MIKOVINY SÁMUEL DOCTORAL SCHOOL OF EARTH SCIENCES

THESES OF DOCTORAL (PHD) DISSERTATION

ROCK PHYSICAL INVESTIGATIONS OF ACOUSTIC RELAXATION PROCESSES

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I. SCIENTIFIC BACKGROUND AND AIMS

The laboratory investigations of acoustic wave velocities and attenuation have had an important role in the international researches for decades. The refraction and reflection seismic measurements contribute to the understanding of subsurface structures up to several kilometres within a large area. In contrast, the acoustic well logging provides information from a shorter distance around the borehole, but the vertical resolution can reach the accuracy of centimetres. The advantage of ultrasonic laboratory measurements is that the different physical environments (pressure, temperature, pore saturation) can be modelled under controlled conditions. Its drawback is that the small samples prepared from cores represent the subsurface formation only to a limited extent. However, the information gained during the laboratory tests is essential for describing and understanding the propagation characteristics of acoustic waves and the underground formations.

The wave propagation velocity and attenuation of acoustic waves obtain important information about the physical properties of rocks. These parameters are affected by the mineral composition, fracturing, pore types and properties of pore fluids, therefore the knowledge gained with laboratory measurements are very useful for other practical applications as well.

Several studies containing results of laboratory acoustic velocity and attenuation/quality factor measurements are published (for example Yu et al. 1993, Khazanehdari and McCann 2005, Zimmer 2013, Gomez et al. 2010). The qualitative descriptions of the pressure dependence (Wyllie et al. 1958, Birch 1960, Walsh and Brace 1964) report usually an exponential relation. Beside them, one can find empirical relations in the literature where the optimal parameters of the regression functions are given (Eberhart-Phillips et al. 1989, Wepfer and Christensen 1991, Khaksar et al. 1999, Wang et al. 2005), but they cannot be considered physical models. The pressure dependence can be influenced by the presence of several mechanisms, for example, the closure of microcracks or the decrease of pore volume, or different frictions on grains or microcracks. Generally, the equilibrium in a medium is eliminated if the environment is changing. It is well known, that all systems want to reach a state where its energy is minimal. It means that the rocks are also trying to reach a new equilibrium state adapted to the altered parameters, which requires time. This transition is considered the relaxation, which is characteristic of several physical and chemical processes. For acoustic waves, the mechanisms arising due to variations in pressure (for example closure of pore space/micro cracks) do not follow the changes immediately. Therefore, the introduced rock physical models are considered relaxation models.

The researches at the Department of Geophysics, University of Miskolc (Dobróka et al. 2008, Dobróka and Somogyiné Molnár 2012) aim to develop rock physical models that provide physical explanations for the pressure dependence of acoustic wave velocities and attenuation. Results on longitudinal waves were published by Somogyiné Molnár (2013) in her PhD dissertation.

The aim of my doctoral research was to continue developing rock physical models that explain the pressure dependence of the velocity and quality factor of shear waves and give the physical meaning of the internal parameters of the models. In the first part of my dissertation only one influencing mechanism – the closure of pore space – is considered during the investigations of shear wave velocity-pressure and quality factor-pressure relations. Therefore, these models are called the „β-σ" and „Q_β-σ" Single Relaxation Models (SRM, in the Hungarian terminology „β-σ" and „Q_β-σ" Egyszerű Relaxációs Modellek (ERM)). The Single Relaxation Models can be applied in practice well, but in some cases, it is advisable to further refine them. The reality can always be approximated better with a model, where more phenomena effecting our investigated process are considered. Therefore, in the second part of my thesis work, I further developed the Single Relaxation Models and I introduced the „v-σ" and „Q-σ" Double Relaxation Models (DRM, in Hungarian terminology „v-σ" and „Q-σ" Kettős Relaxációs Modellek (KRM)). They assume that two relaxation processes are present simultaneously. Since more inner processes can be activated in the rocks if the pressure is increased, I formulated a theoretical suggestion for the Generalized „v-σ" and „Q-σ" Relaxation Models (GRM, in the Hungarian terminology Általánosított „v-σ" and „Q-σ" Relaxációs Modellek (ÁRM)), which describe the total effect of any number of phenomena.

II. ACCOMPLISHED INVESTIGATIONS

During my research I followed the principles of continuum mechanics, therefore I introduced my dissertation with its basics and the related rock physical models continued with a short overview of international literature about the pressure dependence of acoustic wave velocities and attenuation. It includes the laboratory measurements and the empirical relations and models based on the results.

As the first step of the model development, I formulated new rock physical models for the pressure dependence of transverse wave velocity and quality factor. The basic idea – that the main driving force for the pressure dependence is the change in pore volume – is the same as it was in the previous work of Somogyiné Molnár (2013) who introduced model equations for the longitudinal wave in a similar manner. The applicability of the new „β-σ" and Q_β-σ" Single Relaxation Models was tested on literature and own measurement data. The parameters of their exponential model equations were estimated with geophysical inversion.

It was investigated and proved that the parameters λ_V and λ_Q occurring in the transverse and longitudinal (proposed by Somogyiné Molnár 2013) model equations can be considered common parameters. Thus, the processing of P and S wave velocity and quality factor data is possible in a joint inversion procedure, which increases the estimation accuracy of the model parameters. The relative data distances between measured and calculated data were calculated. In case of velocities, its value is around 1 %, for the quality factors it is 4-8 % (The reason for the larger distance is the greater error of measurement data). These results are accurate enough for the engineering problems. It means that the Single Relaxation Models describing the pressure dependence of acoustic wave velocities and quality factors are well applicable is practice.

After determining the model parameters, the calculation of velocities and quality factors is possible at any pressure within the framework of the model. Based on these results, the pressure dependent elastic moduli (Lamé parameters, Poisson number, bulk and Young's moduli) and loss angles can be deduced as well. For the calculations, some examples were presented.

I investigated the impact of different overdetermination ratios on the accuracy of inversion, and how the start model parameters influence the estimation results. I found that the model can give a suitable estimate for the „non-measured" pressure ranges, regardless of whether the measured values are missing from the low or high pressure ranges. Furthermore, the starting model parameters can be easily defined from the measured values.

The reality can always be approximated better with a model, where more phenomena effecting our investigated process is considered. Therefore, I further developed the Single Relaxation Models and I introduced the „v-σ" and „Q-σ" Double Relaxation Models (DRM, in Hungarian terminology „v-σ" and „Q-σ" Kettős Relaxációs Modellek (KRM)). They assume that two relaxation processes are present simultaneously. They require the determination of new rock physical parameters as well. The applicability of the models was tested on data sets published in the literature and my own measurements made at the Department of Geophysics. It was proved that the new Double Relaxation Models provide the more accurate description of the phenomena in comparison to the Single Relaxation Models. Based on the velocities determined with the DRM, the pressure dependent moduli become more accurate as well.

Since more inner processes (closure of pore space or micro cracks, friction on the grains or crack surface etc.) can be activated in the rocks if the pressure is increased, the combination of these elemental changes influences the acoustic absorption-dissipation characteristics. Following this idea, I formulated a theoretical suggestion for the Generalized „v-σ" and „Q-σ" Relaxation Models (GRM, in the Hungarian terminology Általánosított „v-σ" and „Q-σ" Relaxációs Modellek (ÁRM)), which describe the total effect of any number of phenomena.

III. NEW SCIENTIFIC RESULTS

Thesis statement 1

The "β-σ" Single Relaxation Model explaining the pressure dependence of the transverse wave velocity with a single extended quantity – the pore volume – is based on the fact that the grains in the rock get closer to each other when the pressure increases. Thereby the pore volume decreases, and higher transverse wave velocities are measured. Based on the differential equations describing the processes above, the model equation

$$\beta = \beta_0 + \Delta\beta_0 (1 - exp(-\lambda_V \sigma))$$

was derived, where beside the transverse wave velocity β and pressure σ the meaning of the three model parameters are: β_0 transverse wave velocity measured at atmospheric pressure, $\Delta\beta_0$ the difference between the transverse wave velocities measured at maximal and atmospheric pressure i.e. the velocity drop, λ_V new rock physical parameter, which expresses the logarithmic pressure sensitivity of the velocity drop.

Thesis statement 2

The "Q_β-σ" Single Relaxation Model explaining the pressure dependence of the transverse wave quality factor with a single extended quantity – the pore volume – is based on the fact that the grains in the rock get closer to each other when the pressure increases, i.e. the pore volume decreases. Because of the closer contact between the particles, the waves suffer less attenuation, i.e. the value of the quality factor increases. Based on the differential equations describing the processes above, the model equation

$$Q_\beta = Q_{\beta 0} + \Delta Q_{\beta 0} (1 - exp(-\lambda_Q \sigma))$$

was derived, where beside the transverse wave quality factor Q_β and pressure σ the meaning of the three model parameters are: $Q_{\beta 0}$ transverse wave quality factor measured at atmospheric pressure, $\Delta Q_{\beta 0}$ the difference between the transverse wave quality factors measured at maximal and atmospheric pressure i.e. the quality factor drop, λ_Q new rock physical parameter, which expresses the logarithmic pressure sensitivity of the quality factor drop.

Thesis statement 3

Determining the acoustic wave velocities often results in difficulties due to measurement technology: the noise is usually too high in the low pressure range, and new micro cracks may be generated in the high pressure range. I have demonstrated with tests that the proposed model leads to reliable results.

a) Examining the overdetermination ratio of the problem by excluding data measured in certain pressure ranges, I found that the proposed rock physical model gives reliable estimates for the non-measured pressure ranges.

b) Investigation results of the choice of start model indicate that the initial model parameter values can be safely selected based on the measured data. I have found that the process achieves optimal results even with far start model parameters, with a small iteration number.

Thesis statement 4

The Single Relaxation Models introduced for the pressure dependence of acoustic velocities and quality factors give the possibility to deduce material characteristic parameters in a pressure range given by the framework of the model as well. Thus, the pressure dependent elastic parameters provide important information on rocks for engineering practice.

Thesis statement 5

As a result of the model development of the description of pressure dependent acoustic wave velocities, I introduced the „v-σ" Double Relaxation Model. It involves the effect of two relaxation processes from the extensive quantities playing role in this phenomenon. The model equation was derived

$$v = v_{max} - \Delta v_1\, exp(-\lambda_{V1}\sigma) - \Delta v_2\, exp(-\lambda_{V2}\sigma)\,,$$

where v indicates the velocity, σ is the pressure, and the model parameters are the velocity at maximal pressure v_{max}, the Δv_1 and Δv_2 velocity drops, as well as the λ_{V1} and λ_{V2} rock physical parameters.

Thesis statement 6

To further develop the Single Relaxation Model describing the pressure dependence of acoustic wave quality factors, the effect of two relaxation processes was considered. Thus, I introduced the model equation of the new „Q-σ" Double Exponent Model

$$Q = Q_{max} - \Delta Q_1\, exp(-\lambda_{Q1}\sigma)) - \Delta Q_2\, exp(-\lambda_{Q2}\sigma))\,,$$

where Q is the quality factor, σ is the pressure. Three model parameters should be determined: Q_{max} is the quality factor at maximal pressure, ΔQ_1 and ΔQ_2 are the quality factor drops, λ_{Q1} and λ_{Q2} are rock physical parameters.

Thesis statement 7

The Double Relaxation Models include the effects of two phenomena due to pressure increase, but third, fourth, and even more processes can be activated and take part in the pressure dependence of acoustic parameters. Therefore, I formulated the Generalized Relaxation Models as a new conceptual recommendation. For both velocities and quality factors, I assumed that there are M numbers of phenomena occurring in the rocks under loading, for which each i-th internal process has an extensional X_i. From the differential equations describing the processes, I introduced the model equations

a) Generalized „v-σ" Relaxation Model:

$$v = v_{max} - \sum_{i=1}^{M} \Delta v_i \; exp(-\lambda_{Vi}\sigma),$$

b) Generalized „Q-σ" Relaxation Model:

$$Q = Q_{max} - \sum_{i=1}^{M} \Delta Q_i \; exp(-\lambda_{Qi}\sigma).$$

PRACTICAL APPLICATION OF THE RESULTS

Investigations of seismic/acoustic waves are the physical basis of surface seismic and acoustic well logging methods. The absorption-dissipation characteristics of elastic waves depend on many factors including rock composition, porosity, rock pressure, volume and quality of pore fluid. The sum of these effects is reflected in field measurement data. The velocities and quality factors measured in the laboratory under varying conditions contribute to the understanding of the processes in rocks, which makes it possible to set up rock physical models as presented in this paper.

The researches on the pressure dependence of acoustic parameters are important because increasing velocities can be measured with increasing depth under the surface. Therefore, the physical connection between the parameters must be known, and it helps to transform the seismic time sections into depth profiles. Nowadays the non-conventional reservoirs become more important. They are characterized mostly by low porosity and permeability; thus, enhanced oil recovery should be applied for extraction. For the fracturing, the in-situ stresses should be known which may be estimated from the acoustic parameters.

Based on the acoustic velocities and quality factors, the dynamic elastic moduli and loss angles can be deduced. With the proposed models, the velocities and quality factors can be calculated for a wide range of pressures, so the pressure dependence of these moduli can be specified as well, which is useful in solving engineering (geophysical, geotechnical) tasks. The improved rock physical models also increase the estimation accuracy of these parameters.

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