Krauklis waves as indicator of fractured zones in reservoir rocks: Rock-physics modeling

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Krauklis Waves as Indicator of Fractured Zones in Reservoir Rocks – Rock Physics Modeling

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Summary

We developed a method for calculating the effective viscoelastic properties of anisotropic fractured rocks incorporating the effect of low-velocity and dispersive Krauklis waves arising in thin fractures. The method is based on the Rock Physics modeling allowing us to consider components whose moduli are viscoelastic. We introduce so-called “Krauklis substance” and determine its viscoelastic moduli from the known velocity of Krauklis wave. Then, we model a fractured rock as a two-component medium considering the Krauklis substance like a component filling the fractures. We demonstrate an anisotropic behavior of dispersion of elastic wave velocities and its attenuation in the seismic frequency range for two models of carbonate rock having a set of aligned fractures filled with fluids of different viscosity (brine and oil).

Introduction

Fractured zones are of great interest for exploration geophysics since they serve as a channel for hydrocarbon flow. Krauklis waves discovered in the middle of 20th century are specific waves that arise in thin fractures at a low-frequency range (Krauklis, 1962). Significantly, that this wave can be initiated by the both source types – incident P- or S-wave (Frehner, 2014). Korneev (2008) calculated P-wave velocity and attenuation of these waves assuming that the fracture with viscous fluid should be sufficiently narrow to consider that its walls are parallel. Among other parameters characterizing the elastic properties of embedding rock and fracture geometry these waves depend on the fluid viscosity and exhibit quite high attenuation in the seismic frequency range. This fact makes these waves rather attractive for detection of fractured zones and estimation of fluid type filling the fractures. In this work we follow an idea of Korneev & Goloshubin (2015) and current realization of the idea by Krylova & Goloshubin (2016, 2017) who presented a method for calculating the P-wave velocity of an isotropic rock containing a set of randomly oriented fractures. This method was based on a specific average procedure applied to the velocities of the host rock and Krauklis wave. In the present research we use the effective medium theory (EMT) to solve the averaging problem. As known, this theory allows us to consider elliptical heterogeneities (or inclusions) of different shape and orientation. The properties of heterogeneities can be of any symmetry types and their elastic moduli may be rather contrasting. Note that according to the theoretical results of Hashin (1970) the same formulas of EMT methods can be applied if the moduli of heterogeneities are viscoelastic as well – a special theorem has been proven.

Among many EMT methods we apply the generalized singular approximation method (GSA) (Shermergor, 1977) since it gives us a possibility to a some degree take into account the connectivity of heterogeneities via a specific choice of so-called “comparison body” reflecting rock’s microstructure (Bayuk and Chesnokov, 1998; Bayuk et al., 2008).

Theory

The Hashin (1970) theorem sounds “The effective complex moduli of a viscoelastic heterogeneous specimen are found by replacement of phase elastic moduli by phase complex moduli in the expressions for the effective elastic moduli of an associated heterogeneous elastic specimen, with identical phase geometry”. Note that considering a two-phase composite medium Hashin also showed that if one component is pure elastic and the other is viscoelastic only in shear but pure elastic in bulk modulus (like the majority of viscoelastic liquids) the resulting effective properties of the composite are viscoelastic in the both bulk and shear.

We assume that a substance in a thin fracture has viscoelastic isotropic properties with P-wave velocity equal to that of Krauklis wave. We call it “Krauklis substance”. The velocity of the substance is a complex number that can be represented in the form:

\[ \frac{V_{p_{k}}}{\rho} = M = \rho (V_{p_{k}})^{2} = (K + \frac{4}{3} \mu) = K_{real} + \frac{4}{3} \mu_{real} + i(K_{imag} + \frac{4}{3} \mu_{imag}), \]

where \( V_{p_{k}} \) is the Krauklis wave velocity, \( K \) and \( \mu \) are the bulk and shear moduli of the viscoelastic Krauklis substance, and \( i \) is its density. The density is a real value. We assume that the Krauklis substance is viscoelastic only in shear moduli, and its bulk modulus is elastic. In this case we can write

\[ M = (K_{real} + \frac{4}{3} \mu_{real}) + i(\frac{4}{3} \mu_{imag}). \]

According to the work of Nakagawa et al. (2016) waves of two modes are initiated in the fracture. However only the symmetric mode waves are the waves propagating primarily in the fluid within the fracture, and this is the Krauklis wave having complex P-wave velocity consisting of the real and imaginary parts. This means that the shear
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wave of asymmetric wave whose velocity is close to that of the background medium (matrix) is outside the fracture. The only “exotic” shear wave that formally appears in the Krauklis substance due to equation (2) has zero real part and non-zero imaginary part controlled by the imaginary shear modulus. The imaginary part of this velocity is

\[ V_{s_{imag}} = \sqrt{\frac{\mu_{mag}}{\rho_\beta}}. \]  

(3)

where

\[ \mu_{mag} = \frac{3}{4} \text{Im}(M) \]  

(4)

is the shear modulus of the Krauklis substance. Finally, the bulk modulus of the Krauklis substance is

\[ K = K_{real} = M - \frac{4}{3} \mu_{mag}. \]  

(5)

The M value is calculated from the Krauklis wave velocity (Korneev, 2008):

\[ M = \rho \left[ \frac{\omega \mu}{\rho_f} \left( 1 - \frac{V_s^2}{V_p^2} \right) \right]^{2/3} \left[ \frac{\beta}{1 + \sqrt{\frac{\beta}{3} + \beta}} \right]^{2/3}, \]

(6)

\[ \beta = \frac{\hbar^2 \alpha \rho_f}{12 \eta}. \]

Here \( \rho \) and \( \rho_f \) are the density of mineral matrix and fluid; \( h \) is the fracture thickness; \( \mu, V_p, \) and \( V_s \) are the shear modulus and velocities of compressional and shear waves of the mineral matrix; \( \omega \) is the angular frequency; \( \eta \) is the fluid viscosity.

For calculating the effective tensor of viscoelastic properties of a rock containing thin fractures filled with the Krauklis substance we apply the formulas of GSA method (Bayuk and Chesnokov, 1998)

\[ C = \left( C(r) \left[ I - g(C(r) - C^*) \right]^{-1} \right) \left( I - g(C(r) - C^*) \right)^{-1}, \]

(7)

where \( C(r) \) is the stiffness tensor of mineral substance or Krauklis substance; \( g \) is the tensor controlled by the fracture’s aspect ratio and their connectivity; \( I \) is the unit tensor. Angular brackets mean the volume averaging. The tensor \( C^* \) is the comparison body that according to the theory is arbitrary. This allows us to choose it reflecting a degree of fracture connectivity in the form

\[ C^* = (1 - f) C^{\text{min}} + f C^{\text{f}}, \]

where \( C^{\text{min}} \) and \( C^f \) are the stiffness tensors of mineral and Krauklis substances. As was mentioned in Bayuk and Chesnokov (1998) this choice of comparison body produces intermediate microstructures between the two – “isolated inclusions in a mineral matrix” \( (f = 0) \) and “isolated ellipsoidal mineral particles in a material of inclusions” \( (f = 1) \) that, respectively, corresponds to the upper and lower Hashin-Shtrikman bounds.

Examples

We consider two models of a carbonate rock with parallel fractures: 1) brine-saturated and 2) oil-saturated. For the both models the moduli of Krauklis substance are calculated by formulas (3) – (6). The fluid density is taken to be 1 g/cm\(^3\) (we neglect a small difference in the fluids density), but the dynamic viscosity of oil (10 cP) is one order of magnitude greater than that for brine (1 cP). The mineral matrix is limestone having \( V_p = 5.8 \) km/s, \( V_s = 3.2 \) km/s, and density 2.7 g/cm\(^3\). The fractures height is 1 mm and length is 1 m. Therefore, their aspect ratio is 0.001. We consider a volume of 300 x 300 x 300 cubic meters and put in this volume the fractures such that their density is equal to 0.13. The fracture density is calculated as \( \frac{Na^3}{V} \), where \( N \) is the fracture number in the volume \( V \), and \( a \) is the major semi-axis of fractures. This corresponds to the fracture relative volume (fracture porosity) equal to 0.05%.

The models are of transversely isotropic symmetry. The effective viscoelastic tensor of models is calculated by formula (7) with parameter \( f = 0.7 \). According to our practice, this value was commonly inverted from experimental data for reservoir rocks. The velocities in a given direction are calculated from the complex tensor \( C^* \) with the help of Green-Christoffel equation.

Figures 1-7 show the real parts of P- and S-wave velocities and their attenuation versus angle to the fractures normal for models of brine- and oil-saturated rocks. As expected, the attenuation in the oil-saturated rock is more pronounced compared to that of brine-saturated rock. Almost three-fold difference in attenuation between brine- and oil-saturated rocks is observed. The velocities change nonlinearly with frequency and angle with the fractures normal. For \( V_p \) the most pronounced change with frequency is seen from 0 to 45 degrees relative to the fracture normal. However, the dependence for S-waves is different. It is important that the maximum attenuation is observed in the “intermediate” angle – around 15-45 degrees for P-waves and 35-45 degrees for S-waves. This angle is slightly sensitive to the fluid viscosity. The anisotropy of P-wave velocities (the difference between the maximum and minimum velocities) decreases with frequency, whereas this dependence is opposite for S-wave velocities (for \( V_s \)). The \( V_s \) velocity of brine-saturated rock is nonsensitive to the frequency, however this is not the case for oil-saturated rock. The angle of \( V_s \) and \( V_s \) intersection moves towards higher...
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values with frequency (from 35 to 45 degrees for oil-saturated rock). Figure 8 shows the frequency dependence of Thomsen HTI parameters calculated for carbonate rock with vertical fractures. Our calculations show that the frequency dependences of the Thomsen parameters for brine-saturated rock is not significantly different.

Conclusions

A Rock Physics modeling of Krauklis waves effect on viscoelastic properties of anisotropic brine- and oil-saturated rocks containing parallel fractures is carried out. It is demonstrated that in the seismic frequency range the Krauklis waves cause a pronounced attenuation of the P-

and S-waves that is angular dependent and shows maximum at “intermediate” angle between the wavefront and fracture normal. The attenuation in oil-saturated rock is almost three times higher compared with that for brine-saturated case (for 1 cP and 10 cP viscosity of brine and oil). The Vp, Vsv and Vsh velocities exhibit different sensitivity to the frequency for different angles between the wavefront and fracture normal.

Acknowledgments

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Figure 1: Real part of P-wave velocities vs angle with the fractures normal in the model with brine-saturated (solid curves) and oil-saturated (dotted curves) fractures.

Figure 2: Attenuation of P-wave velocities vs angle with the fractures normal for the model with oil-saturated fractures.

Figure 3: Attenuation of P-wave velocities vs angle with the fractures normal for the model with brine-saturated fractures.

Figure 4: Real part of S-wave velocities vs angle with the fractures normal in the model with brine-saturated fractures.
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Figure 5: Attenuation of S-wave velocities vs angle with the fractures normal in the model with brine-saturated fractures.

Figure 6: Real part of S-wave velocities vs angle with the fractures normal in the model with oil-saturated fractures.

Figure 7: Attenuation of S-wave velocities vs angle with the fractures normal in the model with oil-saturated fractures.

Figure 8: Dependence of the Thomsen parameters on frequency (for HTI oil-saturated rock).
EDITED REFERENCES
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