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Summary of the Doctoral thesis

Aproximace statických modulů hornin z dynamických modulů stanovených akustickou karotáží pomocí T-matrix modelu

Approximation of static moduli of rocks from dynamic moduli determined by sonic well logging using T-matrix model

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Outline

Abstrakt (CZ)

Práce se zabývá využitím T-matrix modelu k odhadu statických modulů hornin ve vrtu z dynamických modulů stanovených pomocí akustické karotáže. Navrženým postupem je možné stanovit hodnoty modulů, které jsou blízké hodnotám statických modulů, které by byly zjištěny zatěžovací zkouškou.

Postup je postavený na úvaze, že neporušená hornina o dostatečné pevnosti v prostém tlaku σ_c a dostatečně vysoké hodnotě statického Youngova modulu E_S, vykazuje víceméně lineární elastické chování. V takovém případě jsou hodnoty statických a dynamických modulů totožné. Tato skutečnost byla experimentálně ověřena pro horniny s hodnotami σ_c a E_S v řádu vyšších desítek MPa respektive GPa. V případě přítomnosti porušení v takovéto hornině se ale její chování stává nelineárně elastickým. Míra této nelinearity roste s rostoucí mírou porušení. Důsledkem toho je, že mezi hodnotami statických a dynamických modulů vznikne rozdíl.

Ke stanovení tohoto rozdílu je využito T-matrix modelu. To je model založený obecně na anizotropní matrici s elipsoidálními inkluzemi, které se mohou navíc navzájem ovlivňovat. Výsledkem modelování jsou hodnoty elastických konstant, které se označují jako efektivní moduly. Tyto moduly zahrnují i vliv pórovitosti a poruch v hornině, a tak slouží jako odhad statických modulů.

Vstupními daty pro zkonstruování a výpočet T-matrix modelu jsou, kromě dynamických modulů z akustické karotáže, i data ze souboru dalších karotážních metod, které přinášejí informaci o litologii a jejích změnách podél osy vrtu a údaje o porozitě a hustotě zastižených hornin. Dále jsou použity statické moduly stanovené na vybraných vzorcích z vrtného jádra a akustický sken stěny vrtu, ze kterého je interpretována přítomnost trhlin.

Vrtný profil je na základě výsledků interpretace karotážních dat zjednodušen a rozdělen na kvazihomogenní vrstvy. V rámci těchto vrstev jsou z vrtných jader vybrány jednotlivé vzorky, na kterých jsou následně stanoveny statické moduly jednoosou zatěžovací zkouškou v laboratoři. Z těchto statických modulů a rozdělení do vrstev je sestaven výchozí vrstevnatý model. Stanovená porozita podél osy vrtu je společně s nalezenými trhlinami vyhodnocena do tzv. porozity efektivního média.

Ověření navrženého postupu bylo provedeno na experimentálním vrtu, vyhloubeném v silurských vápencích. Z vrtného jádra byly odebrány kromě vzorků pro sestavení a kalibraci modelu navíc i kontrolní vzorky, které posloužily pouze k ohodnocení funkčnosti modelu. Spočtené hodnoty efektivních modulů v příslušné hloubkové úrovni byly porovnávány s hodnotami statických modulů stanovených laboratorně na kontrolních vzorcích. Porovnání dynamických a efektivních hodnot Youngova modulu s hodnotami statických modulů ukázalo, že u většiny kontrolních vzorků došlo ke zmenšení původního rozdílu, který činil až 40 % hodnoty statického modulu, na méně než 10%.

Abstract (EN)

Thesis deals with an approximation of static moduli in wells from dynamic moduli determined by acoustic well logging using T-matrix model. Proposed approach makes possible to determine moduli values, which are close to values of static moduli, which would be determined by loading tests.

This approach is based on an idea, that an intact rock with sufficiently high compressional strength σ_c and sufficiently high value of static Young's modulus E_s, manifests more or less linear elastic behaviour. In such case, the values of static and dynamic moduli are identical. This fact has been experimentally verified for rocks with values of σ_c and E_s in order of higher tens of MPa and GPa respectively. In case of a rock damage presence in such rock, it's behaviour becomes nonlinearly elastic. The amount of nonlinearity is proportional to increasing amount of rock damage. This results in the difference between values of static and dynamic moduli.

T-matrix model is used to quantify this difference. This model is based on an anisotropic rock matrix with ellipsoidal inclusions. These inclusions can affect each other. The result of this model calculation is a group of values of elastic constants, which we call effective moduli. These effective moduli include the effect of porosity in the rock as well and they serve as an estimate of static moduli.

Input data for T-matrix model construction and calculation are based on several following parameters. Firstly it is acoustic well logging providing dynamic moduli. Secondly it is data from the set of other well logging methods which provide information about lithology and its changes along the borehole and porosity and density data of rocks in which the borehole is situated. Further on, static moduli determined by loading tests on selected core samples and acoustic scan of borehole wall from which presence of cracks is interpreted, are used.

Based on results of well logging data interpretation, the borehole profile is simplified and divided into quasihomogeneous layers. Within these layers, individual core samples are selected on which static moduli

are determined by uniaxial static loading tests in laboratory. By combination of these static moduli and layered profile, the initial layered model is put together. Determined porosity of rock along the borehole is interpreted, in combination with detected cracks, into so called effective medium porosity.

Verification of proposed approach has been carried out on experimental well, drilled in Silurian limestones. Aside from core samples used for putting together the model and its calibration, a set of control samples has been taken. These served for model functionality evaluation only. Effective moduli values calculated in depths respective to control samples have been compared to static moduli values, determined on these samples in laboratory. The final comparison of dynamic and effective values of Young's modulus with static values showed significant mitigation of initial difference. For majority of control samples, the difference dropped from initial value of around 40 % of static modulus value, to less than 10 %.

1 Introduction

Calculations in construction and mining industry commonly demand determination of elastic moduli of the rocks. These moduli can be determined by static tests, most usually uniaxial compressive tests, either in laboratory or in-situ. The results of these tests are static moduli of studied rock (Zhang, Bentley 2005; Karam 2004; Holt et al. 2013). It is frequently easier to determine dynamic moduli of the rock instead of static ones (Fei et al. 2016). Dynamic moduli can be determined from values of elastic wave propagation velocities. Measurements of these velocities are much easier to perform both in the laboratory and in-situ as well (e.g. Stan-Kłeczek 2016; Konečný et al. 2015). A major problem is a principal difference between static and dynamic moduli because their values can differ for same rock type. This is often result of different porosity, damage, and weathering. Scope of submitted Ph.D. thesis is to find a way how to determine static moduli from measured dynamic moduli. This problem has drawn attention in the past as well as in the present, e.g. Fjær, Holt 1994, Fjær 2009, Karam 2004, Zhang, Bentley 2005, Martínez-Martínez et al. 2012 and Fjær 2019.

2 Aims of the study

Main goal of this work is to extend conventional methodology of joint evaluation of well logging data acquired by various well logging methods with emphasis on acoustic well logging with full waveform registration (FWS – Full Wave Sonic). The extended methodology would make possible the transition from dynamic moduli determined by using the FWS to static moduli. This approach is believed to have significant potential for the purposes of building industry and mining in shallow depths (depths in order of first hundreds of meters under the surface, where we assume that cracks are not completely closed due to overburden pressure). Methodology extension is to be performed through T-matrix model application (Jakobsen et al. 2003), where the results of well logging data and laboratory static loading tests evaluation are used as input. As a result of this extension, values of so called effective moduli, which are close to values of static moduli, are to be obtained.

3 Material and methods

Conventional approach is to calculate only dynamic moduli of the rock. This calculation is based on combination of results from density log with velocities of longitudinal (p-) and shear (s-) waves from FWS. With the new approach using T-matrix model it is possible to approximate rock's behaviour during static loading test. The T-matrix model evaluation requires input consisting of:

- simplified borehole profile where quasihomogeneous layers are represented by their static moduli values determined on core samples by static loading tests in laboratory.
- dynamic moduli curves from FWS.
- porosity curve of rocks surrounding the borehole.
- acoustic scan of borehole wall, from which presence, dimensions and orientations of cracks can be interpreted.

To create initial simplified layered borehole profile with quasihomogeneous layers, we need data from natural gamma log, resistivity/induction log, density log, neutron log, FWS log, acoustic borehole imager (ABI) log and borehole camera record.

When the initial layered borehole profile is established, it is possible to choose samples from borehole core for uniaxial static loading tests in laboratory. Samples should be chosen inside of quasihomogeneous layers which can be then represented by respective values of static moduli from laboratory test. Evaluation of FWS log provides curves of p- and s-waves' velocities, which directly lead to

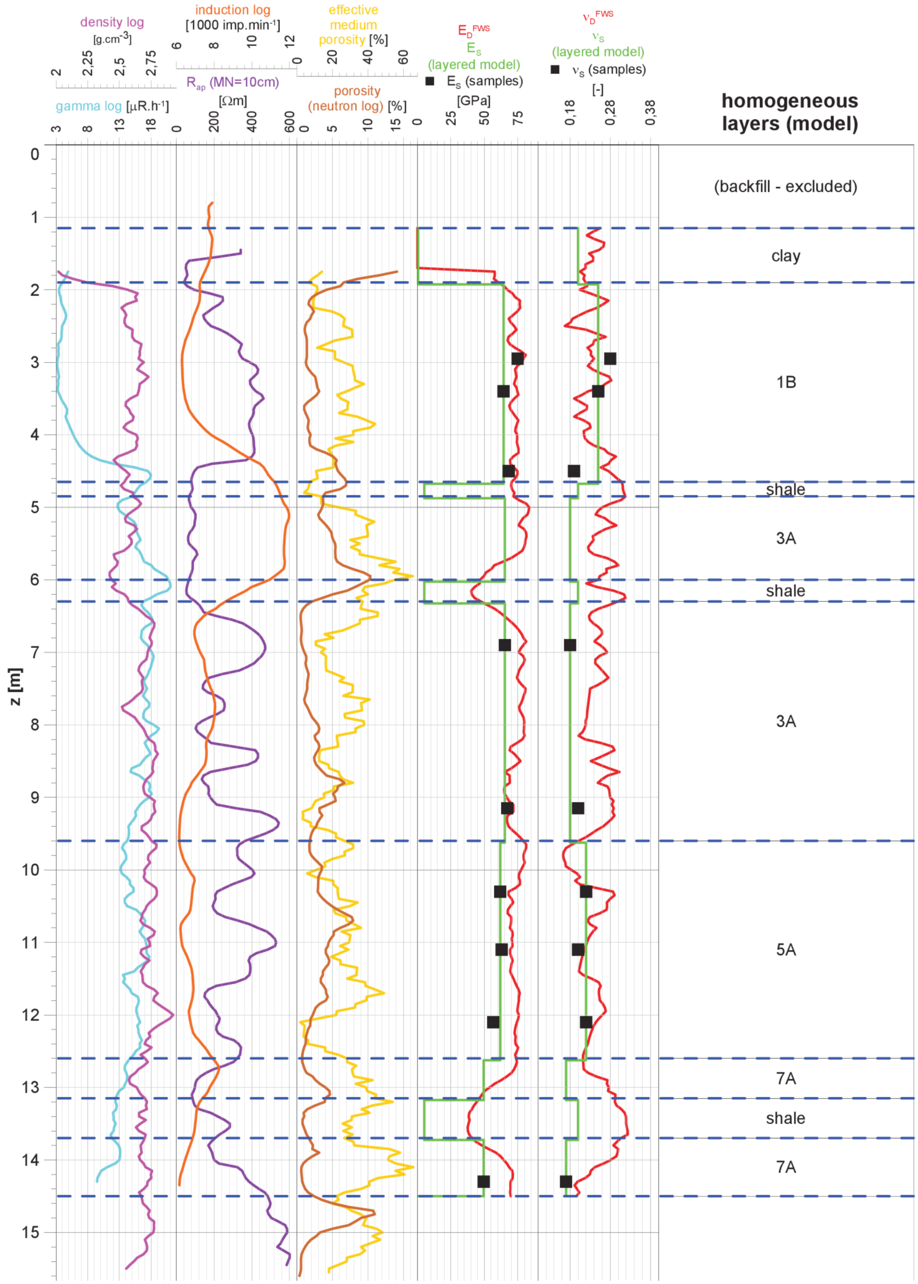

Figure 1: Well logging data and initial layered model of the borehole profile constructed from static moduli values determined on borehole core samples. Boundaries of layers are marked with blue dashed line. Markings of samples corresponding to each layer are in the first column on the right side (Chalupa et al. 2018).

calculation of dynamic Poisson's ratio ν_D curve. Combination of curves of p- and s-wave velocities with density log curve, allows us to calculate dynamic Young's modulus E_D curve.

The last step in T-matrix model input preparation is so called effective medium porosity calculation. For this calculation, we need porosity curve, which has been evaluated from neutron log and/or density log data. We also need locations, dimensions and orientations of cracks interpreted from acoustic scan of borehole wall done using ABI tool. Combining these data together in sliding window along the borehole axis allows us to calculate the total porosity of effective medium. Each value is the sum of the partial contributions of all cracks detected in the scope of the sliding window in given position and the porosity detected via neutron log. The porosity from neutron log is considered to be the porosity of intact rock. Based on degree of seismic signal attenuation and thickness of these cracks on ABI borehole

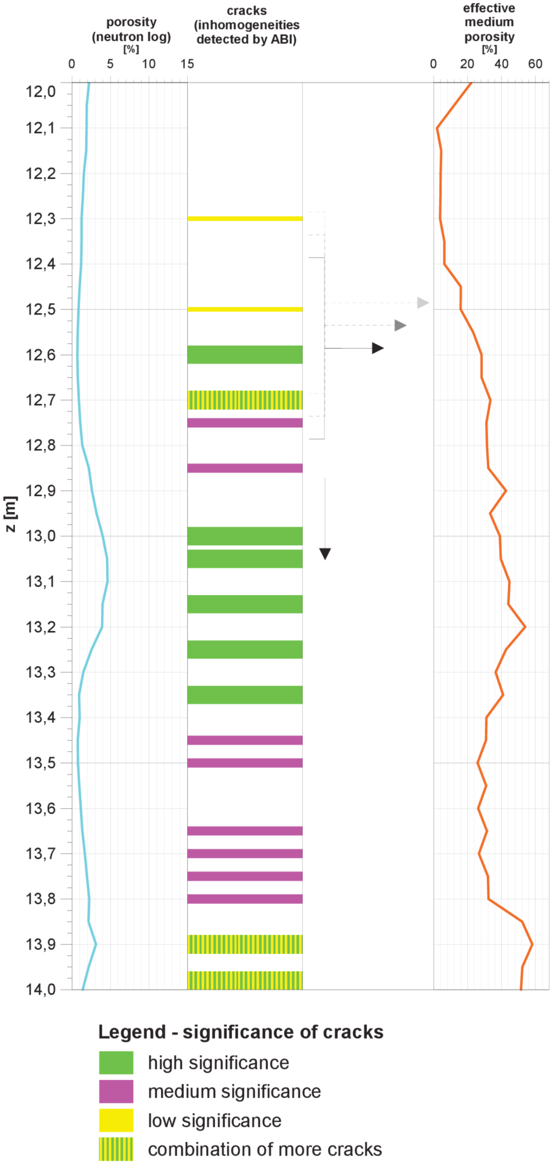

Figure 2: Illustration of porosity of effective medium calculation mechanism. The calculation is done within sliding 40 cm long window. The value of porosity of effective medium is determined as a sum of porosity from neutron log and contribution of all cracks detected by ABI tool. Contribution of each crack is transformed to porosity value through crack classification into pre-defined categories (Chalupa et al. 2018).

wall image, the cracks detected by the ABI tool were divided into four categories - major cracks, moderate cracks, minor cracks and veins. Each of the given categories is represented by average crack thickness - 40, 20 and 10 mm in the same order. The thickness of veins was considered to be 0 mm due to the minimal contrast of elastic properties with respect to surrounding rock. Porosity values were then calculated for individual categories of cracks corresponding to the presence of a single crack in the interval of the sliding window. This was carried out as the ratio of average crack thickness in the given category to the length of the sliding window (40 cm). In this way the categories of cracks were assigned porosity values of 10% (major; average crack thickness in ABI image was 40 mm), 5% (moderate; average crack thickness in ABI image was 20 mm), and 2.5% (minor; average crack thickness in ABI image was 10 mm).

The porosity contribution of veins filled with calcite was considered 0%. The total contribution of all cracks of various categories present within the interval of sliding window length is calculated as their sum.

The practical realization of the model calculation is presented using data from experimental measurements at the Kosov quarry, located in the middle of Bohemia in Czech Republic. Initial layered model and dynamic moduli curves are presented in Figure 1. The procedure of effective medium porosity calculation is illustrated in Figure 2, along with the resultant curve.

In the actual effective moduli calculation, the dynamic moduli represent the reference environment, the fluctuation of which we calculate using the T-matrix model. The size of these deviations is determined by the static moduli. These are measured on samples and assigned to corresponding layers of the borehole profile along with the calculated porosity of effective medium. The calculation described above is then used to obtain values of effective moduli - curves for the entire borehole profile. These curves are analogous to the dynamic moduli curves from FWS.

4 Results and discussion

T-matrix model calculations yielded a curve of effective elastic Young's modulus E_{ef} and Poissons ratio ν_{ef}. In Figure 3 these effective moduli are plotted along with the curves of original dynamic moduli and static moduli of the initial layered model. The graph is divided into two parts. The first one illustrates values of Young’s modulus, the second one, values of Poisson’s ratio. The conversion to effective moduli can roughly be expressed as shifting the original red curves of the dynamic moduli

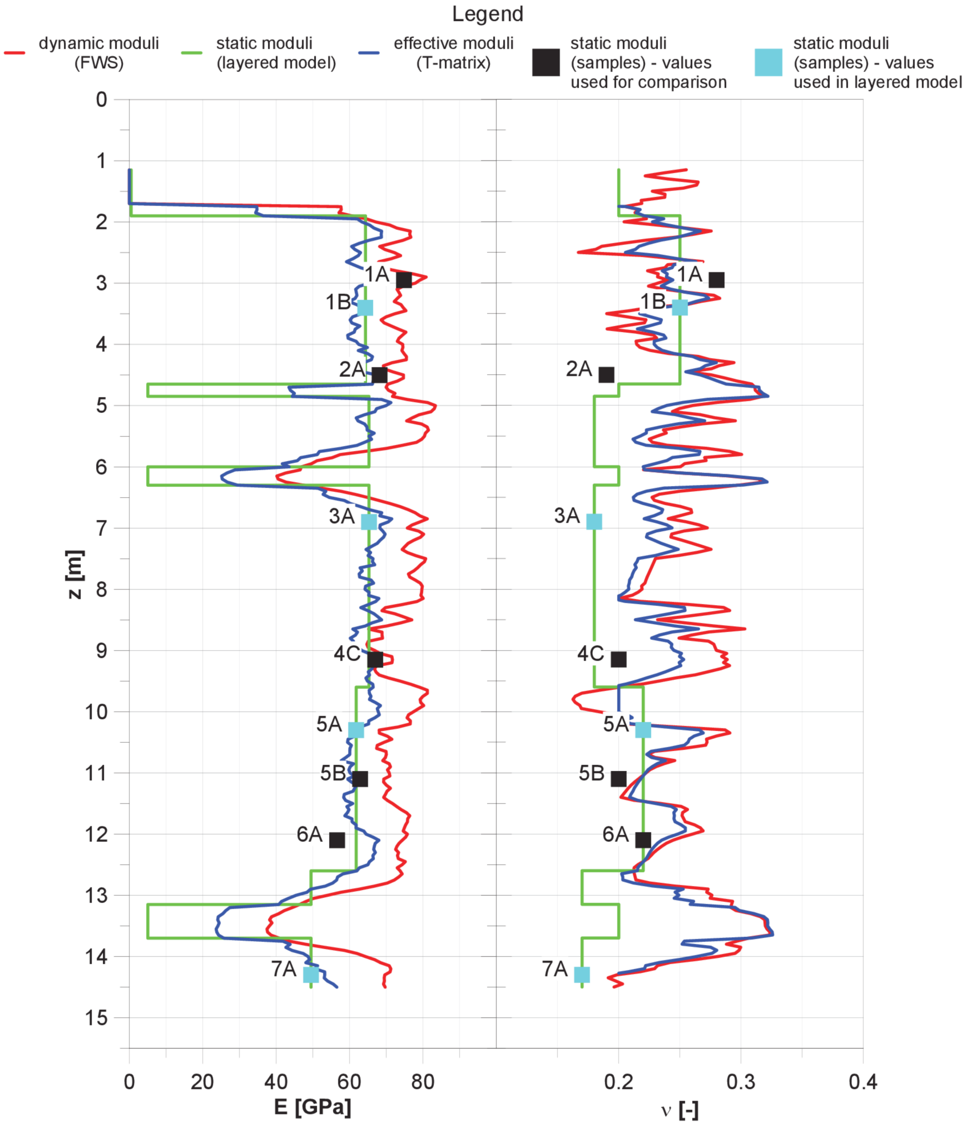

Figure 3: Elastic moduli curves. Static moduli correspond to initial layered model curve, further on, dynamic moduli curve from FWS and curve of calculated effective moduli are depicted. Borehole core sampling positions are marked and it is distinguished between samples used for initial layered construction model and control samples (Chalupa et al. 2018).

(FWS) to the left towards the green static moduli curve of the initial layered model in order to obtain the blue curve of effective moduli.

In the case of effective Young’s modulus, the drop in values compared with dynamic Young’s modulus is clearly evident. The green and red curves do cross near the shale layers, but this is only the effect of smoothing the step changes of Young’s modulus values at the boundary of two layers. For Poisson’s ratio the drop between effective and dynamic values is not so unambiguous. At certain intervals it is clear, but elsewhere the change is negligible or there was even a slight increase. This does not happen for Young’s modulus. This fact is confirmed by results (Fei et al. 2016), where it was found that while the static and dynamic values of Young’s modulus correlate satisfactorily, there is no clear correlation for Poisson’s ratio from the same set of measurements. For these reasons, the main attention here is focused on analysis of the calculated effective Young’s moduli.

As seen in Figure 3, the static Young’s modulus values determined from laboratory samples represent the elastic properties of the most compact sections of the borehole profile in the upper half of the borehole (to a depth of approx. 8 m). In layers of the initial layered model, samples are always located at the depth of the local maximum on the dynamic Young’s modulus curve. For the Poisson’s ratio values the situation is analogous. However instead of local maxima, in this case there are local minima. This is in line with the observation that compact intervals are the most suitable for collecting borehole samples. These intervals are most likely to yield cores suitable for preparing laboratory specimens. In the lower part of the borehole, where the level of rock disruption is generally higher, this correlation is not clear. As rock disruption increases, the chances of obtaining a suitable core (especially with respect to dimensions) falls.

To allow verification of the functionality of the model, the initial static moduli curves were created with data from only four of a total of nine collected samples (1B, 3A, 5A, 7A; in Table 1 and 2 marked with ″*″). The remaining five samples (1A, 2A, 4C, 5B, 6A; see Table 1 and 2) were marked as control samples and data from them were used to compare and conclude whether the results of calculation (effective moduli) corresponded to the actual static moduli determined for control samples. The initial and calculated moduli are given in Table 1.

Table 1: Initial and calculated moduli. Moduli marked with a stripe are average values over an interval up to 20 cm in direct proximity to sample collection. The "FWS" superscript indicates dynamic moduli from well logging measurement. Only samples marked "" were used to construct the initial layered model (Chalupa et al. 2018).*

sample	$\bar{E}_D^{FWS}$ [GPa]	E_S [GPa]	$\bar{E}_{ef}$ [GPa]	$\bar{\nu}_D^{FWS}$ [-]	ν_S [-]	$\bar{\nu}_{ef}$ [-]
1A	78,8	74,8	66,9	0,23	0,28	0,24
1B*	74,7	64,3	63,5	0,23	0,25	0,24
2A	73,6	68,2	66,2	0,28	0,19	0,27
shale (4,70-4,85 m)	71,2	5,0	44,2	0,31	0,20	0,32
shale (6,05-6,30 m)	43,3	5,0	27,0	0,28	0,20	0,28
3A*	79,1	65,3	69,6	0,25	0,18	0,23
4C	71,6	67,0	67,8	0,29	0,20	0,25
5A*	69,5	61,8	60,4	0,28	0,22	0,26
5B	70,2	62,9	60,4	0,22	0,20	0,22
6A	74,0	56,6	67,0	0,24	0,22	0,23
shale (13,20-13,70 m)	39,6	5,0	24,9	0,31	0,20	0,32
7A*	69,5	49,5	53,4	0,20	0,17	0,19

One of the advantages of using the T-matrix model to assess effective moduli of rock around the borehole is that it is possible to include layers that do not need to be clearly identified in the original dynamic modulus curve. Layers can be defined based on assessing information from the borehole core, from ABI, and possibly from a camera recording. If these sources provide us with information about the presence of such layer, we can include it in the model.

Table 2: Comparison of initial dynamic moduli from well logging and effective moduli from the T-matrix model with static moduli determined on samples. The comparison is carried out for the average values of dynamic or effective moduli of layers up to 20 cm thick at the collection depth of the particular sample. These average moduli are marked with a stripe. δ indicates relative errors normalized by the value of the corresponding static modulus. Only samples marked "" were used to construct the initial layered model (Chalupa et al. 2018).*

sample	$\bar{\nu}_D^{FWS}-\nu_S$ [-]	$\delta\left(\bar{\nu}_D^{FWS}-\nu_S\right)$ [%]	$\bar{\nu}_{ef}-\nu_S$ [-]	$\delta\left(\bar{\nu}_{ef}-\nu_S\right)$ [%]	$\bar{E}_D^{FWS}-E_S$ [GPa]	$\delta\left(\bar{E}_D^{FWS}-E_S\right)$ [%]	$\bar{E}_{ef}-E_S$ [GPa]	$\delta\left(\bar{E}_{ef}-E_S\right)$ [%]
1A	-0,046	-16,4	-0,039	-14,1	4,0	5,4	-7,9	-10,5
1B*	-0,019	-7,5	-0,011	-4,4	10,4	16,3	-0,8	-1,2
2A	0,090	47,2	0,079	41,5	5,4	7,9	-2,0	-2,9
shale (4,70-4,85 m)	0,114	56,9	0,117	58,6	66,1	1311,8	39,1	776,7
shale (6,05-6,30 m)	0,081	1,6	0,083	1,7	38,3	760,0	22,0	436,1
3A*	0,073	40,5	0,050	27,8	13,8	21,2	4,3	6,7
4C	0,086	43,1	0,051	25,3	4,6	6,8	0,8	1,1
5A*	0,062	28,3	0,044	19,8	7,7	12,5	-1,4	-2,2
5B	0,018	8,9	0,019	9,5	7,3	11,5	-2,5	-4,0
6A	0,023	10,4	0,014	6,5	17,4	30,8	10,4	18,4
shale (13,2-13,7 m)	0,113	56,5	0,115	57,7	34,6	686,4	19,8	393,6
7A*	0,026	15,2	0,019	11,2	20,0	40,4	3,9	8,0

The use of the T-matrix model to calculate effective moduli of rock encountered in the borehole profile achieved several improvements, especially in the Young's modulus curve:

- The effective modulus values are for most of the borehole profile comparable with static moduli determined on samples. In shale layers with low strength σ_c we did not achieve full agreement between effective and static Young's modulus values (more details in Table 2).
- The effective modulus curve contains significantly more information about the borehole profile than the original dynamic modulus curve. Thanks to the inclusion of the observed low strength layers into the model, they are more visible in the effective Young's modulus curve. Together with lithological information about the layers in the borehole profile (from the borehole core or ABI) this safely indicates layers of low strength σ_c. Interpreted dynamic Young's modulus curve display this information to a

certain degree, but these layers are significantly highlighted in the effective Young’s modulus curve (see Figure 3).

The table 2 shows that effective modulus calculation achieved significantly better agreement with static modulus than dynamic modulus did. For better illustration, the deviations of dynamic and effective modulus values from static modulus values are given here. The dynamic moduli represent the standard interpretation of sonic well logging while the interpretation by means of effective moduli is improved by the T-matrix model. In the case of dynamic and effective moduli, the average values from close vicinity of the sample collection depths are compared. Deviations are expressed in the form of absolute difference (errors), relative errors were calculated by normalizing using the corresponding value of static modulus. Significant improvement is clear for the majority of deviant values. In the case of Young’s modulus, for most samples the absolute differences decreased from values around 10 GPa, maximum up to 20 GPa, to just a few GPa. Relative errors reaching up to 40 % dropped to under 10 %.

The shale layers differ from the surrounding limestone and contrast greatly with respect to strength σ_c and Young’s modulus. The difference in the value of static Young’s modulus is roughly 70 GPa. Although the drop in the value of calculated effective modulus in these layers was considerable, the difference between the static and effective Young’s modulus is still several times the value of static modulus. Corresponding to this are also the high values of relative errors normalized by this low static modulus value. For Poisson’s ratio there was no decrease in the difference between static and effective value. Relative error values even increased slightly by a few tenths to a few percentage points. From a practical point of view there was no significant change. Effective moduli in these layers thus cannot be considered equivalent to static moduli.

5 Conclusions

The research conducted in this Ph.D. thesis demonstrated the potential use of the T-matrix model for determining the effective moduli of rock by converting the dynamic moduli determined by sonic well logging using the FWS tool. In this manner, effective moduli suitable for practical calculations along the entire borehole profile were obtained, with the exception of layers with low strength σ_c and low Young’s modulus. Thanks to the model calculation these layers were reliably identified. However, it is always necessary to verify how much effective moduli within, the scope of these layers, approximate the actual static moduli of the given layer.

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