MIKOVINY SÁMUEL DOCTORAL SCHOOL OF EARTH SCIENCES

Theses of doctoral dissertation

PRESSURE DEPENDENCE OF PROPAGATION PROPERTIES OF ELASTIC WAVES – NEW PETROPHYSICAL MODELS

Author:
JUDIT SOMOGYINÉ MOLNÁR

Scientific advisor:
DR. MIHÁLY DOBRÓKA
professor,
doctor of technical sciences

University of Miskolc
Department of Geophysics
Miskolc
2013

I. SCIENTIFIC BACKGROUND AND AIMS

The velocity of elastic waves propagating in rocks are influenced by the type and structure of the rock composed of variable amount of minerals and other matrix constituents, porosity, type and quantity of pore content, as well as microcracking. Microcracks open and close under the change of pressure. Similarly the size of pores can change with pressure. This leads to fact that the propagation velocity and absorption coefficient of seismic/acoustic wave vary with pressure. Several qualitative ideas exist describing the pressure dependence of seismic velocity, e.g., such that pore volume reduces with increasing pressure, thus increasing velocity can be measured on the rock sample (Birch 1960). Brace and Walsh (1964) explains the stress dependence of this phenomenon by the closure of microcracks.

The velocity vs. pressure relationship can be characterized by exponential functions (Wang et al. 2005; Singh et al. 2006). Several empirical models exist to describe the pressure dependence of longitudinal acoustic wave velocity. These models usually provide only the determination of the parameters of a suitably chosen formula based on mathematical regression but the physical meaning of pressure-velocity connection is left unexplained (Wepfer and Christensen 1991, Ji et al. 2007). For the better understanding of the phenomenon as well as adequate interpretation of laboratory measurement data a qualitative model is required which gives also the physical meaning of the phenomena of pressure dependence.

In the framework of my doctoral research based on the physical background of change of microcracks in rocks and pore volume under pressure, I develop petrophysical models which provide the connection of the propagation velocity as well as attenuation (quality factor) of seismic/acoustic wave and rock pressure. The models provide physical explanation for the phenomena of pressure dependence and give the physical meaning of the model parameters. The developed pressure dependent velocity model can be applied both in case of pressurization and depressurization cycles, i.e. in my present work I also explain the phenomenon of acoustic hysteresis as well.

In order to prove the applicability of the rock physical models they were tested on acoustic data measured under different pressure in laboratory. In my PhD thesis I present the main measurement methods, as well as the measured longitudinal acoustic velocity and quality factor data, which partly originated from measurements made at the Department of Geophysics, in part from the literature. I deduce the parameters appearing in the models from measurement data by means of a linearized inversion method. In my thesis, I discuss the details of the joint inversion algorithm which enables the processing of pressurization and depressurization cycles, as well as propagation velocity and quality factor models jointly. I show that the theoretical data calculated by the rock physical models fit accurately to measurement data, which proves that the suggested petrophysical models describe the real geological situation appropriately.

II. ACCOMPLISHED INVESTIGATION

In my PhD thesis I reviewed the qualitative models describing pressure dependence of the longitudinal acoustic wave and quality factor published in literature and presented the main methods of measurement of wave propagation characteristics, as well as summarized briefly the foregoing literature referred to regression description of pressure dependence. To reasonably interpret laboratory measurement data, a quantitative model which provides also the physical explanation of the phenomena is required. In my research work, beyond the presented regression formulas and discovering the specific physical characteristics (determining the phenomenon) of the rock, I developed a physical model and explained the phenomenon of pressure dependence. During my research accepting the qualitative literary history I followed the idea of Brace and Walsh (1964), which claims that microcracks open and close in rocks under the change of pressure. Likewise, I took the conception of Birch (1960) as a basis. It states that pore volume reduces with increasing pressure, thus increasing velocity and quality factor can be measured on the core sample. Based on these physical principles some differential equations describing the phenomenon were set up, with that of solution easily understood formulas could be deduced. The developed models provide the connection of propagation velocity of acoustic wave and quality factor as well as rock pressure for the pressurization stage. Following these considerations the depressurization cycle can also be described, hence in my dissertation I developed a rock physical model valid for the depressurization stage. Therewith the combination of the created models for both uploading and unloading cycles allowed us to develop a petrophysical model describing the phenomenon of acoustic hysteresis.

In order to prove the applicability of the rock physical models they were tested on acoustic data measured under pressure. The parameters appearing in the model equations were determined by means of linearized (partly joint) inversion methods. Aware of the parameters by comparing the calculated data based on the rock physical models to the measurement data, an accurate fitting was found. During the inversion procedure the RMS of fitting in data space was calculated, which was obtained under 0,5% in case of the acoustic velocity model for instance. In my research I gave the estimation errors of model parameters, as well as the correlation matrix and mean spread for each processed measurement data set, too. The values of mean spread were obtained under 0,5 for all samples, which confirms the reliability of the inversion results.

With the estimated - by quality checked inversion - model parameters based on the presented petrophysical models it becomes possible to introduce a new rock physical analysis method, which can be directly applicable to the petrophysical practice.

III. NEW SCIENTIFIC RESULTS

Thesis 1

Combining the qualitative conception on the basis of the alteration of microcracks of Brace and Walsh (1964), as well as the idea of change in pore volume after Birch (1960), I introduced the notation of the extensive quantity X relevant to the description of pressure variation to which I set up a differential equation based on simple physical considerations

$$dX = -\lambda X \, d\sigma$$

and provided the pressure dependence of this quantity to the pressurization stage

$$X = X_0 e^{-\lambda\sigma}.$$

On the basis of the latter

a) I set up the differential equation of the microcrack concentration and by solving it I derived that of pressure dependence

$$N = N_0 e^{-\lambda_N\sigma},$$

where N_0 is the specific number of microcracks at stress free state, λ_N is a new material specific petrophysical parameter.

b) Based on simple physical considerations I gave the connection of the elemental change of propagation velocity and the infinitesimal microcrack concentration, then by applying the described results in subthesis 1a) I provided the differential equation of the velocity-pressure function. With the solution of the equation the velocity-pressure function valid in the framework of the model could be obtained:

$$v = v_0 + \Delta v_0 (1 - e^{-\lambda_N\sigma}),$$

where, v_0 is the longitudinal velocity at stress free state and $\Delta v_0 (=\alpha_N N_0)$ is the velocity drop.

c) I gave the physical explanation of the material characteristics (v_0, Δv_0, λ_N) appearing in the petrophysical model.

Thesis 2

Based on Birch's (1960) qualitative model concept I suggested a rock physical model for the description of pressure dependence of longitudinal acoustic velocity for the pressurization cycle.
Within this:

a) Applying the equations of the extensive quantity X - introduced in the thesis 1 - for the change in pore volume I set up the differential equation of the specific pore volume variation, and that of solution I derived that of pressure dependence

$$V = V_0 e^{-\lambda_V\sigma}.$$

b) Based on simple physical considerations I gave the connection of the elemental change of propagation velocity and the infinitesimal pore volume change, then by applying the described results in subthesis 2a) I provided the differential equation of the velocity-pressure function and I found that it is formally the same as the velocity-pressure function suggested in thesis 1

$$v = v_0 + \Delta v_0 (1 - e^{-\lambda_V\sigma}), \qquad \Delta v_0 = \alpha_V V_0.$$

Beyond the formal matching, the value of the petrophysical material characteristics appearing in the model equation and that of connection to the internal petrophysical parameters was different of course.

Thesis 3

I set up a rock physical model for the description of the pressure dependence of quality factor of longitudinal acoustic velocity for the pressurization cycle.

a) Applying the petrophysical model for the specific number of microcracks suggested in subthesis 1a), I set up the differential equation which described the pressure dependence of quality factor. With its solution I derived the quality factor-pressure function:

$$Q = Q_o + \Delta Q_0 \left(1 - e^{-\lambda_N \sigma}\right),$$

where, Q_0 is the quality factor at stress free state, $\Delta Q_0 (=\beta_N N_0)$ is that quality factor range in which it can vary and the meaning of λ is the same as in subthesis 1a).

b) Applying the results introduced for the change of pore volume in subthesis 2a), I provided the differential equation of the quality factor-pressure function and that of solution I derived the pressure dependence of quality factor for rocks to be correspond the model criterion.

Thesis 4

Based on the qualitative model concept of Brace and Walsh (1964) I suggested a rock physical model for the description of the pressure dependence of longitudinal acoustic velocity for the depressurization cycle which was the basis of the introduction of a petrophysical model explaining acoustic hysteresis.

a) With simple physical consideration I set up a differential equation for the pressure dependence of closed number of microcracks $n = N_0 - N$ then I derived that of solution

$$n = n_m e^{-\lambda'(\sigma_m - \sigma)},$$

where σ_m is the maximum applied pressure during pressurization (the depressurization cycle starts from here), n_m is the number of closed microcracks at pressure σ_m, and λ' is the petrophysical material characteristics valid for the depressurization stage.

b) Applying the differential equation established for the connection of elemental change of velocity and the infinitesimal change of open microcrack concentration suggested in subthesis 1b), I derived the velocity-pressure function valid for the depressurization cycle.

$$v = v_m - \alpha n_m \left(1 - e^{-\lambda'(\sigma_m - \sigma)}\right),$$

where v_m is the measurable velocity at the applied maximum pressure.

c) I provided a joint function to describe acoustic hysteresis by integrating the velocity-pressure function for the pressurization cycle (to maximum pressure σ_m) suggested in thesis 1 and the velocity-pressure function for depressurization stage starting from stress σ_m after subthesis 4b). Hereby – considering the physical models behind thesis 1 and 4 – a physical model which explained the phenomenon of acoustic hysteresis was obtained.

Thesis 5

The model parameters of the petrophysical models introduced in theses 1-4 were estimated by the linearized inversion of laboratory measurement data.

a) I estimated the petrophysical material characteristics (v_0, Δv_0, λ) appearing in the model law - based on laboratory measurement data – by following the least squares method and using the phase velocity-pressure function suggested in theses 1 and 2 as model laws (as the solution of the direct problem). According to the requirements of the quality checked inversion I provided the estimation errors of model parameters, as well as the elements of correlation matrices.

b) I performed joint inversion to estimate the parameters (v_0, Δv_0, Q_0, ΔQ_0, λ) appearing in the model equations by using the phase velocity-pressure function suggested in theses 1 and 2, as well as the quality factor-pressure function introduced in thesis 3 as model laws - based on laboratory measurement data (phase velocity and quality factor) published in literature -. According to the requirements of the quality checked inversion I provided the estimation errors of model parameters, as well as the elements of correlation matrices.

c) I used a joint inversion technique to estimate the model parameters (v_0, Δv_0, v_1, Δv_1, λ, λ') of the acoustic hysteresis model - by using own laboratory velocity (longitudinal) data measured during both cycles on core samples - based on the determined functions for the pressurization and depressurization cycles in thesis 4c) as model equations.

Calculated data based on the petrophysical model parameters as results of my single and joint inversion experiments - a technical point of view in all respects - showed an accurate fitting with laboratory measurement data

PRACTICAL APPLICATION OF THE RESULTS

In the framework of the PhD thesis petrophysical model development was carried out. The suggested models describe the pressure dependence of propagation velocity and quality factor of seismic/acoustic waves. The material (petrophysical) parameters which play an important role of the phenomena of pressure dependence can be determined - by the help of the model equations and using laboratory measurement data of rock samples - by the presented single, as well as joint inversion methods. The introduced new material properties during modelling are feasible to the physical characterization of rocks, i.e. the scope of parameters describing material quality of rocks is expanding.

The suggested models are contributed to a better understanding of the physical properties of rocks. It is particularly important that the phenomenon of acoustic hysteresis becomes modellable by applying the model equations valid in the pressurization and depressurization cycles. The results may serve as a starting point of further research.

The knowledge of depth dependence of seismic velocity is the basic issue of seismic interpretation. Since the increase in the depth also means an increase in rock pressure, the developed models in the dissertation play an important role in the transformation of the time profile to depth profile.

BIBLIOGRAPHY CITED IN THE THESIS

Birch F. 1960. The velocity of compression waves in rocks to 10 kilobars, Part 1. Journal of Geophysics Research, 65, 1083-1102.

Brace W.F., Walsh J. B. 1964. A fracture criterion for brittle anisotropic rock. Journal of Geophysics Research, 69, 3449-3456.

Ji S., Wang Q., Marcotte D., Salisbury M.H., Xu Z. 2007. P wave velocities, anisotropy and hysteresis in ultrahigh-pressure metamorphic rocks as a function of confining pressure. Journal of Geophysics Research, 112, B09204.

Singh R., Rai C., Sondergeld C. 2006. Pressure dependence of elastic wave velocities in sandstones. SEG/New Orleans 2006 Annual Meeting.

Wang Q., Ji S.C., Salisbury M.H., Pan M.B., Xia B., Xu Z.Q. 2005. Pressure dependence and anisotropy of P-wave velocities in ultrahigh-pressure metamorphic rocks from the Dabie-Sulu orogenic belt (China): Implications for seismic properties of subducted slabs and origin of mantle reflections. Tectonophys., 398, 67– 99.

Wepfer W.W., Christensen N.I. 1991. A seismic velocity-confining pressure relation, with applications. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, 28, 451– 456.

IV. LIST OF RELATED PUBLICATIONS AND PRESENTATIONS

JOURNAL ARTICLES

1. DOBRÓKA M., SOMOGYI MOLNÁR J. 2012. New petrophysical model describing the pressure dependence of seismic velocity. Acta Geophysica, 60(2), pp. 371-383. IF: 0.617. DOI: 10.2478/s11600-011-0079-0

2. DOBRÓKA M., SOMOGYI MOLNÁR J. 2012. The pressure dependence of acoustic velocity and quality factor — new petrophysical models. Acta Geodaetica et Geophysica Hungarica, 47(2), pp. 149-160. IF: 0.346. DOI: 10.1556/AGeod.47.2012.2.4

3. DOBRÓKA M., SOMOGYINÉ MOLNÁR J. 2012. Kőzetfizikai modell az akusztikus hiszterézis leírására. Magyar Geofizika, 53(2), pp. 73-79.

4. SOMOGYINÉ MOLNÁR J., DOBRÓKA M. 2011. A szeizmikus/akusztikus sebesség és a jósági tényező kőzetnyomástól való függését leíró kőzetfizikai modellek. Magyar Geofizika, 52(3), pp. 128-134.

PROCEEDINGS OF INTERNATIONAL CONFERENCES (EXTENDED ABSTRACTS)

1. DOBRÓKA M., SOMOGYI MOLNÁR J., SZABÓ N.P. 2013. New Results in Modeling the Phenomenon of Acoustic Hysteresis. 75th EAGE Conference & Exhibition incorporating SPE EUROPEC 2013, London, United Kingdom, 2013.06.10-13. (Accepted in 27 February 2013)

2. DOBRÓKA M., SOMOGYI MOLNÁR J. 2012. Physical explanation of the stress dependence of seismic/acoustic velocity and quality factor. SEG Istanbul 2012 - International Geophysical Conference And Oil & Gas Exhibition, Istanbul, Turkey, 2012.09.17-19. pp. 1-4.

3. SOMOGYI MOLNÁR J., PARIPÁS A.N., DOBRÓKA M., ORMOS T. 2012. New petrophysical model describing the acoustic hysteresis. Near Surface Geoscience, Proceedings, Paris, France, 2012.09.02-05. pp. 1-4.

4. SZEGEDI H., SOMOGYI MOLNÁR J., DOBRÓKA M. 2011. The pressure dependence of acoustic velocity – a new petrophysical model. 6th Congress of Balkan Geophysical Society, Proceedings, Budapest, 2011.10.03-06. P19, pp. 1-4. (ISBN 978-90-73834-16-3)

5. DOBRÓKA M., SOMOGYI MOLNÁR J. 2011. Pressure dependence of seismic Q - a new petrophysical model. Near Surface 2011 – the 17th European Meeting of Environmental and Engineering Geophysics of the Near Surface Geoscience Division of EAGE, Proceedings, Leicester, United Kingdom, 2011.09.12-14. P16, pp. 1-4. (ISBN 978-90-73834-15-6)

6. SOMOGYI MOLNÁR J., SZEGEDI H., DOBRÓKA M. 2011. New petrophysical models for describing pressure-dependent acoustic velocity and absorption coefficient in porous rocks. 73rd EAGE Conference & Exhibition incorporating SPE EUROPEC, Proceedings, Vienna, Austria, 2011.05.23-26. P082, pp. 1-4. (ISBN 978-90-73834-12-5)

7. MOLNÁR J., DOBRÓKA M. 2010. A new petrophysical model for describing the pressure-dependent acoustic velocity in rocks. Near Surface 2010 – the 16th European Meeting of Environmental and Engineering Geophysics of the Near Surface Geoscience Division of EAGE, Proceedings, Zürich, Switzerland, 2010.09.06-08. B16, pp. 1-4. (ISBN 978-90-73781-88-7)

8. MOLNÁR J., DOBRÓKA M. 2010. A new petrophysical model for describing the pressure dependence of seismic velocity in rocks. Junior Scientist Conference, Proceedings, Vienna, Austria, 2010.04.07-09. pp. 139-140. (ISBN 978-3-200-01797-9)

PROCEEDINGS OF DOMESTIC CONFERENCES

1. DOBRÓKA M., SOMOGYI MOLNÁR J. 2012. Description of pressure dependence of acoustic velocity during pressurization and depressurization cycles. Conference & Exhibition on Earth Sciences and Environmental Protection, Miskolc, 2012.09.27-29. pp. 32.

2. SOMOGYI MOLNÁR J. 2012. Description of acoustic hysteresis – new petrophysical model. 8th International Conference of PhD Students, Miskolc, 2012.08.05-11. pp. 1-6. (ISBN:978-963-661-994-7)

3. SOMOGYINÉ MOLNÁR J. 2011. Új kőzetfizikai modellek a longitudinális sebesség és a jósági tényező nyomásfüggésének leírására. Doktoranduszok Fóruma, Műszaki Földtudományi Kar Szekciókiadvány, Miskolc, 2011.11.08. pp. 55-63.

4. SOMOGYI MOLNÁR J., DOBRÓKA M. 2011. Explanation of the stress dependence of seismic/acoustic velocity and absorption coefficient in porous rocks. XXV. microCAD International Scientific Conference, Proceedings, Section B, Miskolc, 2011.03.31-04.01. pp. 35-40. (ISBN 978-963-661-955-8)

5. SOMOGYI MOLNÁR J. 2011. Development of new petrophysical models for the explanation of seismic/acoustic properties of porous rock continua. Meeting of Young Geoscientists, Proceedings, Győr, 2011.03.25-26. pp. 30-31.

6. MOLNÁR J. 2010. A new petrophysical model for describing the pressure dependence of seismic velocity and absorption coefficient. 7th International Conference of PhD Students, Proceedings, Miskolc, 2010.08.08-13. pp. 39-44. (ISBN 978-963-661-941-1)

7. DOBRÓKA M., MOLNÁR J. 2010. Inversion-based petrophysical model for describing the pressure dependence of seismic veolcity. XXIV. microCAD International Scientific Conference, Proceedings, Section G, Miskolc, 2010.03.17-19. pp. 79-84. (ISBN 978-963-661-911-4)

INTERNATIONAL CONFERENCE PRESENTATIONS

1. SOMOGYI MOLNÁR J., M. DOBRÓKA 2013. New Petrophysical Models for Explaining the Pressure Dependence of Acoustic Velocity and Hysteresis, Advances in Geophysical Inverse Theory Workshop, Rome, Italy, 2013.02.04.

2. DOBRÓKA M., SOMOGYI MOLNÁR J. 2012. Physical explanation of the stress dependence of seismic/acoustic velocity and quality factor. SEG Istanbul 2012 - International Geophysical Conference And Oil & Gas Exhibition, Istanbul, Turkey, 2012.09.17-19.

3. SOMOGYI MOLNÁR J., PARIPÁS A.N., DOBRÓKA M., ORMOS T. 2012. New petrophysical model describing the acoustic hysteresis. Near Surface Geoscience, Paris, France, 2012.09.02-05.

4. DOBRÓKA M., SOMOGYI MOLNÁR J. 2011. Pressure dependence of seismic Q - a new petrophysical model. Near Surface 2011 – the 17th European Meeting of Environmental and Engineering Geophysics of the Near Surface Geoscience Division of EAGE, Leicester, United Kingdom, 2011.09.12-14.

5. SOMOGYI MOLNÁR J., SZEGEDI H., DOBRÓKA M. 2011. New petrophysical models for describing pressure-dependent acoustic velocity and absorption coefficient in porous rocks. 73rd EAGE Conference & Exhibition incorporating SPE EUROPEC, Vienna, Austria, 2011.05.23-26.

6. MOLNÁR J., DOBRÓKA M. 2010. A new petrophysical model for describing the pressure-dependent acoustic velocity in rocks. Near Surface 2010 – the 16th European Meeting of Environmental and Engineering Geophysics of the Near Surface Geoscience Division of EAGE, Zürich, Switzerland, 2010.09.06-08.

7. MOLNÁR J., DOBRÓKA M. 2010. A new petrophysical model for describing the pressure dependence of seismic velocity in rocks. Junior Scientist Conference, Vienna, Austria, 2010.04.07-09.

DOMESTIC CONFERENCE PRESENTATIONS

1. DOBRÓKA M., SOMOGYI MOLNÁR J. 2012. Description of pressure dependence of acoustic velocity during pressurization and depressurization cycles. Conference & Exhibition on Earth Sciences and Environmental Protection, Miskolc, 2012.09.27-29.

2. SOMOGYI MOLNÁR J. 2012. Description of acoustic hysteresis – new petrophysical model. 8th International Conference of PhD Students, Miskolc, 2012.08.05-11.

3. SOMOGYINÉ MOLNÁR J. 2011. Új kőzetfizikai modellek a longitudinális sebesség és a jósági tényező nyomásfüggésének leírására. Doktoranduszok Fóruma, Miskolc, 2011.11.08.

4. SOMOGYINÉ MOLNÁR J., DOBRÓKA M. 2011. Kőzetmintákon mért sebesség és jósági tényező adatok inverziója - új kőzetfizikai modellek alkalmazása a nyomásfüggés leírására. MTA-MGE-ME Inversion Conference, Miskolc, 2011.11.07.

5. SOMOGYI MOLNÁR J., DOBRÓKA M. 2011. Explanation of the stress dependence of seismic/acoustic velocity and absorption coefficient in porous rocks. XXV. microCAD International Scientific Conference, Section B, Miskolc, 2011.03.31-04.01.

6. SOMOGYI MOLNÁR J. 2011. Development of new petrophysical models for the explanation of seismic/acoustic properties of porous rock continua. Meeting of Young Geoscientists, Győr, 2011.03.25-26.

7. MOLNÁR J. 2010. A new petrophysical model for describing the pressure dependence of seismic velocity and absorption coefficient. 7th International Conference of PhD Students, Miskolc, 2010.08.08-13.

8. DOBRÓKA M., MOLNÁR J. 2010. Inversion-based petrophysical model for describing the pressure dependence of seismic veolcity. XXIV. microCAD International Scientific Conference, Section G, Miskolc, 2010.03.17-19.

9. MOLNÁR J., DOBRÓKA M. 2009. A szeizmikus sebesség kőzetnyomástól való függését leíró kőzetfizikai modell paramétereinek inverziós meghatározása. Ifjúsági Előadói Nap, Miskolc, 2009.12.11.

SCIENTIFIC REPORTS

1. DOBRÓKA M., TURAI E., SZABÓ N.P., SOMOGYINÉ MOLNÁR J., SZEGEDI H. 2012. Akusztikus jellemzők nyomásfüggésének vizsgálata és kőzetfizikai modell felállítása, 2012. december.

2. DOBRÓKA M., ORMOS T., VASS P., SZEGEDI H., HERCZEG Á. PARIPÁS A.N., MOLNÁR J. 2009. Laboratóriumi mérések és korszerű szelvényelemzések együttes alkalmazása inverziós eljárással, 2009. november.