P-wave seismic attenuation: Effects of inhomogeneous rock properties based on patchy saturated model

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Summary

The mesoscopic loss is known as the major cause of P-wave seismic attenuation, because it is a consequence of fluid flow at mesoscopic-scale inhomogeneity. In this abstract, we consider a periodically stratified medium and analyze the amount of attenuation and velocity dispersion caused by porosity, partial saturation and gas properties. Two different depths condition, shallow (1-km) and deep (3.5-km), are considered during the modeling. High porosity will lead to low phase velocity and high attenuation. And the attenuation is higher at shallow depths where gas is more compliant. When the gas saturation is between 10% and 50% the phase velocity present a strong dispersion at seismic frequencies. The maximum attenuation is obtained when there is a small amount of gas (around 10% - 20% saturation) in a water-saturated reservoir. The measurements of the phase velocity and quality factor at low frequencies may provide useful information about the fluid type and saturation.

Introduction

The seismic attenuation mechanism are related to the microstructural characteristics of the rock and the fluids in pore spaces. Many studies (e.g., Pride et al., 2004; Müller and Gurevich, 2005) have shown that the major cause of attenuation in porous media is wave-induced fluid flow, especially mesoscopic loss. Previous studies (Carcione and Picotti, 2006) have shown that the fluid modulus and porosity variation are more important compared to other parameters such as the grain and dry-rock moduli. It's an efficient method to analysis how does the parameters affect the velocity and attenuation though controlling a single variable, but we know that porosity do affect the dry-rock moduli and permeability significantly, so it's necessary to take this into consideration when the porosity is changed.

In this paper, we consider the patchy saturated model (White et al., 1975) which used in Carcione and Picotti (2006) to investigate the P-wave seismic attenuation by slow-wave diffusion, and focus on the effects of porosity and patchy saturation. We use the Kozeny-Carman relation (Mavko et al., 1998) and the model of Krief et al. (1990) to obtain the permeability and dry-rock moduli while porosity variation, respectively, and also solve the van der Waals equation to find out the effects of depth on gas properties, which will represent a more realistic situation. We consider different depth cases and compare the phase velocities and attenuation factors to determine the effects of the inhomogeneities.

Frequency-dependent complex bulk modulus

Base on the White model, Carcione and Picotti (2006) presented the formula of the complex modulus for a P-wave traveling along the direction perpendicular to the stratification which is a periodic layered system composed of porous media 1 and 2 with thickness $d_i, i=1,2$ and period d_1+d_2. It is given by

$$E=\left[\frac{1}{E_0}+\frac{2(r_2-r_1)^2}{i\omega(d_1+d_2)(I_1+I_2)}\right]^{-1} \quad , \quad E_0=\left(\frac{p_1}{E_{G1}}+\frac{p_2}{E_{G2}}\right)^{-1} \tag{1}$$

where $p_i=d_i/(d_1+d_2), i=1,2$. and ω is angular frequency. For each medium

$$E_G=K_G+\frac{4}{3}\mu_m \ , \quad K_G=K_m+\alpha^2 M \ , \quad \alpha=1-\frac{K_m}{K_s} \tag{2}$$

$$M=\frac{K_s}{1-\phi-K_m/K_s+\phi K_s/K_f} \ , \quad I=\frac{\eta}{\kappa k}\coth\left(\frac{kd}{2}\right) \ , \quad r=\frac{\alpha M}{E_G} \tag{3}$$

where K_G is the Gassmann modulus, α is the Biot coefficient, K_m and μ_m is the dry-rock bulk and shear modulus, K_s is the solid-grain bulk modulus, K_f is the fluid bulk modulus.

$$k=\sqrt{\frac{i\omega\eta}{\kappa K_E}} \ , \quad K_E=\frac{E_m M}{E_G} \ , \quad E_m=K_m+\frac{4}{3}\mu_m \tag{4}$$

where k is the complex wavenumber, κ is permeability and η is the viscosity.

The complex velocity υ is defined by the relation $\rho\upsilon^2=E$, where $\rho=p_1\rho_1+p_2\rho_2$ is the averaged density. Then, the phase velocity and quality factor are given by

$$\upsilon_p=\left[\mathrm{Re}\left(\frac{1}{\upsilon}\right)\right]^{-1} \ , \quad Q=\frac{\mathrm{Re}(\upsilon^2)}{\mathrm{Im}(\upsilon^2)} \tag{5}$$

Matrix properties

Porosity and permeability are related by the Kozeny-Carman relation

$$\kappa=\frac{B\phi^3 D^2}{(1-\phi)^2} \tag{6}$$

(Mavko et al., 1998), where D is the grain diameter and $B = 0.003$.
Porosity and dry-rock moduli have different relations according to different models, in this abstract we use the model of Krief et al. (1990) to obtain the dry-rock moduli.

$$K_m = K_s(1-\phi)^{3/(1-\phi)}\ ,\quad \mu_m = \mu_s(1-\phi)^{3/(1-\phi)} \tag{7}$$

where μ_s is the solid-grain shear modulus.

Figures 1 (a) and (b) show the permeability increase and dry-rock moduli decrease with porosity respectively, and the magnitude variation is not small which should not be ignored.

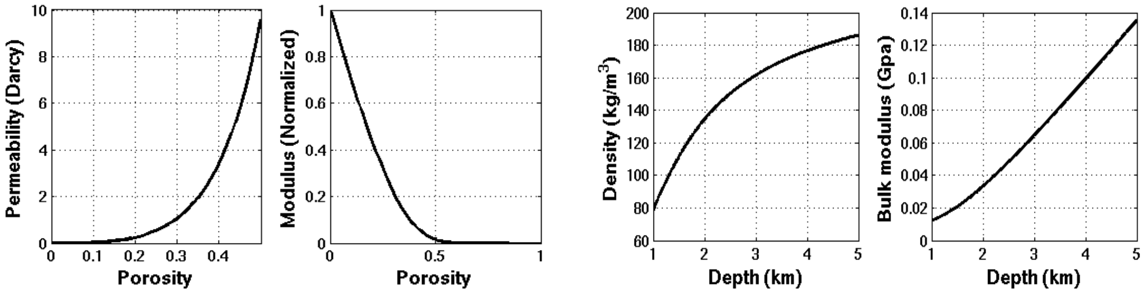


Figure 1 *Matrix properties related to porosity: permeability (a) and normalized modulus (b); Gas properties related to depth: density (c) and bulk modulus (d).*

Fluid properties

The fluid properties depend on pressure and temperature, which depends on the depth z . For simplicity, we consider a constant geothermal gradient $G = 30°C/km$, so that the temperature variation with depth is $T = T_0 + Gz$, where T_0 is the surface temperature. A reference value of the pore pressure is hydrostatic pressure, its given by $p = \rho_w gz$, where g is the acceleration of gravity. We assume the water properties don't change significantly with depth, but the gas in the reservoir will change. The gas will satisfy van der Waals equation (Friedman, 1963)

$$(p + a\rho_g^{\ 2})(1 - b\rho_g) = \rho_g R(T + 273) \tag{8}$$

where ρ_g is gas density, a , b and R are all constant, so the gas density varies with depth. Also the bulk modulus can be calculated by

$$K_g = \frac{4}{3}\left[\frac{\rho_g R(T+273)}{(1-b\rho_g)^2} - 2a\rho_g^{\ 2}\right] \tag{9}$$

We solved the equation (8) and find the real solution expression which is very complicated. The gas density and bulk modulus vary with depth are shown in Figure 1 (c) and (d), both of them increase with depth.

Numerical study and seismic modeling

The periodic layered system composed of media 1 and 2, the two media have the same frame, medium 1 filled with water, and medium 2 with gas. We select 1-km and 3.5-km depth to calculate the gas properties to represent shallow and deep reservoir condition, the two cases have the same matrix, in this abstract, the parameters are given in Table 1.

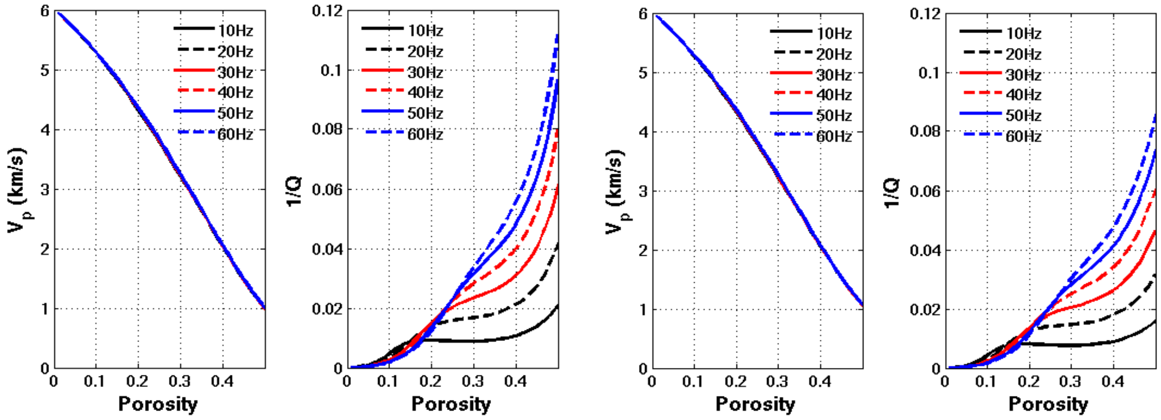
Table 1 *Model parameters*

Matrix	Grain bulk modulus(GPa)	Grain shear modulus(GPa)	Grain density(kg/m^3)
	37	44	2650
Water	Bulk modulus(GPa)	Density(kg/m^3)	Viscosity(cP)
	2.25	1040	3
Gas	Bulk modulus(GPa)	Density(kg/m^3)	Viscosity(cP)
1.0-km	0.012	78	0.15

3.5-km	0.081	170	0.15

The other parameters such as permeability and dry-rock moduli we use equation (6) and (7) to calculate, and these two parameters will affect many complex bulk moduli in the White theory. It is a more complicated issue compared to the method of control a single variable, but it may be more realistic.

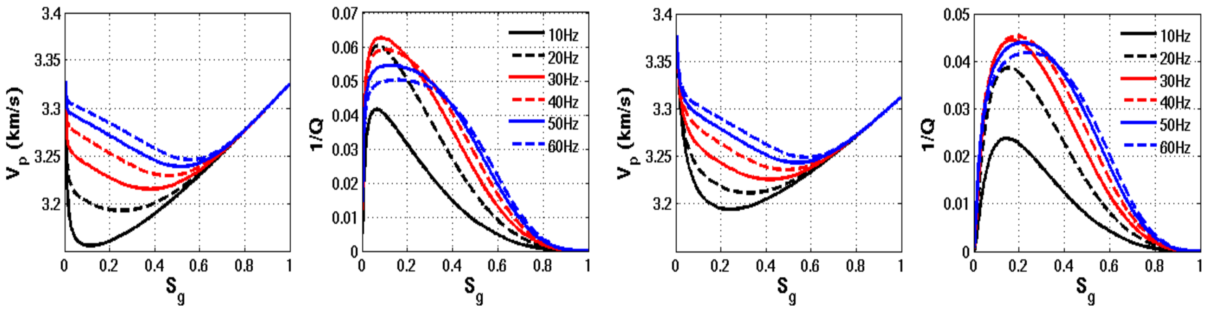
In order to illustrate the effect of porosity, the shallow and deep cases share the same gas saturation of 50%, the differences between the two cases are density and bulk modulus of the gas. Figure 2 shows the phase velocity and attenuation vary with porosity at different frequency corresponding to shallow reservoir (a) (b) and deep reservoir (c) (d). From Figure 2 (a) and (c) we can see that the magnitude of phase velocity decreases monotonically as porosity increases and the effect of frequency on phase velocity is weak, the velocity of the deep case is slightly higher than shallow case. Figure 2 (b) and (d) show the attenuation vary with porosity, its sensitive to frequency, both shallow and deep cases have the same increase trend. When the porosity is lager than 0.2 the attenuation increases as frequency increases, while the porosity less than 0.2 it becomes hard to differentiate. The shallow depth where gas is more compliant has greater attenuation than deep case.



(a) *(b)* *(c)* *(d)*

Figure 2 *Shallow depth (1-km) case: phase velocity (a) and 1/Q (b) with the variation of porosity, frequency and fixed gas saturation of 50%; Deep depth (3.5-km) case: phase velocity (c) and 1/Q (d) with the variation of porosity , frequency and fixed gas saturation of 50%.*

In order to investigate the effect of patchy saturation we set the two cases share a fixed porosity 0.3. Figure 3 shows the phase velocity and attenuation vary with gas saturation (S_g) at different frequency corresponding to shallow reservoir (a) (b) and deep reservoir (c) (d). Figure 3 (a) and (c) show the magnitude of phase velocity first decreases then increases, when the gas saturation is less than 0.6 (water saturation higher than 0.4) the velocity is sensitive to frequency and the location of the minimum value moves towards higher gas saturation when frequency increases; when the gas saturation is larger than 0.6 the phase velocity becomes insensitive to frequency (10Hz-60Hz). As shown in Figure 3 (b), the maximum attenuation occurs at around 10% gas saturation, when the gas saturation is less than 50% the attenuation first increases then decreases with increasing frequency; when the gas saturation is larger than 50% the attenuation increases with frequency. The deep case (d) is similar to shallow case (b), but the maximum attenuation occurs at around 20% gas saturation and the attenuation is lower than shallow case. Another difference is the frequency when the maximum attenuation occurs in a fixed small gas saturation condition.



(a) *(b)* *(c)* *(d)*

Figure 3 *Shallow depth (1-km) case: phase velocity (a) and 1/Q (b) with the variation of gas saturation, frequency and fixed porosity of 0.3; Deep depth (3.5-km) case: phase velocity (c) and 1/Q (d) with the variation of gas saturation , frequency and fixed porosity of 0.3.*

Conclusions

We take the effects of porosity on permeability and dry-rock moduli into consideration to calculate the phase velocity and seismic attenuation based on patchy saturated model. The maximum attenuation is occurred when there is a small amount of gas (around 10% - 20% saturation) in a water-saturated sand reservoir, when the gas saturation is between 10% and 50% the phase velocity present a strong dispersion. Another important feature, observed in reservoirs partially saturated with gas, is that the high porosity will lead to low phase velocity and high attenuation, and the attenuation is higher at shallow depths where gas is more compliant. The measurements of the quality factor at low frequencies may provide useful information about the fluid type and saturation.

Acknowledgements

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