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REKAYASA

NUMERICAL COMPUTATION STUDY OF SEISMIC WAVE IN FRACTURED RESERVOIR ROCK USING MATLAB 6.5.1

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Fractured reservoir rock becoming important study recently, it is due to the high demand of oil and gas. Some of fractured reservoir are basement rock, carbonate as well as vulcanic rock. They have two kinds of porosity, primary and secondary porosity. The primary porosity is caused by matrix and frame, and it is much smaller compared to secondary porosity that caused by fractured zone. Elastic isotropy is assumed in most cases of seismic analysis, processing and interpretation. Anisotropic especially transverse isotropic behavior of seismic velocity, however, is found to exist in most crustal and subsurface media especially in fractured reservoir rock. In this research, some studies are done to investigate the effect of saturation on three types of fracture: isotropic, vertical transverse isotropic and horizontal transverse isotropic rock. They are studied using analytical model through extended Gassmann modeling and seismic core physics laboratory. The analytical model of fractured zone is derived by extending Gassmann equation for anisotropic model, it is known as Brown-Korringa equation. This equation model the effect of fluid saturation in anisotropic fractured reservoir rock. The samples of fractured rock are built from fractured sandstone in several conditions, such as: isotropic, vertical transverse isotropic and horizontal transverse isotropic. Then, they are measured in high pressured laboratory with several types scenarios, such as variation of both overburden and pore pressure, several types of saturation: SWIRR (saturated water irreducible), full water saturated and light oil saturated. The results of numerical modeling show that in traverse isotropic media, both of P and SV wave increase due to the fluid inclusion. The SH wave velocity is unaffected by fluid inclusion. These results are different compared to isotropic Gassmann equation's assumption that S wave velocity is not sensitive to fluid substitution. Experimental studies confirmed the results. In isotropic sample, P wave velocity increase around 25% to 52% with water inclusions, and 12% to 41% due to light oil inclusions. On vertical traverse isotropic (VTI) media, P wave increase up to 34% due to water saturation, and in horizontal traverse isotropic (HTI) media increase around 13% to 17%. Several types of AVO responses due to the fluid inclusion in fractured reservoir rocks are also presented also in this paper.

Fluid in fractured rock, extended Gassmann, seismic core measurement

I. Introduction

Many factor influencing seismic velocity in medium such as: pressure, fluid content, porosity, temperature, clay content and anisotrophy degree. One of anistrophy type is transverse isotrophy that is generally represented by Thomsen parameter [1]. Anisotropy medium is caused by two factors, they are: intrinsic factor and fracture type[2].

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Assumption that reservoir rock has isotropic character is no longer adequate in geophysics data that requires high accuracy. Almost of crustal rocks have anisotrophic character. The anisotrophy causes some mistakes in geophysics data such as: mistake analysis of AVO, mistake in reservoir elastic constant determination like poisson ratio, bulk modulus, shear modulus, and it cause some difficulties in NMO analysis that is known as " hockey stick effect [3], furthermore it causes splitting phenomenon or birefringence in S wave. Due to transverse isotrophy fracture is also anisotrophy case study, splitting phenomenon is studied intensively in this paper also. Studying existence of fracture in reservoir plays important role in reservoir productivity and horizontal well drilling design.

In this paper, we model seismic wave propagation parameter and elastic constant of fracture through Brown-Korringa equation [4] that is the extended version of Gassmann equation. Then, we measured the seismic wave parameter through the real core sample data in fractured condition.

Generally in the anisotrophic fractured rock, the seismic wave is depend on the incident angle. The existence of fluid in both vertical transverse isotrophy (VTI) fracture and horizontal transverse isotrophy (HTI) fracture affects velocity increasing. This velocity increasing is equivalent linearly with fluid content of fracture. In isotropic transverse fracture, this increase is caused by increasing C_{33} component when the fracture is fluid saturated. In TI medium, the attendance of fluid raises SV (Shear-Vertical) wave. Theoretically, this fluid affected velocity is caused by the sensitivity of Thomsen parameter e to the fluid saturation. While S horizontal(SH) wave velocity is not affected by fluid saturation, it is because C_{55} stiffness component is not sensitive to the fluid content. The behavior of S wave in anisotrophy fracture are different with one in isotrophy case study. Change of S wave velocity because attendance of fluid saturant do not happened in isotrophic case, and it can not be explained by Gassmann equation, therefore the extended of Gassmann equation should be exercised through Brown-Korringa equation[4].

BASIC THEORY

Relationship between stress tensor and strain tensor in general, according to Hooke's law can be written as (1).

$$\sigma_{ij} = C_{ijkl}\varepsilon_{kl}$$

Where σ_{ij} denotes stress tensor, C_{ijkl} denotes stiffness tensor and ε denotes strain tensor. In the case transverse isotrophic fracture, the stiffness tensor is expressed by equation (1) for vertical transverse isotrophy (VTI) and equation (2) for horizontal traverse isotrophy (HTI).

$$C \equiv \begin{pmatrix} C_{11} & (C_{11}-2C_{66}) & C_{13} & 0 & 0 & 0 \\ (C_{11}-2C_{66}) & C_{11} & C_{13} & 0 & 0 & 0 \\ C_{13} & C_{13} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{55} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{pmatrix} \tag{2}$$

$$C \equiv \begin{pmatrix} C_{11} & C_{13} & C_{13} & 0 & 0 & 0 \\ C_{13} & C_{33} & (C_{33}-2C_{44}) & 0 & 0 & 0 \\ C_{13} & (C_{33}-2C_{44}) & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{55} \end{pmatrix} \tag{3}$$

Brown dan Korringa [4] have conducted an extension of Gassmann theory for fluid substitution in anisotrophy case, the stiffness tensor of the extension o Gassmann for anisothrophic in saturated condition (fluid inclusion) [5] is expressed by equation (4)

$$C_{ij}^{sat} = \begin{pmatrix} \frac{1}{\frac{1}{C_{11}} - \frac{a^2}{\zeta}} & \frac{1}{\frac{1}{C_{12}} - \frac{ab}{\zeta}} & \frac{1}{\frac{1}{C_{13}} - \frac{ab}{\zeta}} & 0 & 0 & 0 \\ \frac{1}{\frac{1}{C_{12}} - \frac{ab}{\zeta}} & \frac{1}{\frac{1}{C_{22}} - \frac{a^2}{\zeta}} & \frac{1}{\frac{1}{C_{13}} - \frac{ab}{\zeta}} & 0 & 0 & 0 \\ \frac{1}{\frac{1}{C_{13}} - \frac{ab}{\zeta}} & \frac{1}{\frac{1}{C_{13}} - \frac{ab}{\zeta}} & \frac{1}{\frac{1}{C_{33}} - \frac{b^2}{\zeta}} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{pmatrix}$$

4)

Where a, b and

$$a = \left(\frac{1}{C_{11}} + \frac{1}{C_{12}} + \frac{1}{C_{13}}\right) - \frac{1}{3K_o}$$

$$b = \left(\frac{2}{C_{13}} + \frac{1}{C_{33}}\right) - \frac{1}{3K_o}$$

$$\zeta = \left(\frac{1}{K_{dry}} - \frac{1}{K_o}\right) + \left(\frac{1}{K_f} - \frac{1}{K_o}\right)\phi$$

$$a = \left(\frac{1}{C_{11}} + \frac{1}{C_{11} - 2C_{66}} + \frac{1}{C_{13}}\right) - \frac{1}{3K_o}$$

In the case of transverse isotrophy medium, a and b can be expressed as following:

$$b = \left(\frac{2}{C_{13}} + \frac{1}{C_{33}}\right) - \frac{1}{3K_o}$$

The existence of fluid in fracture influences compliance or stiffness value, it directly causes change of seismic wave velocity and Thomsen parameter as following [1]:

$$v_p^{sat}(\theta) = \alpha_0^{sat}\sqrt{\left[1 + \varepsilon^{sat} \cdot \sin^2\theta + D^{*sat}(\theta)\right]}$$

$$v_{sh}^{sat}(\theta) = \beta_0^{sat}\sqrt{\left[1 + 2\gamma^{sat} \cdot \sin^2\theta\right]} = \beta_0^{sat}\sqrt{\left[1 + 2\gamma \cdot \sin^2\theta\right]} = v_{sh}(\theta)$$

$$\alpha_0^{sat} = \sqrt{\frac{C_{33}^{sat}}{\rho}} \qquad \beta_0^{sat} = \sqrt{\frac{C_{55}^{sat}}{\rho}}$$

$$D^{*sat} = \frac{1}{2}\left(1 - \left(\frac{\beta_0^{sat}}{\alpha_0^{sat}}\right)^2\right) \bullet \left\{\left[1 + \frac{4\delta^{*sat}}{\left(1 - \left(\frac{\beta_0^{sat}}{\alpha_0^{sat}}\right)^2\right)^2}\sin^2\theta \cdot \cos^2\theta + \frac{4\left(1 - \left(\frac{\beta_0^{sat}}{\alpha_0^{sat}}\right)^2 + \varepsilon^{sat}\right)\varepsilon^{sat}}{\left(1 - \left(\frac{\beta_0^{sat}}{\alpha_0^{sat}}\right)^2\right)^2}\sin^4\theta\right]^{1/2} - 1\right\}$$

where

(9)

sat index shows saturated condition. As seen in above equation, the existence of fluid in fractured medium only affects in P wave velocity and SV wave velocity, and it do not affect in SH wave velocity. Furthermore, compliance and stiffness tensor in transverse isotrophy and fluid saturated is stated as following

$$\varepsilon^{sat} = \frac{C_{11}^{sat} - C_{33}^{sat}}{2C_{33}^{sat}}$$

(10)

$$\gamma^{sat} = \frac{C_{66}^{sat} - C_{55}^{sat}}{2C_{55}^{sat}} = \frac{C_{66} - C_{55}}{2C_{55}} = \gamma$$

(11)

$$\delta^{sat} = \frac{1}{2C_{33}^{sat\,2}}\left[2(C_{13}^{sat} + C_{55})^2 - (C_{33}^{sat} - C_{55})(C_{11}^{sat} + C_{33}^{sat} - 2C_{55})\right]$$

(12)

and,

$$C_{11}^{sat} = \frac{1}{\frac{1}{C_{11}} - \frac{a^2}{\zeta}} \qquad C_{13}^{sat} = \frac{1}{\frac{1}{C_{13}} - \frac{ab}{\zeta}}$$

$$C_{33}^{sat} = \frac{1}{\frac{1}{C_{33}} - \frac{b^2}{\zeta}}$$

C_{11}, C_{13}, C_{33}, C_{55}, C_{66} are expressed as following

$$C_{33} = \rho \cdot \alpha_o^2$$

$$C_{55} = \rho \cdot \beta_o^2$$

$$C_{11} = (2\varepsilon + 1)C_{33} \quad \text{dan} \quad C_{66} = (2\gamma + 1)C_{55}$$

(14)

Where
d*®

$$C_{13} = -C_{55} + \sqrt{C_{55}^2 + \frac{1}{2}\left[2\delta^* C_{33}^2 - 2C_{55}^2 + (C_{33} - C_{55})(C_{11} + C_{33} - 2C_{55})\right]}$$

The existence of fluid in fracture will raise stiffness value of medium significantly, it is caused by increasing compressibility K_f .

NUMERICAL STUDY OF FLUID INCLUSION EFFECT IN FRACTURE TO THE AVO PARAMETER

Using MATLAB 6.5.1 we studied AVO (amplitude various offset) parameter change to the fluid change of fluid content of fracture. This experiment is to design the best AVO parameter that most sensitive to detect fluid content in fracture. We use following data to model the AVO :

Physical data of upper Medium
- Density :1000 kg/m³
- a : 900 m/s
- b : 500 m/s

Physical data of Lower Medium
- Density : 1473.9 kg/m³
- a : 1842.10 m/s
- b : 1195.47 m/s

Anisotropy Degree

VTI :

$$C_{33} = \rho \cdot \alpha_o^2 = (1473.9)(1842.10)^2 = 5.0\,\text{GPa}$$

$$C_{55} = \rho \cdot \beta_o^2 = (1473.9)(1163.29)^2 = 1.9\,\text{GPa}$$

HTI :

$$C_{11} = \rho \cdot \alpha_o^2 = (1473.9)(1941.748)^2 = 5.6\,\text{GPa}$$

$$C_{66} = \rho \cdot \beta_o^2 = (1473.9)(1226.21)^2 = 2.2\,\text{GPa}$$

d : 0.1, e : 0,06 dan g : 0.08
Bulk Modulus of Fluids : 2.2 GPa (water)
Bulk Modulus of Material : 40 GPa
Porosity : 0,27

Figure 1, show the result of the modeling.

CONCLUSIONS

It is shown in figure 1 that we can model the AVO response using MATLAB 6.5.1 as numerical computation. According to the result, we see that AVO respon is increase with incident angle due to fluid inclusion

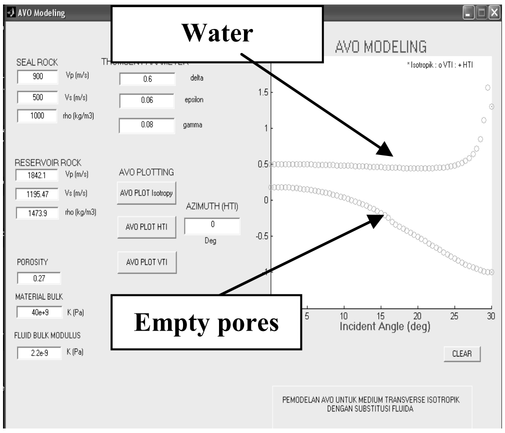

Figure1
AVO Modeling Using MATLAB 6.5.1

about 30 %. The increase is caused by bulk modulus of the pore fluid.

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