Frequency dependent attenuation and dispersion in patchy-saturated porous rocks

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ABSTRACT

From seismic wave equations in modified patchy-saturated model established on the basis of the White model, we derive the formulas of reciprocal quality factors and velocities of the two kinds of P-waves and analyze the seismic attenuation and velocity dispersion of the two kinds of P-waves in patchy-saturated rocks within the seismic band. Through comparison of seismic attenuation in modified patchy-saturated, Biot and BISQ models, we find that seismic attenuation in a modified patchy-saturated model is much higher than that in the other two models--about 1000 times higher. Therefore, modified patchy-saturated model can describe seismic propagation more accurately in the seismic band and can be used in seismic exploration. Owing to the importance of porosity, permeability and fluid saturation, we also study and analyze the effects of these three factors on seismic attenuation and velocity dispersion of P-waves in patchy-saturated rocks within the seismic band. The conclusions are: Seismic attenuation of the fast P-wave increases with increasing frequency, while attenuation of the slow P-wave decreases with increasing frequency within the seismic band. As rock porosity goes up with other parameters constant, seismic attenuation and velocity dispersion of the fast P-wave increases with porosity. When the porosity is very low, velocity dispersion is not obvious within seismic band due to insufficient fluid in the pores. As for the effect of permeability on the fast P-wave, the attenuation peaks move to high frequency as rock permeability increases. Moreover, at low frequencies (below about 10Hz), attenuation for low permeability is greater than that for high permeability, and velocity dispersion is also more obvious at low frequencies than that at high frequencies. When water saturation becomes high or gas saturation becomes low with other parameters constant, seismic attenuation and velocity dispersion of the fast P-wave increase within the seismic band. For the slow P-wave, attenuation increases with increasing porosity and gas saturation and decreasing rock permeability. Velocity dispersion is always apparent no matter what porosity, permeability or fluid saturation is within the seismic frequency band.

INTRODUCTION

Attenuation and dispersion often occur as seismic waves propagate in underground media, especially in oil and gas reservoirs (Rapoport et al., 2004; Chapman et al., 2006; Quintal et al., 2011; Yan et al., 2014). A good understanding of seismic attenuation and velocity dispersion is of great importance to seismic interpretation and inversion and also is helpful to infer the fluid type and property. However, the physical mechanisms

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responsible for such high attenuation and dispersion in the seismic band are currently not fully understood. In seismic exploration, we are most interested in the wave-induced fluid flow mechanism. At present, numerous models for seismic attenuation and velocity dispersion from wave-induced flow have been developed with varying degrees of rigor and complexity (Müller et al., 2010). These models can be categorized roughly into three groups: the Biot model, the BISQ model and the patchy-saturated model. Biot (1956) first considered the relative flow between fluid phase and solid phase in fluid-saturated porous rocks and established the seismic wave equations in poroelastic fluid-saturated media (Biot, 1956a, 1962). The attenuation and dispersion is theoretically quantified by Biot's theory of poroelasticity (Biot, 1956a, 1956b, 1962; White, 1986; Bourbié et al., 1987; Pride, 2005). However, the predicted attenuation based on the Biot model can only be applied for the ultrasonic band and was much smaller than that measured in the seismic frequency range(1-100Hz) (Berryman, 1988). Biot flow is a kind of global or macroscopic flow which only considers flow along the wave propagation direction between the pore fluid and rock skeleton resulting from wavelength-scale pressure gradients. In fact, adjacent pores have different aspects and thus can cause local pressure gradients between these pores. This local or pore-scale fluid flow is known as squirt flow (Mavko and Nur, 1979) and is a kind of microscopic fluid flow which is perpendicular to the wave propagation. Both Biot flow (global flow) and squirt flow exist in fluid-containing porous media. Therefore, Dvorkin and Nur (1993) proposed a model that combined both mechanisms based on one-dimensional isotropic pores which is called Biot-Squirt (BISQ) model. Unfortunately, the seismic attenuation predicted by BISQ model only applies to the ultrasonic frequency range (Dvorkin et al., 1994; Dvorkin et al., 1995). Furthermore, it cannot describe the relative relation of the seismic amplitude between P-waves of the first and second kind (Bordakov, 1999).

Wave induced fluid flow can also be caused by pressure gradients between areas of the rock which are much larger than the typical pore size but much smaller than the seismic wavelength. This kind of fluid flow is called mesoscopic flow. Mesoscale flow was modeled by White (1975) and White et al. (1975). Since the White model, which is also known as the patchy-saturated model, was established, many scientists studied seismic attenuation and velocity dispersion in the patchy saturated model (Dutta and Ode, 1979a, 1979b; Lopatnikov and Gurevich, 1988; Gurevich and Lopatnikov, 1995; Gurevich and Makarynska, 2012; Kuteynikova et al.,2014; Qi et al.,2014; Tisato and Quintal, 2014; Yan et al., 2014; Hu et al., 2014; Yao et al., 2015; Pimienta et al., 2015; Spencer and Shine, 2016). Pride et al. (2004) illustrated that the microscale squirt flow mechanism describes attenuation in the seismic frequency range insufficiently, whereas the mesoscale flow model can account for the attenuation in the low frequency range. Johnson (2001) modified the White model and theoretically analyzed the wave attenuation characteristics in patchy-saturated rocks. However, Johnson didn't propose a new seismic wave equation for patchy-saturated porous rocks. On the basis of White model, we (Zhang and He, 2015) proposed a modified patchy-saturated model and established the corresponding seismic wave equations for partially saturated porous rocks.

This paper is a sequel to our previous work (Zhang and He, 2015). In this paper, we obtain the reciprocal quality factor Q-1 through solving the seismic wave equations to study the frequency dependent attenuation of the patchy-saturated model. Moreover, we compare the seismic attenuation in this modified patchy-saturated model with that in the Biot and BISQ modes. Furthermore, we study the effects of porosity, permeability and fluid saturation on seismic attenuation and velocity dispersion in patchy-saturated rocks.

SEISMIC WAVE EQUATIONS IN MODIFIED PATCHY-SATURATED MODEL

The modified patchy-saturated model we established before is shown in Figure 1. This model was proposed according to the White model which suggested that some regions were fully saturated with water and others were fully saturated with gas.

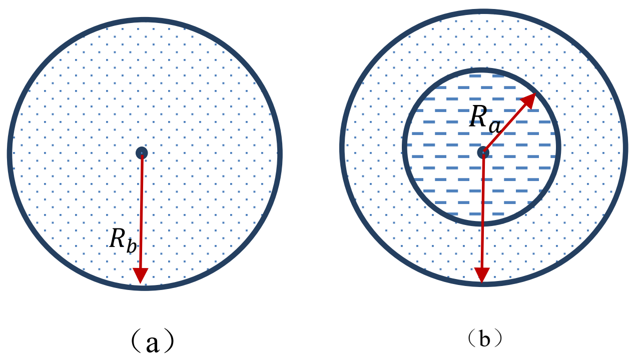

FIG.1. Modified patchy-saturated model for porous media

Figure 1a shows the rock skeleton and two kinds of fluids where the dots represent for fluid 1 and dashes represent for fluid 2. For convenience, we rearrange the model to be as in Figure 1b, which consists of two concentric spheres with radii R_a and R_b. The volume of the inner sphere, which is saturated with fluid 2 (gas pocket in the White model), is the total space of pores filled with fluid 2 in Figure 1a. The outer space represents the rock skeleton and the pores filled with fluid 1. To study the seismic attenuation in such media, White assumed that: The seismic wavelength is much larger than the gas pocket size and there is no interaction between two gas pockets. Besides this, we assumed that there is no movement between fluid 1 and the skeleton but there is relative movement between fluid 2 and the skeleton. On the basis of the above, the dilatational wave equations in modified patchy-saturated model were established as follows:

$$\rho \frac{\partial^2 \theta}{\partial t^2} + \rho_{f_2} \frac{\partial^2 \varepsilon}{\partial t^2} = H\nabla^2\theta + 2\gamma D\nabla^2\varepsilon, \qquad (1)$$

$$\rho_{f_2}\frac{\partial^2\theta}{\partial t^2}+m\frac{\partial^2\varepsilon}{\partial t^2}=2\gamma D\nabla^2\theta+2D\nabla^2\varepsilon-\frac{\eta_2}{\kappa}\frac{\partial\varepsilon}{\partial t}, \qquad (2)$$

with

$$\rho=(1-\phi)\rho_s+\phi S_1\rho_{f_1}+\phi S_2\rho_{f_2},$$

$$\theta=\nabla\cdot\vec{u},$$

$$\varepsilon=\nabla\cdot\vec{w},$$

$$\vec{w}=\phi(\vec{U}-\vec{u}),$$

$$S_1+S_2=1,$$

$$\gamma=1-\frac{\overline{K}_m}{\overline{K}_s},$$

$$\overline{K}_s=K_m+\frac{(1-K_m/\mathrm{K}_s)^2}{(\phi S_1/(1-\phi S_2))(1/K_{f_1}-1/K_s)+(1/K_s)(1-K_m/K_s)},$$

$$D=\frac{\overline{K}_s}{2}\left[\gamma+\frac{S_2\phi}{K_{f_2}}(\overline{K}_s-K_{f_2})\right]^{-1},$$

$$m=s\frac{\rho_{f_2}}{\phi S_2},$$

where ρ is the total mass of the patchy-saturated porous rock per unit volume, ρ_s is the mass density of solid grains; S_1, ρ_{f1} and η_1 (for later use) are the saturation, density and viscosity of fluid 1, respectively; S_2, ρ_{f2} and η_2 are the saturation, density and viscosity coefficient of fluid 2, respectively; θ and ε are volume strains of the "solid" (frame rock containing fluid 1) and that of fluid 2 relative to "solid", respectively; $\vec{u}$ is the displacement vector of the "solid" of the patchy-saturated porous rock, $\vec{w}$ is the displacement vector of fluid 2 relative to solid and $\vec{U}$ is the displacement vector of fluid 2; ϕ is the porosity of the rock; H is the plane-wave modulus of partially-saturated rock, $H = K + \frac{4}{3}\mu$, K and μ are bulk and shear moduli of the patchy-saturated rock, respectively; $\overline{K}_m$ and $\overline{K}_s$ are the bulk moduli of the skeleton containing fluid 1, but excluding fluid 2 and the frame filled with fluid 1, respectively; According to Gassmann's equation(Gassmann,1951), the expression of $\overline{K}_s$ is listed above; K_m is the bulk modulus of frame containing pores, K_{f1} is the bulk modulus of fluid 1, K_{f2} is the bulk modulus of fluid 2; s is a structure constant depending on the pore structure and orientation; κ is permeability of the porous rock; t is time.

The bulk modulus K of the patchy-saturated rock can be computed by the following formula Johnson (2001) established:

$$K(\omega) = K_{BGH} - \frac{K_{BGH} - K_{BGW}}{1 - \zeta + \zeta\sqrt{1 - i\omega\tau / \zeta^2}},$$

where K_{BGH} satisfies(Hill ,1963,1964):

$$\frac{1}{K_{BGH} + \frac{4}{3}\mu} = \frac{S_1}{K_{BG}(K_{f_1}) + \frac{4}{3}\mu} + \frac{S_2}{K_{BG}(K_{f_2}) + \frac{4}{3}\mu},$$

with

$$K_{BG}(K_{f_1}) = \frac{K_s + [\phi(K_s / K_{f_1}) - \phi - 1]K_b}{1 - \phi - (K_b / K_s) + \phi(K_s / K_{f_1})},$$

$$K_{BG}(K_{f_2}) = \frac{K_s + [\phi(K_s / K_{f_2}) - \phi - 1]K_b}{1 - \phi - (K_b / K_s) + \phi(K_s / K_{f_2})}.$$

And K_{BGW} satisfies the following:

$$K_{BGW} = \frac{K_s + \left\{\phi\left[\frac{K_s(S_1 K_{f_2} + S_2 K_{f_1})}{K_{f_1} \cdot K_{f_2}}\right] - \phi - 1\right\}K_b}{1 - \phi - (K_b / K_s) + \phi\left[\frac{K_s(S_1 K_{f_2} + S_2 K_{f_1})}{K_{f_1} \cdot K_{f_2}}\right]},$$

where τ and ζ are:

$$\tau = \left[\frac{K_{BGH} - K_{BGW}}{K_{BGH} \cdot G} \right]^2,$$

and

$$\zeta = \frac{(K_{BGH} - K_{BGW})}{2K_{BGW}} \cdot \frac{\tau}{T}.$$

For the expressions of G and T see our previous work (Zhang and He, 2015). ω is angular frequency of seismic waves.

COMPARISON OF ATTENUATION IN PATCHY, BIOT AND BISQ MODELS

In order to explore the high attenuation in a modified patchy-saturated model, we compare it with the Biot and BISQ models.

Through solving wave equations (1) and (2), we can obtain the reciprocal quality factor to study the seismic attenuation in the modified patchy-saturated model. We assume that the plane wave propagates in the x-direction. Let $u = u_0 e^{i(k'x - \omega t)}$, $U = U_0 e^{i(k'x - \omega t)}$, then $w = \phi(U - u) = \phi(U_0 - u_0) e^{i(k'x - \omega t)}$, where complex wavenumber k' and wavenumber k via $k' = k + i\alpha$ and α is the attenuation coefficient. Substituting the above expressions into equations (1) and (2), we can obtain:

$$\begin{aligned} &\left(4\gamma^2 D^2 - 2DH\right) k'^4 + \left(2D\rho\omega^2 - 4\gamma D\rho_{f_2}\omega^2 + m\omega^2 H + i\frac{\eta_2}{\kappa}\omega H\right) k'^2 \\ &+ \rho_{f_2}^2 \omega^4 - m\rho\omega^4 - i\frac{\eta_2}{\kappa}\rho\omega^3 = 0. \end{aligned} \tag{3}$$

Let

$$A = 4\gamma^2 D^2 - 2DH,$$

$$B = 2D\rho\omega^2 - 4\gamma D\rho_{f_2}\omega^2 + m\omega^2 H + i\frac{\eta_2}{\kappa}\omega H,$$

$$C = \rho_{f_2}^2 \omega^4 - m\rho\omega^4 - i\frac{\eta_2}{\kappa}\rho\omega^3,$$

we get:

$$Ak'^4 + Bk'^2 + C = 0.$$

Then we have:

$$k_{1,2}^{'\,2} = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A}.$$

So,

$$k_{1,2} = \mathrm{Re}(\sqrt{k_{1,2}^{'}}), \quad \alpha_{1,2} = \mathrm{Im}(\sqrt{k_{1,2}^{'}}),$$

and

$$v_{1,2} = \frac{\omega}{k_{1,2}} = \frac{\omega}{\mathrm{Re}(\sqrt{k_{1,2}^{'}})}, \quad Q_{1,2}^{-1} = \frac{v_{1,2}\alpha_{1,2}}{\pi f} = \frac{2\alpha_{1,2}}{k_{1,2}} = \frac{2\,\mathrm{Im}(\sqrt{k_{1,2}^{'}})}{\mathrm{Re}(\sqrt{k_{1,2}^{'}})}, \tag{4}$$

where $k_{1,2}$ and $\alpha_{1,2}$ represent the wavenumber and attenuation coefficient of two kinds of P-waves, respectively; $v_{1,2}$ and $Q_{1,2}^{-1}$ represent the velocity and the reciprocal quality factor of two kinds of P-waves, respectively. The symbol "Re" and "Im" represent real part and imaginary part of a complex number, respectively.

Biot's P-wave equations for a fluid-saturated porous medium are written as follows (Biot 1962; Dutta and Ode, 1979a):

$$\rho \frac{\partial^2 \theta}{\partial t^2} + \rho_f \frac{\partial^2 \varepsilon}{\partial t^2} = H\nabla^2\theta + 2\gamma D\nabla^2\varepsilon, \tag{5}$$

$$\rho \frac{\partial^2 \theta}{\partial t^2} + m \frac{\partial^2 \varepsilon}{\partial t^2} = 2\gamma D\nabla^2\theta + 2D\nabla^2\varepsilon - \frac{\eta}{\kappa}\frac{\partial \varepsilon}{\partial t}, \tag{6}$$

with

$$\rho = (1-\phi)\rho_s + \phi\rho_f,$$

$$H = \lambda + 2\mu = K + \frac{4}{3}\mu,$$

$$\gamma = 1 - \beta = 1 - \frac{K_m}{K_s},$$

$$D = \frac{K_s}{2}\left[\gamma + \frac{\phi}{K_f}(K_s - K_f)\right]^{-1},$$

where ρ is the mass density of fluid saturated rock(i.e., the total mass of the fluid-solid aggregate per unit volume), ρ_f and ρ_s are the mass densities of the pore fluid and pure rock; η is fluid viscosity; λ and μ are Lame constants, μ is also known as the shear modulus of the rock; K_s is the bulk modulus of the compact solid; K_f is the bulk modulus of fluid; Other parameters not explicitly defined here have the same meanings as previously indicated.

Still considering plane waves in x-direction, we can get the formula (7) by using the same method as in the modified patchy-saturated model.

$$Ak'^4 + Bk'^2 + C = 0, \tag{7}$$

where

$$A = 4\gamma^2 D^2 - 2DH,$$
$$B = 2D\rho\omega^2 - 4\gamma D\rho_f\omega^2 + m\omega^2 H + i\frac{\eta}{\kappa}\omega H,$$
$$C = \rho_f^2\omega^4 - m\rho\omega^4 - i\frac{\eta}{\kappa}\rho\omega^3.$$

Then we can get the same expressions for velocity and reciprocal quality factor as equation (4) but with different A, B and C expressions.

In the BISQ model, the velocity and reciprocal quality factor of P-waves can be expressed as (Dvorkin et al., 1994):

$$v_{1,2} = \frac{1}{\mathrm{Re}(\sqrt{Y_{1,2}})}, \quad Q_{1,2}^{-1} = \frac{2\,\mathrm{Im}(\sqrt{Y_{1,2}})}{\mathrm{Re}(\sqrt{Y_{1,2}})}, \tag{8}$$

with

$$Y_{1,2} = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A}, \quad A = \frac{\phi FSH}{\rho_2^2},$$

$$B=\frac{FS(2\gamma-\phi-\phi\frac{\rho_1}{\rho_2})-(H+FS\frac{\gamma^2}{\phi})(1+\frac{\rho_a}{\rho_2}+i\frac{\omega_c}{\omega})}{\rho_2},$$

$$C=\frac{\rho_1}{\rho_2}+(1+\frac{\rho_1}{\rho_2})(\frac{\rho_a}{\rho_2}+i\frac{\omega_c}{\omega}),\qquad \frac{1}{F}=\frac{1}{K_f}+\frac{1}{\phi K_s}(\gamma-\phi),$$

$$S=1-\frac{2J_1(\lambda R)}{\lambda R J_0(\lambda R)},\ \lambda^2=\frac{\rho_f\omega^2}{F}(\frac{\phi+\rho_a/\rho_f}{\phi}+i\frac{\omega_c}{\omega}),$$

$$\rho_1=(1-\phi)\rho_s,\quad \rho_2=\phi\rho_f,\ \omega_c=\frac{\eta\phi}{\kappa\rho_f},\quad \gamma=1-\frac{K_b}{K_s},$$

where J_0 and J_1 are zero-order and one-order Bessel functions; H is the plane-wave modulus of the drained skeleton; R is the characteristic squirt-flow length; ω_c is Biot's characteristic angular frequency; ρ_a is the additional density introduced by Biot (1956) to quantify inertial coupling between the solid and the fluid; Other parameters not explicitly defined have the same meanings as previously mentioned.

We using the parameters (John, 2001; Huang et al., 2012) in Table 1 to discuss the seismic attenuation in three models. In the Biot and BISQ models, the fluid in pores corresponds to fluid 2 in the modified patchy-saturated model. In table1, the parameter K_m used for computing is not listed. We use the following empirical formula to obtain it:

$$K_m=K_s\left(1-\frac{\phi}{\phi_c}\right)^n,$$

where ϕ_c is critical porosity of porous sand. Here we use the value 0.307. n is also an experienced value which is greater than or equal to 1. Here we use the value 1.

Table 1. Elastic parameters of three models

frame parameters	values	fluid parameters	values
ϕ	0.3	S_1	0.5
K_s	38×10^9 Pa	S_2	0.5
μ	14.61×10^9 Pa	K_{f_1}	2.25×10^9 Pa
κ	$1.0\times10^{-13}m^2$	K_{f_2}	1.0×10^5 Pa
ρ_s	2650 $kg\cdot m^{-3}$	ρ_{f_1}	1000 $kg\cdot m^{-3}$
R_a	7.937cm	ρ_{f_2}	78 $kg\cdot m^{-3}$
R_b	10cm	η_1	$1.0\times10^{-3}Pa\cdot s$
R	0.1cm	η_2	$1.0\times10^{-5}Pa\cdot s$
s	2		

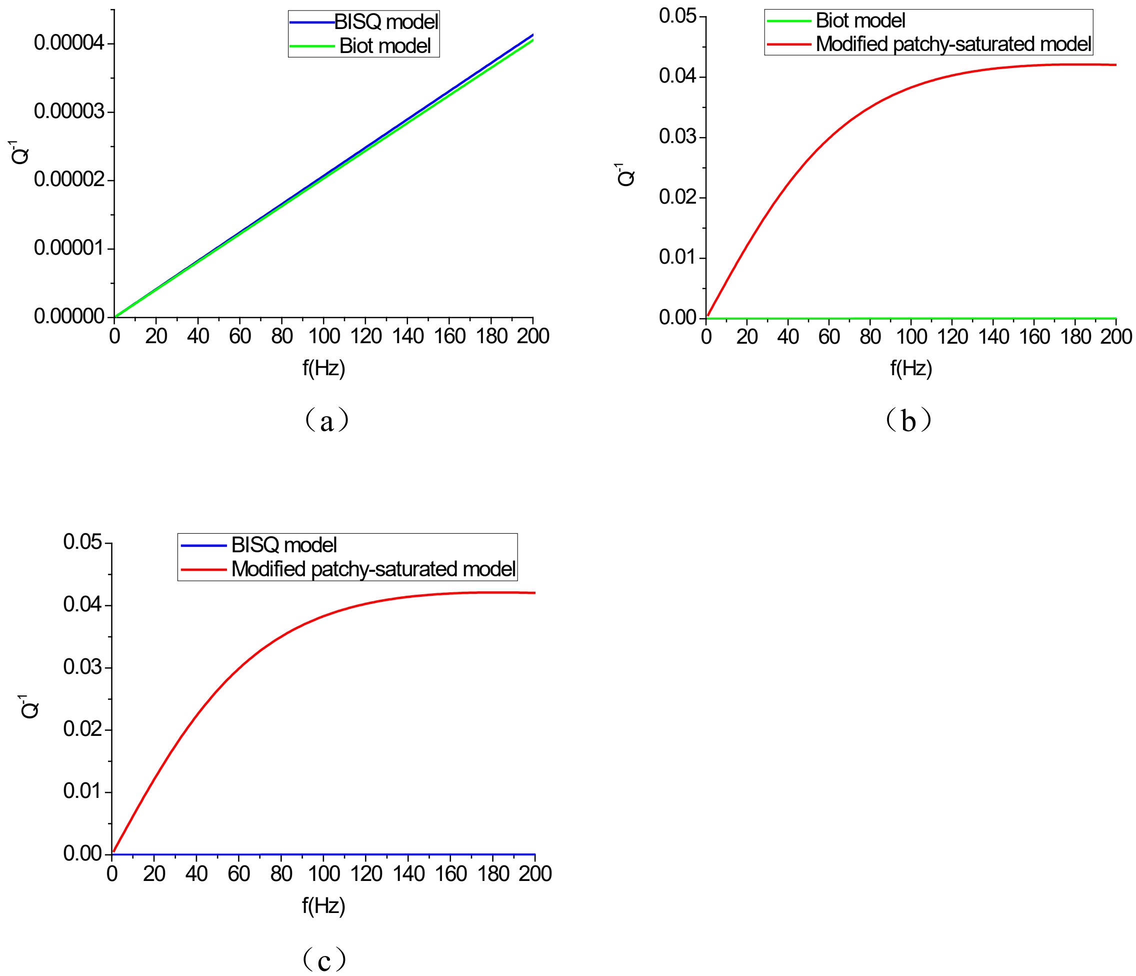

FIG. 2. Comparison of reciprocal quality factors in three models: (a) Attenuation comparison of the Biot and BISQ models. (b) Attenuation comparison of the Biot and modified patchy-saturated models. (c) Attenuation comparison of the BISQ and modified patchy-saturated models.

Figure 2 shows the reciprocal quality factor Q^{-1} changing with frequency (1-200Hz). From Figure 2, we can see that the attenuation in the BISQ model is slightly greater than that in the Biot model (Figure 2a), while the attenuation in the modified patchy-saturated model is about 1000 times greater than that in the Biot and BISQ models (Figure 2b and Figure 2c), within the seismic frequency band. Therefore, the modified patchy-saturated model shows high attenuation in the seismic frequency band, can describe the fluid flow in real rocks more accurately, and can be used to seismic exploration.

ATTENUATION AND DISPERSION IN MODIFIED PATCHY-SATURATED ROCKS

Field data and many studies show that pore fluid properties have a major effect on attenuation and velocity dispersion of seismic waves (Yin et al., 1992; Pride et al.,2004; Chapman et al., 2006; Müller et al., 2008, 2010; Quintal et al., 2009; Mavko and Vanorio, 2010; Quintal, 2012; Quintal et al., 2012; Tisato and Madonna, 2012; Madonna and Tisato, 2013; Beresnev, 2014). Therefore, research on seismic attenuation and velocity dispersion is quite important in exploration geophysics for finding economically viable hydrocarbon reservoirs. Since porosity and permeability are vital properties of reservoirs, and fluid saturation can reflect the quantity of the oil and gas in pores directly, research on the effects of porosity, permeability and saturation on seismic attenuation and velocity dispersion is most important both in exploration and development geophysics.

From the above discussion, we know that there is large attenuation in the modified patchy-saturated model at low frequencies (below 200Hz) and this can be used in seismic exploration. In this section, we further study the attenuation in patchy-saturated rocks and discuss the effects of rock porosity, permeability and fluid saturation on seismic attenuation and velocity dispersion.

First, we discuss porosity's effect on seismic attenuation and dispersion in patchy-saturated rocks. Figure 3 shows that the reciprocal quality factor and velocity of the two kinds of P-waves change with frequency when the rock has different porosity. The rock parameters we used are in Table1. The only parameter we varied is porosity ϕ.

From Figure 3a and Figure 3b, we can see that both fast P-wave and slow P-wave exhibit large attenuation in patchy-saturated rocks within the seismic frequency band. The attenuation of the slow P-wave is much higher than that of the fast P-wave, which is consistent with Biot's theory in the ultrasonic band. For the fast P-wave, attenuation becomes higher with increasing frequency and porosity (Figure 3a), because the amount of fluid increases with increasing porosity at the same degree of saturation. From Figure 3c, we can see that velocity dispersion of the fast P-wave becomes obvious with increasing porosity. When the rock porosity is 10%, there is very little velocity dispersion, because the amount of fluid is too small. This shows that it is the presence of fluid that causes velocity dispersion of the fast P-wave. The property of the slow P-wave is different from the fast P-wave. It has large velocity dispersion even if the rock porosity is small (Figure 3d). The attenuation of slow P-wave increases with increasing porosity and decreasing frequency (Figure 3b).

Next we discuss the effect of permeability on seismic attenuation and dispersion in patchy-saturated rocks (Figure 4). We continue to use the rock parameters in Table1 and we only changed the permeability κ.

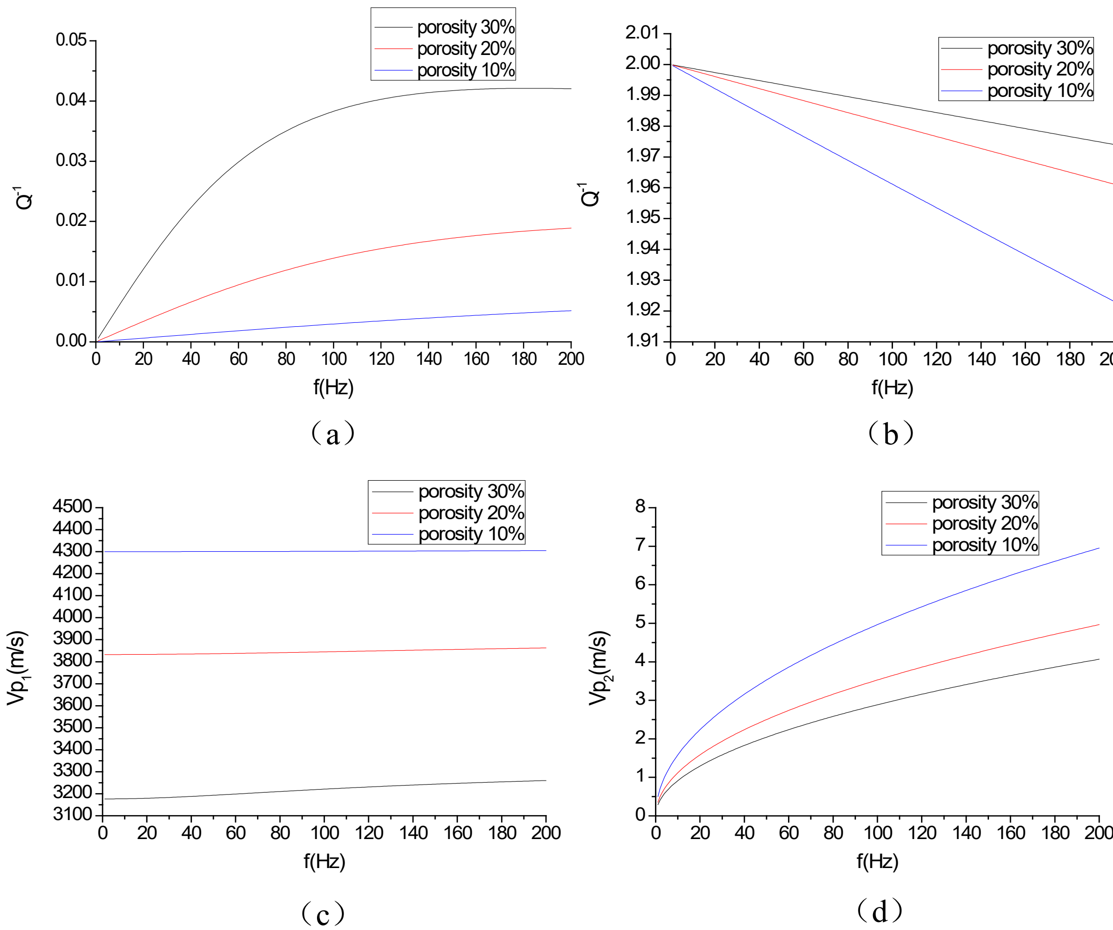

FIG. 3. Attenuation and dispersion of the two kinds of P-waves with different porosity in patchy-saturated rocks: (a) Reciprocal quality factor of the fast P-wave versus frequency with different porosity. (b) Reciprocal quality factor of the slow P-wave versus frequency with different porosity. (c) Velocity of the fast P-wave versus frequency with different porosity. (d) Velocity of the slow P-wave versus frequency with different porosity.

From Figure 4a, we can see that the peak of the reciprocal quality factor of the fast P-wave moves to high frequency with increasing permeability. Furthermore, at low frequencies (below about 10Hz), the attenuation of the fast P-wave increases with decreasing permeability. The reason is possibly that there is low fluid mobility when the permeability is low and thus viscosity of the fluid is relatively high and leads to higher attenuation. Velocity dispersion of the fast P-wave is obvious when the rock permeability is high, whereas it only appears in the low frequency band when the rock permeability is low (Figure 4c). Therefore, low frequency is more important than high frequency for detecting oil and gas reservoirs. For the slow P-wave, the rules of attenuation and dispersion are different (Figure 4b and Figure 4d). Velocity dispersion appears at different permeability and it becomes severe with increasing permeability whereas attenuation increases with decreasing permeability.

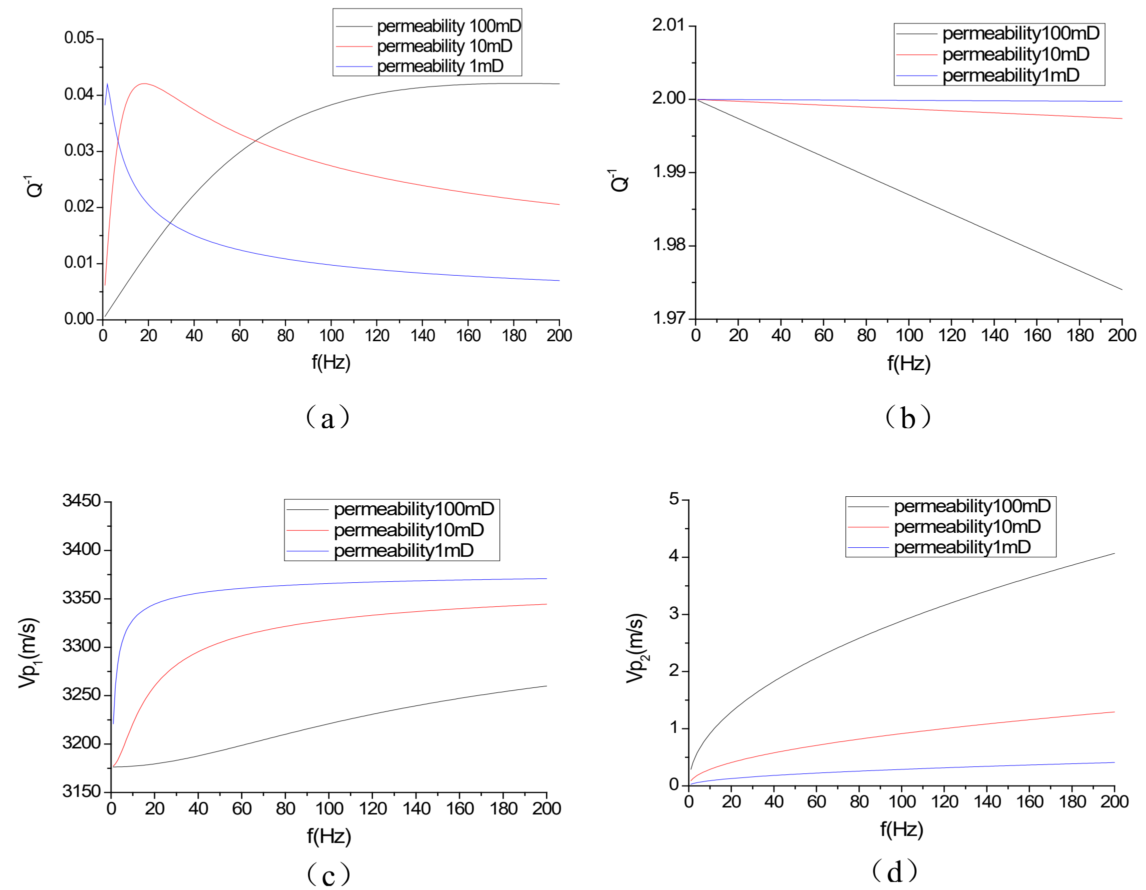

FIG. 4. Attenuation and dispersion of the two kinds of P-waves with different permeability in patchy-saturated rocks: (a) Reciprocal quality factor of the fast P-wave versus frequency with different permeability. (b) Reciprocal quality factor of the slow P-wave versus frequency with different permeability. (c) Velocity of the fast P-wave versus frequency with different permeability. (d) Velocity of the slow P-wave versus frequency with different permeability.

Now, we discuss the effect of saturation on seismic waves. Quintal et al. (2010, 2011) studied the impact of fluid saturation on the reflection coefficient of a poroelastic layer. Dupuy (2014) analyzed the influence of saturation on AVO attributes for patchy-saturated rocks. Kuteynikova et al. (2014) combined numerical modeling in poroelastic media and laboratory measurements of seismic attenuation in partially saturated sandstone samples to study the effects of fluid saturation on seismic attenuation. Hence, fluid saturation is an important factor to seismic waves. We change the parameters S_1 and S_2 in Table 1 to compute the reciprocal quality factor and velocity of seismic waves in patchy-saturated rocks (see Figure 5).

Figure 5a shows that attenuation of the fast P-wave increases with increasing frequency within the low frequency band (below about 60Hz). When gas saturation increases, the attenuation of the fast P-wave in patchy-saturated rocks decreases, which is consistent with the results that Nie et al. (2012) achieved through studying wave attenuation in the BISQ model, and Deng et al. (2012) obtained through studying wave attenuation in a periodic layered patchy-saturated model. Kuteynikova et al. (2014) also concluded that the attenuation of the fast P-wave with water saturation of 90% is greater than that with water saturation of 83.6% through numerical modeling and laboratory measurement of seismic attenuation in partially saturated rock. The velocity dispersion of the fast P-wave increases with increasing water saturation (Figure 5c), which also agrees with Deng et al. (2012). The attenuation of the slow P-wave increases with increasing gas saturation and decreasing frequency (Figure 5b), while velocity increases with decreasing gas saturation and increasing frequency (Figure 5d).

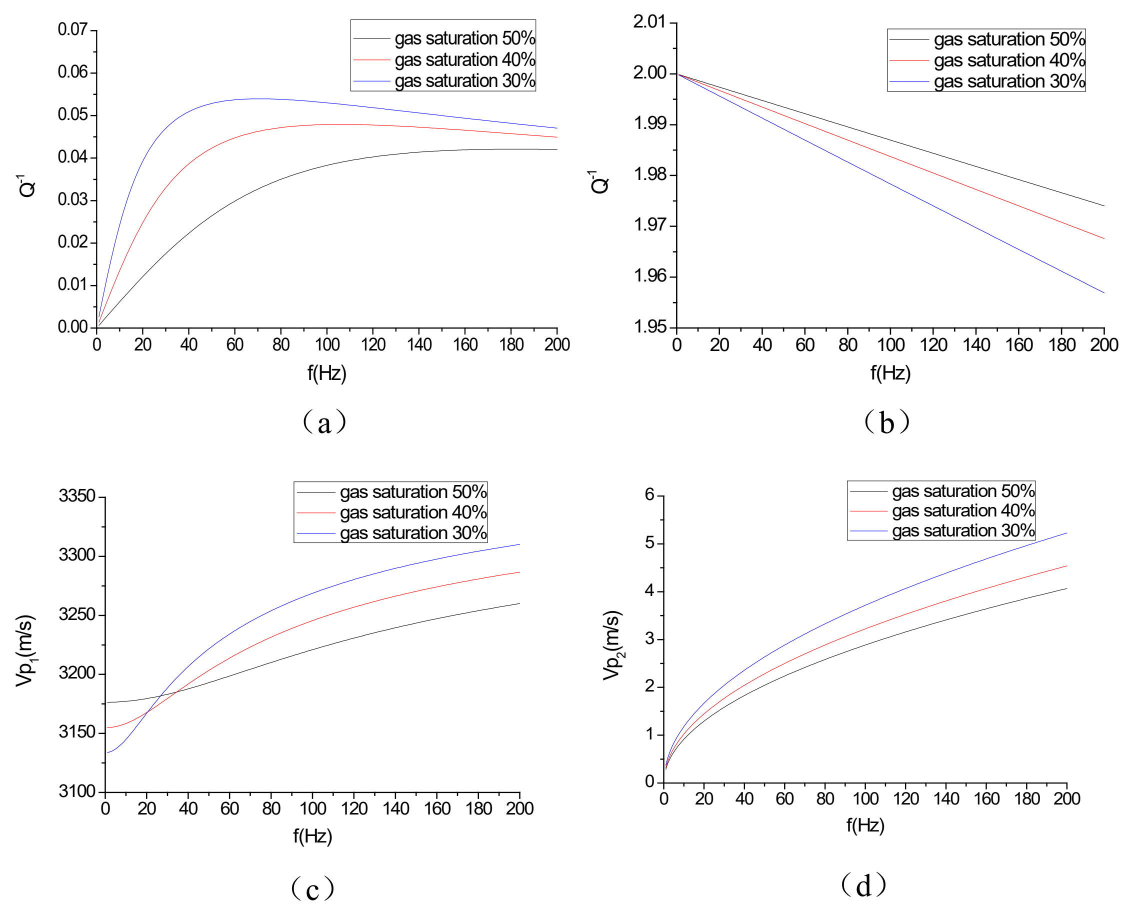

FIG. 5. Attenuation and dispersion of the two kinds of P-waves with different gas saturation in patchy-saturated rocks: (a) Reciprocal quality factor of the fast P-wave versus frequency with different saturation. (b) Reciprocal quality factor of the slow P-wave versus frequency with different saturation. (c) Velocity of the fast P-wave versus frequency with different saturation. (d) Velocity of the slow P-wave versus frequency with different saturation.

CONCLUSIONS

We derived the reciprocal quality factor and velocity versus frequency from the seismic equations in a modified patchy-saturated model and studied the seismic attenuation and velocity dispersion of the two kinds of P-waves in patchy-saturated rocks. By comparing with the Biot and BISQ models, we find that seismic attenuation of the fast P-wave in modified patchy-saturated model is much higher than that in Biot and BISQ models, by about 1000 times, within the seismic band. Therefore, the modified patchy-saturated model can describe seismic waves in real rocks more accurately and can be used in seismic exploration. By studying the effects of porosity, permeability and fluid saturation on seismic attenuation and velocity dispersion, we obtained the following conclusions:

First, seismic attenuation of the fast P-wave increases with increasing porosity and frequency within the seismic band. When the porosity is low (below 10%), velocity dispersion is not obvious, and when the porosity becomes higher, it becomes apparent. For the slow P-wave, seismic attenuation is much higher than that of the fast P-wave and velocity dispersion is obvious with different porosity. When frequency becomes high, seismic attenuation decreases whereas seismic attenuation increases with increasing porosity at frequencies 1- 200Hz.

Second, attenuation peaks of the fast P-wave move to high frequencies as rock permeability increases. Moreover, at low frequencies (below about 10Hz), attenuation increases with decreasing permeability. When rock permeability is low, the fluid mobility is small and thus viscosity of the fluid is relatively high and leads to higher attenuation. Velocity dispersion of the fast P-wave is obvious only at low frequencies. For the slow P-wave, seismic attenuation and velocity dispersion are all apparent even if the rock permeability is very low. Seismic attenuation increases with decreasing frequency and increasing permeability.

Third, seismic attenuation of the fast P- wave increases with increasing frequency and decreasing gas saturation or increasing water saturation within the seismic band. Velocity dispersion of the fast P-wave becomes severe as the gas saturation goes down. For the slow P-wave, seismic attenuation decreases as the frequency increases. When the gas saturation becomes high, attenuation goes up. As for velocity dispersion, it increases with decreasing gas saturation.

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