are necessary. The analysis of the dilatometer field tests results demonstrated that these tests are suitable for various geological environments, and should be part of the next stages of the site investigation. Drilling to a depth of more than 500 m and geophysical testing, including 3D seismic measurement, must be performed to confirm suitable geomechanical parameters in the vertical and horizontal direction.

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