Seismic low-frequency effects from fluid-saturated reservoir

Gennady M. Goloshubin, ZapSibNIIGG, Tyumen,Russia
Valeri A. Korneev, Lawrence Berkeley National Laboratory, Berkeley, California*

Summary

The normal incidence of P- elastic wave reflected from a thin porous dry and water saturated layer is considered. The effect of stronger reflections and travel time delays from water saturated layer is observed at low frequencies. We compared the results of laboratory modeling with “frictional-viscous” theoretical model and found that low (< 5) values of attenuation parameter Q and its approximate proportionality to frequency can explain the effect. The values of Q were determined in a separate experiment using recordings of a transmitted field for a thick porous layer, where water saturated layer had attenuation about two times higher then in a dry layer. These findings can be used for detecting and monitoring liquid saturated areas in thin porous layers.

Introduction

The relationship between seismic response and a fluid saturation in reservoir depends on porosity and permeability of the reservoir rocks, viscosity of the fluid, reservoir thickness and physical properties of the surrounding medium. But there is some general connection between character of a porous layer saturation and seismic response. In particular there are differences in reflections from the porous layer in cases of gas either oil/water saturation. In case of oil saturation relatively gas saturation we can see phase shift and energy redistribution from the first to the second phase and from high to low frequencies [5,7]. In this case the low frequency mean the ratio of the porous fluid-saturated layer thickness to wavelength is less than 1/10. There is the same phenomenon in case of reflection from water-saturated layer [5,6]. We try to explain frequency-dependent reflectivity of the porous fluid-saturated layer by viscoelastic model and low frequency-dependent Q values. Experimental studies have shown that intrinsic attenuation is strongly affected by the porous media and fluid saturation [1,3,8,9,11,13]. It is well accepted that Q is frequency-dependent and changed dramatically over liquid saturation and may be less than 10 in sedimentary rocks [9,12]. Fluid may change Q in metamorphic rocks [10] down to 14 and in limestone [4] from 200 (dry) to 20-40 (water saturated). We investigate low-frequency anomalies of seismic reflections from porous layers by physical modeling and analytical solutions by taking into account low frequency-dependent Q values.

Theory

We consider 1D wave propagation equation of motion in the form

$$\frac{d^2u}{dt^2}-\beta\frac{du}{dt}-\gamma\frac{d^2}{dx^2}\frac{du}{dt}-v^2\frac{d^2u}{dx^2}=0\,, \tag{1}$$

where u is a displacement vector. The second term in equation is known as frictional dissipative force, whereas the third term describes viscous dumping. We will correspondingly call the constants β and γ as “frictional” and “viscous” attenuation parameters. Here we do not discuss physical interpretation of these parameters, which is a separate issue. Parameter v is a phase velocity in a non-dissipative medium. A general method of solution derivation for such equations described in [14]. The effect of the third term was studied in [2]. We derive the result when both dissipative terms are present and seek a solution in the form of harmonical wave

$$u=\exp(ikx-\alpha x)\exp(-iwt) \tag{2}$$

with wave number k, attenuation coefficient α and angular frequency ω. The attenuation parameter Q is defined through the expression

$$Q=k/2\alpha \tag{3}$$

This form of solution also allows introduction of another kind of attenuation mechanism by making velocity v a complex value, when $1/v=a+ib$. With an absence of the two previous types of energy dissipation this form gives the easiest way of introduction of attenuation with constant value of Q, when in the final expressions for wave propagation solutions one must separate real and imaginary parts of the propagation terms. This easiness was probably the main reason for appearance of the Q=const “legend”. From the structure of Eq. (1) it follows that the frictional term dominates at low frequencies, while at high frequencies the viscous term takes over and therefore the viscosity is the main factor which is responsible for wave dissipation. Substitution of Eq.(2) in Eq.(1) gives the following expressions for k and α

$$\alpha = \frac{vp}{q}, \quad k = \frac{wq}{v} \tag{4}$$

where $$q = \sqrt{\frac{1}{2} - p\gamma + \sqrt{\frac{1}{4} + \frac{p}{2}\left(\frac{v^2\beta}{\omega^2} - \gamma\right)}}\ , \qquad p = \frac{1}{2}\frac{\omega^2\gamma + v^2\beta}{v^4 + \omega^2\gamma^2} \tag{5}$$

When $\gamma = 0$, $$q = \frac{1}{\sqrt{2}}\sqrt{1 - \sqrt{1 + \frac{\beta^2}{\omega^2}}}\ , \qquad p = \frac{\beta}{2v^2}, \tag{6}$$

and Q $\approx \sqrt{\omega}$ at low frequencies

When $\beta = 0$, $$q = \sqrt{\frac{1}{2} - p\gamma + \sqrt{\frac{1}{4} + \frac{p}{2}\gamma}}\ , \qquad p = \frac{1}{2}\frac{\omega^2\gamma}{v^4 + \omega^2\gamma^2}, \tag{7}$$

And Q $\approx \omega^{-1}$ at low frequencies.

Thus the decrease of Q at low frequencies can be explained by a presence of frictional dissipation mechanism. Now we consider a reflection of a plane wave normally incident upon an attenuative layer of a thickness h, which characterized by velocity v_2 of wave propagation and density ρ_2. The layer is placed between two halfspaces h both characterized by velocity v_1 and density ρ_1.. A reflection coefficient of such a layer has the form

$$R = r\left(1 - \frac{2d}{1+d}\frac{\exp(-2h(ik_2 + \alpha_2))}{1 - d\exp(-i2hk_2)}\right), \qquad r = \frac{1-d}{1+d}, \quad d = \frac{ik_2 - \alpha_2}{ik_1 - \alpha_1}\frac{{v_2}^2\rho_2}{{v_1}^2\rho_1}, \tag{8}$$

where lower indexes 1 and 2 at wave numbers k, and attenuation coefficients α correspond to halfspaces and the layer respectively.

Examples

We used a set of laboratory ultra-sonic experiments to investigate the differences of reflections from dry- and water-saturated layers. The set of experiments was conducted to observe the reflected and refracted waves from thick and thin porous layers (both dry- and water-saturated) separately. Plexiglas was used as a homogeneous constant-velocity background medium. The porous layer in each case was carried out with artificial sandstone and hermetically sealed with special construction to obtain its saturation by fluid. The construction was acoustically isolated and didn't create any oscillations in wavefield.

Fig.1 Physical modeling experimental setup for porous layer attenuation measurements in dry and water saturated layers.

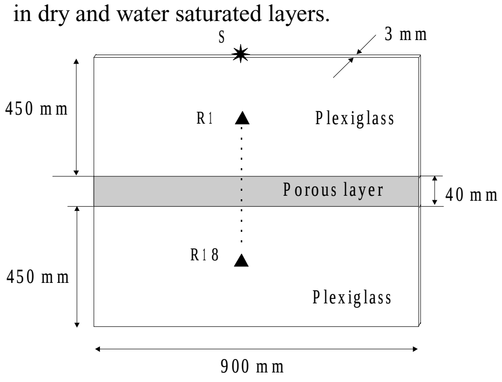
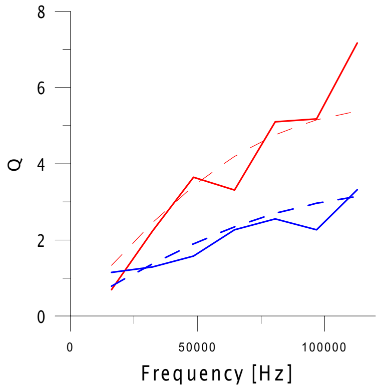


Fig. 2 Experimental (solid lines) and theoretical (dashed lines) values of Q Vs frequency for dry (red) and water saturated (blue) porous layers



The physical modeling data were recorded using VSP experimental setup shown on Fig.1 to measure of Q factor vs frequency in thick porous layer for both dry and water saturation. The layer was 40 mm thick and had 0.32 porosity and about 300 mDarcy permeability. The velocities and densities of the used materials were: Vp=1700 m/sec, Vs=1025 m/sec, D=1800 kg/m3 (dry layer); Vp=2100, Vs=1250, D=2500 (water-saturated layer); and Vp=2300, Vs=1340, D=1200 (plexiglas). We used a transmitted wave to determine Q in both cases. The measured values of Q and their theoretical approximations using Eq. (4) are shown on Fig. 2. The values of attenuation parameters were estimated as $\beta = 80000 \quad 1/s$, $\gamma = 0.3 \quad m^2/s$ for the dry layer and $\beta = 150000 \quad 1/s$, $\gamma = 1.0 \quad m^2/s$ for the water-saturated layer. The reflection coefficient of a thin layer was investigated using same materials and Common Offset Gather (COG) observation system. The offset was much smaller than depth to the layers and reflection angle was practically equal to zero. The thickness of the layer was taken equal 7 mm. The recorded traces are shown on the left panels of the Fig.3. The reflection coefficient water-saturated/dry ratios vs frequency (Fig.4) and travel time delays (Fig.5) were computed and compared with theoretical curves, where previously found attenuation parameters β and γ were used.

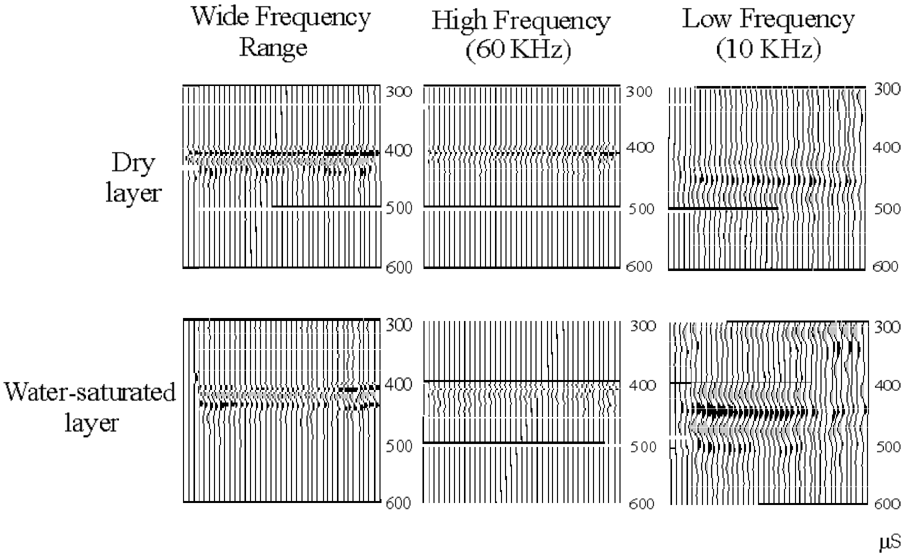


Fig.3 Data (left panels) and imaging of thin porous layers using common offset gathers by different filtering for dry and water saturated cases.

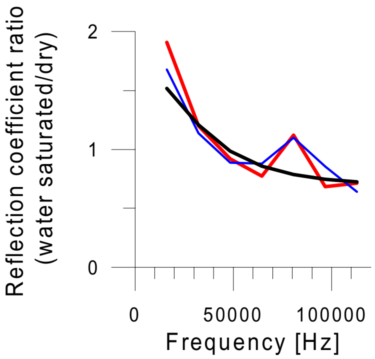


Fig.4 Reflection coefficient ratios (water saturated/dry) vs frequency computed from data (red), theory for a layer (blue), and theory for a halfspace (black).

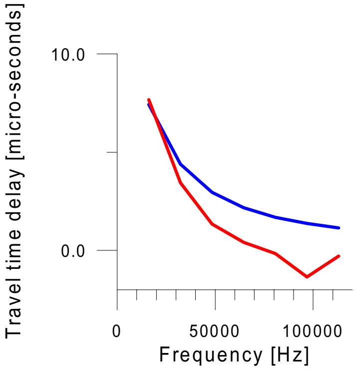


Fig.5 Travel time delays of reflected wave from water saturated layer with respect to a reflection from a dry layer from data (red) and a theory (blue).

Discussion

Measurements of Q factor for porous layer revealed very low values for both dry and water saturated cases. These values are close to seismic extremes but their existence can be explained by very small thicknesses, which can not absorb seismic wave energy completely. Field measurements of Q have effective character where thin highly attenuative layers do not define the measured value, but rather provide a small contribution. For the water saturated layer we found lower values of Q which showed increase in both "frictional" and " "viscous" attenuation. In all cases Q monotonically increases with frequency. While the behavior of reflection coefficient from attenuative layer is rather complex the ratio of reflection coefficients for water saturated and dry layers reveal strong and monotonic increase of reflection amplitude at low frequencies. The rate of this increase is more profound for the reflections from thin layer compare to the reflections from a thicker layer or a half space. This reflection feature is a useful indicator of attenuative properties of thin porous layers. Attenuation for such layers strongly depends on a character of liquid saturation. The observed reflection travel time change fits theoretical predictions quite well. Layer with higher attenuation creates travel time delays increasing as frequency approaches zero. This property was observed on real data and can serve as an additional indication of liquid saturation in porous layers. The differences of dry and water saturated layer reflectivities are clearly seen using imaging of COG at high and low frequency domains (Fig.3). Physical interpretation of "frictional" dissipation term remains uncertain. The similar effect can be achieved also by incorporation of elastic deformation term in Eq. (1).

Conclusions

The low frequency seismic reflection from the porous fluid-saturated was investigated using "frictional-viscous" theoretical model giving frequency dependent low Q factor. We compared the results of laboratory modeling with "frictional-viscous" model and found that low (< 5) values of the Q and its decrease at approaching zero frequency can explain the effect. It gives distinctive reflection anomalies for wave parameter ratios. The found amplitude and phase reflection properties can be used for detecting and monitoring liquid saturated areas in thin porous layers.

References

[1] Bourbie, T., Coussy, O., and Zinszner., B., 1987, Acoustics of Porous Media: Gulf Publishing Co, Houston

[2] Caviglia, G., and Morro, A., 1988, Inhomogeneous waves and sound absorption in viscous fluids: Physics Letter A, 134, no.2, 127-130.

[3] Dasgupta, R., Clarc, R.A, 1998, Estimation of Q from surface seismic reflection data: Geophysics, v. 63, 2120-2128.

[4] Gadoret, T., Mavko, G., and Zinszner, B., 1998, Fluid distribution effects on sonic attenuation in partially saturated limestones: Geophysics, v. 63, 154-160.

[5] Goloshubin, G.M., and Bakulin, A.V., 1998, Seismic reflectivity of a thin porous fluid-saturated layer versus frequency: 68th SEG Meeting, New Orleans, 976-979.

[6] Goloshubin, G.M., Verkhovsky, A.M., and Kaurov, V.V., 1996, Laboratory experiments of seismic monitoring: 58th EAEG Meeting, Amsterdam.

[7] Goloshubin, G.M., Helle, H.B., and Kovalev, V.P., 1994, Seismic resonances of a porous fluid-saturated layer: 56th EAEG Meeting, Vienna.

[8] Hauge, P.S., 1981, Measurements of attenuation from vertical seismic profiles: Geophysics, v. 46, 1548-1558.

[9] Jones, T.D., 1986, Pore fluids and frequency-dependent wave propagation in rocks: Geophysics, v. 51, 1939-1953.

[10] Pujol, J.M., Luschen, E., and Hu, Y., 1998, Seismic wave attenuation in metamorphic rocks from VSP data recorded in Germany's continental super-deep borehole: Geophysics, v. 63, 354-365.

[11] Raikes, S.A., and White, J.E., 1984, Measurements of earth attenuation from downhole and surface seismic recording: Geophysical Prospecting, v. 32, 892-919.

[12] Sams, M.S., Neep, J.P., Worthington, M.H., and King M.S., 1997, The measurement of velocity dispersion and frequency-dependent intrinsic attenuation in sedimentary rocks: Geophysics, v.62, 1456-1464.

[13] Seismic Wave Attenuation, 1981, Geophysics reprint series, No2: SEG, Edited by D. H. Jonson and M. N. Toksoz.

[14] Smirnov, V. I., 1964, A course of higher mathematics, Oxford, New York, Pergamon Press, Vol.2

Acknowledgments

This work is a result of collaboration of Center Computational Seismology at Ernest Orlando Lawrence National Laboratory where it was supported by the Office of Science, Office of Basic Energy Sciences, Division of Engineering and Geosciences of the U.S. Department of Energy under Contract No.DE-AC03-76SF00098 and Physical Modeling Laboratory at ZapSibNIIGG. In particular we would like to thank Alexander Verkhovsky, Viktor Kaurov, Anatoly Kondrashov and Alexander Kondrashov for providing help in obtaining experimental data sets.