Frequency-dependent seismic reflection from a permeable boundary in a fractured reservoir

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Summary

The coefficients of normal reflection and transmission of a planar *p*-wave from a permeable boundary in a fractured reservoir are studied in low-frequency range. The coefficients are expressed as power series with respect to a small dimensionless parameter, which is the product of the reservoir fluid mobility and density, and the frequency of the signal. The coefficients of such series are functions of mechanical properties of the reservoir rock and fluid. The zero-order terms of the reflection and transmission coefficients have a form similar to the one derived from the classical theory, without accounting for fluid flow. There is a strong similarity to Gassman's effective medium model. The next power expansion term both for reflection and transmission coefficients is proportional to the square root of the small parameter described above. Unlike frequency-dependent terms, the zero-order coefficient does not depend on the permeability contrast.

The functional structure of the reflection and transmission coefficients provides opportunities for seismic inversion and suggests new seismic attributes.

Introduction

Fractured reservoirs are typical for many hydrocarbon-producing regions (Romm, 1966; van Golf-Racht, 1982). The presence of fractures at different scales has a significant impact on the flow properties of reservoir rock. Two or more scales of permeability are usually observed. A connected system of fractures, due to relatively simple geometry of the pore space, is highly permeable for fluid flow. The matrix, due to the tortuous pores and pore throats, is significantly less permeable. At the same time, the total volume of the fractures is usually small and the matrix blocks contain most part of the reservoir fluid. This contrast leads to the dual porosity model of reservoir rock, which was originally proposed by Barenblatt *et al.* (1960). According to this model, the fluid flow in matrix blocks is local: it only supports the exchange of fluid between individual blocks and the surrounding fractures. In large scale, fluid flows through the fractures only. This model has been tested and confirmed by reservoir engineering practice (Warren and Root, 1963; Romm, 1966; van Golf-Racht, 1982). Pride and Berryman (2003ab) have proposed a dual-porosity medium model where both media support large-scale fluid flow. They have combined this model with Biot's theory of poroelasticity (Biot 1956ab) to study attenuation of elastic waves in fractured reservoirs.

In this study, we apply Barenblatt's approach to flow in fractured rocks. A combination of this approach with Biot's theory of elastic wave propagation in permeable porous media leads to a model, which we call Biot-Barenblatt poroelastic model of fractured rock. In fact, the applicability of this model is not limited to fractured rock only. It is justified whenever the permeability of the rock has two or more contrast scales. These scales must be distributed in the medium in such a way that every representative volume comprises both, small-volume highly permeable medium and low-permeable analog of matrix. Recent studies suggest that even in a "classical" porous rock, such as sandstone, the fluid flows through a very small portion of the pore space, while the most part of it is in stagnation.

Our main objective is to characterize normal reflection of an incident *p*-wave from the impermeable bottom of a reservoir. It is a continuation of the previous study (Goloshubin and Silin, 2005), where reflection and transmission coefficients at the impermeable top of a fractured reservoir have been investigated. The important feature is that the reflection and transmission coefficients are frequency-dependant. Therefore, the seismic attributes suggested by the theory also account for the dependence of the reflected signal on the frequency. Targeting low-frequency range of the spectrum, we first develop asymptotic analysis of attenuation in a dual-porosity medium.

Another implication of the presence of fractures is that reservoir layers with different permeabilities and, perhaps, different elastic properties are separated one from another by a permeable interface. Analysis of reflection from the such a permeable boundary is motivated by the necessity of investigation of reflection from a vertically confined layer. However, some of the findings are interesting by themselves. Although such a wave usually quickly dissipates, it still may play a role when the reservoir is relatively thin.

Practicing geophysicists use the frequency-dependent analysis of seismic data for hydrocarbon exploration with success for a long time (Goloshubin et al., 2006). Not only does it make possible to accurately delineate the reservoir, but also to locate the most productive zones and water-oil contact. Examples of such analysis are presented below.

Further presentation is organized as follows. First, we extract a brief summary of asymptotic analysis of elastic wave propagation in a fractured reservoir. Then we present the results of the study of reflection and transmission coefficients for the fast incident waves. At the end, examples of frequency-dependent seismic imaging are presented for illustration.

Asymptotic analysis of *p*-wave propagation in dual-porosity rock

A compression *p*-wave in fluid-saturated porous medium is a superposition of slow and fast waves (Biot 1956ab). These two waves are always coupled and neither one can exist separate from the other. The same holds true in a fractured reservoir. The main difference is that in dual-porosity medium, the permeability is decoupled from the porosity. The permeability of the system of fractures is governed by Darcy's law and is characterized by a coefficient of permeability, κ. Fluid flow in the matrix is local, limited to exchange with the surrounding fractures. Let q denote the volumetric flow rate between matrix blocks and fractures per unit bulk volume of the medium. Then

$$q = -\frac{A}{\eta}\left(p_f - p_m\right)$$

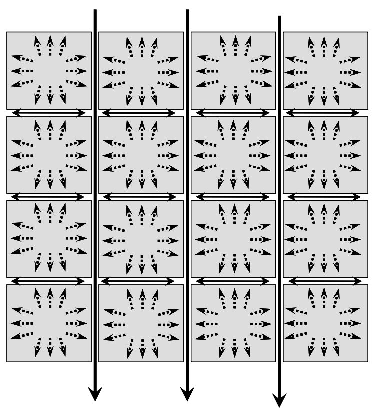

Figure 1. Schematic representation of Barenblatt's dual-porosity medium. The fluid flow is shown by arrows. The fracture pressure gradient is upwards. Local fluid exchange between matrix blocks and the fractures (dashed arrows) is approximately uniform in all direction. The fluid can flow across several blocks only through fractures, solid arrows.

Here η is the fluid viscosity, p_f and p_m are fluid pressures in fractures and matrix, and A is a dimensionless shape factor. The latter is a function of characteristic permeability, size, and shape of the matrix blocks. Let ϕ_m be matrix porosity, ρ_f and ρ_b, respectively fluid and bulk densities, W Darcy velocity of the fluid relative to the rock, β_f the compressibility of the fluid and β the compressibility of drained rock,

$$\beta = \left(K + \frac{4}{3}\mu\right)^{-1}$$

In the last formula, K is the bulk drained modulus and μ is the shear modulus of the rock. Mass and momentum balance equations can be summarized in the following way:

$$\frac{1}{v_b^2}\frac{\partial^2 u}{\partial t^2} + \frac{1}{v_f^2}\frac{\partial W}{\partial t} = \frac{\partial^2 u}{\partial x^2} - \beta\frac{\partial p_f}{\partial x}$$

$$W + \tau\frac{\partial W}{\partial t} = \rho_f\frac{\kappa}{\eta}\beta\frac{\partial p_f}{\partial x} - \rho_f\frac{\kappa}{\eta}\frac{\partial^2 u}{\partial t^2}$$

$$\frac{\partial W}{\partial x} = -\frac{A}{\eta}\left(p_f - p_m\right)$$

$$\frac{\partial^2 u}{\partial t\partial x} + \phi_m\beta_f\frac{\partial p_m}{\partial t} = -\frac{\partial W}{\partial x}$$

The two velocities v_b and v_f are defined as $v_b^2 = \left(\beta\rho_b\right)^{-1}$ and $v_f^2 = \left(\beta_f\rho_b\right)^{-1}$. Neither one of these velocities is a measured physical quantity. They are just convenient notations for the introduction of modified acoustic impedances in the next section. The factor τ has dimensionality of time and reflects the non-equilibrium effects in the fluid flow. These effect are neglected in the classical Darcy flow theory (Hubbert, 1956).

A harmonic wave solution to the system of equations above is a sum of slow and fast waves $u = U^S e^{i(\omega t - k_S x)} + U^F e^{i(\omega t - k_F x)}$, and can be obtained using power-series expansion relative small parameter $\varepsilon = i\frac{\rho_f\kappa\omega}{\eta}$. Here i is the imaginary unity. The main result of this section is asymptotic formulae for the (complex) wave numbers for the slow and fast waves

$$k_F = \gamma_\rho\sqrt{\frac{\gamma_\beta}{1+\gamma_\beta}}\left(1 + O\left(|\varepsilon|\right)\right)\frac{\omega}{v_b}$$

and

$$k_S = \sqrt{\frac{1+\gamma_\beta}{\varepsilon\gamma_\beta}}\left(1 + O\left(|\varepsilon|\right)\right)\frac{\omega}{v_b}$$

Here $\gamma_\rho = \rho_b/\rho_f$ and $\gamma_\beta = \phi\beta_f/\beta$. Note the square root of ε in the denominator on the right-hand side of the last equation.

Reflection from a permeable boundary in a fractured reservoir

Reflection from a permeable boundary

Although the attenuation of the slow wave is high, according to the last equation of the previous section, we have to consider two coupled incident waves, fast and slow. Each of two coupled incident waves, fast and slow, generates a pair of fast and slow reflected waves and one transmitted elastic *p*-wave, Fig. 2. The superposition principle allows for considering each incident wave separately. We denote the respective transmission and reflection coefficients by T_{FF}, T_{FS}, R_{FF}, R_{FS}, *etc.* A double subscript denotes the type of incident and reflected waves. For example, R_{FS} denotes the reflection coefficient corresponding to fast incident and slow reflected wave.

Let subscript 1 and 2 refer, respectively, to the parts of the reservoir above and below the boundary, and let x=0 be the coordinate of the boundary. Mass and momentum conservation imply the following boundary conditions:

$$u_1\big|_{x=0} = u_2\big|_{x=0}$$

$$W_1\big|_{x=0} = W_2\big|_{x=0}$$

$$p_{f1}\big|_{x=0} = p_{f2}\big|_{x=0}$$

$$\frac{1}{\beta_1}\frac{\partial u_1}{\partial x}\bigg|_{x=0} = \frac{1}{\beta_2}\frac{\partial u_2}{\partial x}\bigg|_{x=0}$$

To describe transmission and reflection coefficients, we introduce the following modified acoustic impedances for each of the parts of the reservoir:

$$Z^F = \gamma_\rho\sqrt{\frac{\gamma_\beta+1}{\gamma_\beta}}\frac{1}{\beta v_b}, \qquad Z^S = \sqrt{\frac{\gamma_\beta+1}{\gamma_\rho}}\frac{1}{\beta v_b}$$

The following results have been obtained

$$R_{FF} = R^0_{FF} + R^1_{FF}\sqrt{\varepsilon} + O(|\varepsilon|)$$

$$T_{FF} = T^0_{FF} + T^1_{FF}\sqrt{\varepsilon} + O(|\varepsilon|)$$

$$R_{FS} = R^1_{FS}\sqrt{\varepsilon} + O(|\varepsilon|)$$

$$T_{FS} = T^1_{FS}\sqrt{\varepsilon} + O(|\varepsilon|)$$

for the fast incident wave. The coefficients can be expressed through the properties of the media and the fluid. For example,

$$R^0_{FF} = \frac{Z^F_1 - Z^F_2}{Z^F_1 + Z^F_2}$$

and

$$T^0_{FF} = \frac{2Z^F_1}{Z^F_1 + Z^F_2}$$

So the analogy with the classical reflection and transmission coefficients is clear. The expressions for the other coefficients also involve the modified impedances defined above. It is interesting to notice that T^1_{FF} and R^1_{FF} depend on the ratio characterizing the contrast between the fluid mobilities in different parts of the reservoir, whereas T^0_{FF} and R^0_{FF} do not.

A complete account for the impact of the layered structure of the reservoir on reflection and transmission coefficients requires superposition of the formulae obtained here. The functional structure of the result has a similar asymptotic form. So, we can define a seismic attribute proportional to the first derivative with respect to the frequency of the reflected amplitude. As implied by calculations presented above, such an attribute is proportional to the reservoir fluid mobility and can be used for monitoring and characterization of the reservoir.

Example

Fig. 2 shows a result of frequency-dependent attribute analysis of reservoir monitoring seismic data.

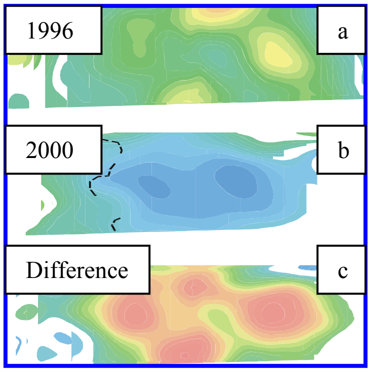

Figure 2. Reservoir monitoring seismic data (Van'egan oil field, Western Siberia). Data are courtesy of Geodata Consulting.

Reflection from a permeable boundary in a fractured reservoir

The maps (Fig. 2) show seismic attribute is proportional to first derivative over frequency at low frequencies. Both (a) and (c) maps are done along reservoir surface. From theoretical point of view the maps of seismic attribute is proportional to fluid mobility. There is remarkable difference (c) bitween the 1996 set of the data (a) and the 2000 set of seismic data (b). Anomalies indicate oil-saturated reservoir zone (a) replaced to water saturation (b) after four years production activity.

Conclusions

The coefficients of normal reflection and transmission of a planar *p*-wave from a permeable boundary in a fractured reservoir are studied in low-frequency range. The coefficients are expressed as power series with respect to a small dimensionless parameter, which is the product of the reservoir fluid mobility and density, and the frequency of the signal. The coefficients of such series are functions of mechanical properties of the reservoir rock and fluid. The zero-order terms of the reflection and transmission coefficients have a form similar to the one derived from the classical theory, without accounting for fluid flow. The next power expansion term both for reflection and transmission coefficients is proportional to the square root of the small parameter described above. This result suggests a new frequency-dependent attribute analysis for mapping reservoir fluid mobility. Images obtained with this attribute show remarkable seismic response to the character of the fluid saturation.

References

Barenblatt, G.I., Zheltov, I.P., and Kochina, I.N., 1960, Basic concepts in the theory of seepage of homogeneous liquids in fissured rocks: Journal of Applied Mathematics, v. 24, 1286-1303.

Biot, M.A., 1956a, Theory of propagation of elastic waves in a fluid-saturated porous solid. I. Low-frequency range: Journal of the Acoustical Society of America, v. 28, 168-178.

Biot, M.A., 1956b, Theory of propagation of elastic waves in a fluid-saturated porous solid. II. Higher frequency range: Journal of the Acoustical Society of America, v. 28, 179-191.

van Golf-Racht, T. D., 1982, Fundamentals of fractured reservoir engineering: Elsevier Scinetific Publishing Company, Amsterdam.

Goloshubin, G., Korneev, V., Silin, D., Vingalov, V., and Connie VanSchuyver, 2006, Reservoir imaging using low frequencies of seismic reflections, The Leading Edge (in press)

Goloshubin, G. M., Silin, D. B., 2005, Using frequency-dependent seismic attributes in imaging of a fractured reservoir zone, 75th SEG Meeting (Houston, Texas).

Hubbert, M.K., 1956, Darcy's law and the field equations of the flow of underground fluids: Transactions AIME, v. 207, 222-239.

Pride, S. R. and Berryman, J. G., 2003a, Linear dynamics of double-porosity and dual-permeability materials. I. Governing equations and acoustic attenuation: Physical review. E v. 68, 036603-1-10.

Pride, S. R. and Berryman, J. G., 2003b, Linear dynamics of double-porosity and dual-permeability materials. II. Fluid transport equations: Physical review. E v. 68, 036604-1-10.

Romm, E. S., 1966, Physical properties of fractured rocks: Nedra, Moscow.

Warren J. E., and Root P. J., 1963, The behavior of naturally fractured reservoirs, SPEJ, 245–255.

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EDITED REFERENCES

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REFERENCES

Barenblatt, G. I., I. P. Zheltov, and I. N. Kochina, 1960, Basic concepts in the theory of seepage of homogeneous liquids in fissured rocks: Journal of Applied Mathematics, **24**, 1286–1303.

Biot, M. A., 1956a, Theory of propagation of elastic waves in a fluid-saturated porous solid, I, Low-frequency range: Journal of the Acoustical Society of America, **28**, 168–178.

———, 1956b, Theory of propagation of elastic waves in a fluid-saturated porous solid, II, Higher frequency range: Journal of the Acoustical Society of America, **28**, 179–191.

Goloshubin, G., V. Korneev, D. Silin, V. Vingalov, and C. VanSchuyver, 2006, Reservoir imaging using low frequencies of seismic reflections: The Leading Edge, **25**, 527.

Goloshubin, G. M., and D. B. Silin, 2005, Using frequency dependent seismic attributes in imaging of a fractured reservoir zone: 75th Annual International Meeting, SEG, Expanded Abstracts, 1417–1420.

Hubbert, M. K., 1956, Darcy's law and the field equations of the flow of underground fluids: American Institute of Mining Engineers Transactions, **207**, 222–239.

Pride, S. R., and J. G. Berryman, 2003a, Linear dynamics of double-porosity and dual-permeability materials, I, Governing equations and acoustic attenuation: Physical Review. E, **68**, 036603-1-10.

———, 2003b, Linear dynamics of double-porosity and dual-permeability materials, II, Fluid transport equations: Physical review, E, **68**, 036604-1-10.

Romm, E. S., 1966, Physical properties of fractured rocks: Nedra.

van Golf-Racht, T. D., 1982, Fundamentals of fractured reservoir engineering: Elsevier Scientific Publ. Co., Inc.

Warren, J. E., and P. J. Root, 1963, The behavior of naturally fractured reservoirs: Society of Petroleum Engineers Journal, **3**, 245–255.