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"THE CHARACTERISTICS OF REFLECTION AND TRANSMISSION COEFFICIENTS OF POROUS MEDIUM SATURATED WITH AN IDEAL FLUID"

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ABSTRACT

The underground rock is composed of rock skeleton and pore fluids. When seismic waves propagate in underground medium, it will show complicated change influenced by pore and pore fluids in rocks. It is very important to study the characteristics of reflection and transmission coefficients of seismic waves at the interface and to analyze the properties of the lithology and pore fluids of porous medium, which can reveal the oil and gas bearing in underground medium. Based on the relationship among wave functions, displacement and stress in porous medium, the equation of reflection and transmission coefficients at the interface of porous medium saturated with an ideal fluid is derived. A geological model with sandstone porous medium in the top layer and mudstone porous medium in the bottom layer, the rock skeleton parameters of which vary with porosities, is established. Based on the equation and the model, the variation of reflection and transmission coefficients with the incident angle at the interface of porous medium is studied under the conditions of different pore fluids filling and different porosities. The study shows that the existence of the pore and pore fluids will impede the reflected and transmitted abilities of seismic waves at the interface of porous medium. Combining with the theory of rock physics and well data, the porosities and pore fluids of porous medium can be identified qualitatively by studying the variation of the reflected fast P- and SV-waves with incident angle. The values of reflection and transmission coefficients of slow P-wave are very small, but the variation of that is relatively large due to the influence of the pore and pore fluids.

1. INTRODUCTION

The underground rock is a porous medium composed of rock skeleton and pore fluids. The properties of rock are not only related to various mineral properties that make up the rock skeleton, but also influenced by many factors, such as pore shape, pore size, pore fluids filling, and so on. When seismic waves propagating in such a porous medium, they show complex reflection and transmission characteristics, which carry a large number of information reflected reservoirs properties of oil and gas bearing. It is of great significance to study the characteristics of reflection and transmission coefficients at an interface of porous media saturated with fluids, which can be used to identify the reservoirs of oil and gas, analyze the properties and distribution of reservoirs, and improve the exploration and development level of oil and gas fields.

Since Biot [1940, 1956, 1957, 1962] proposed the theory of seismic wave propagation in porous medium, many geophysical experts have carried out in-depth research. Yin et al. [2014, 2015, 2016] and Zong and Yin [2017] combined this with pre-stack seismic inversion to realize the fluid identification based on the data and model driven. When the seismic wave impinges perpendicularly at the interface of porous medium, some scholars [Geertsma and Smit, 1961; Silin et al, 2004; Silin and Goloshubin, 2010] analyzed the reflection and transmission problems. They considered that the reflection and transmission coefficients can be expressed as a low frequency asymptotic formula. However, when the seismic wave impinging obliquely, it will bring more abundant information varying with incident angle, which can help us to realize the high accuracy identification of oil and gas reservoirs. Lovera [1987] and Mu [1996] studied the boundary conditions and the reflected and transmitted problem with a seismic wave inclining at the interface of porous medium. For some complex reservoirs, such as the Carbonate Reservoirs and the Reef-Bank Reservoirs, there may be two or more kinds of immiscible fluid in porous media. The types of pore fluids, the volume ratio and the interaction among these fluids will affect the propagation characteristics of seismic waves. Tuncay and Corapcioglu [1996, 1997] and Lo and Sposito [2005] thought that there are three kinds of P-waves and a class of SV-wave propagation in the porous medium saturated with two kinds of immiscible fluids. Some other scholars [Vashisth et al., 1991; Tomar and Arora, 2006; Kumar and Saini, 2012, 2016; Kumar and Sharma, 2013] had carried out a series of in-depth studies on the reflected and transmitted characteristics of this type medium.

A lot of work had been done on the theoretical research of porous medium. However, the characteristics of reflection and transmission coefficients at the interface of porous media saturated with an ideal fluid still need to be furtherly discussed. The difference of the reflected and transmitted characteristics of seismic waves at the interface has not been considered yet under the situations of different pore fluids filling. The variation of porosity is not only directly responsible for reflection and transmission coefficients, but also indirectly influencing their values by affecting rock skeleton. How to establish a comprehensive relationship between the porosity and the coefficients is still a problem to be solved.

In this paper, the equation of the reflection and transmission coefficients at an interface of porous medium saturated with an ideal fluid is derived, whose expression is more concise and geophysical meaning is more clear. Based on previous researches, a geological model characterized by the porosity is established with separating a sandstone porous medium half space and dense mudstone porous medium half space. Combining coefficient equation with geological model, the variation characteristics of the reflection and transmission coefficients with incident angles are analyzed under different conditions of porosities and pore fluids filling, respectively. Some meaningful conclusions are obtained in NUMERICAL ANALYSIS, which provides theoretical support for the identification of oil, gas and water in reservoirs.

2. FORMULATION OF THE PROBLEM

2.1 REFLECTION AND TRANSMISSION

We consider the reflection and transmission problem with a seismic wave impinging obliquely at the interface of porous medium saturated with an ideal fluid. The seismic waves generated at the interface include reflected fast P-wave φ_{11}, reflected slow P-wave φ_{12}, reflected SV-wave φ_{13}, transmitted fast P-wave φ_{21}, transmitted slow P-wave φ_{22}, and transmitted SV-wave φ_{23} (Figure 1). The reflected and transmitted angles of all waves are θ_{11}, θ_{12}, θ_{13}, θ_{21}, θ_{22}, θ_{23}, respectively.

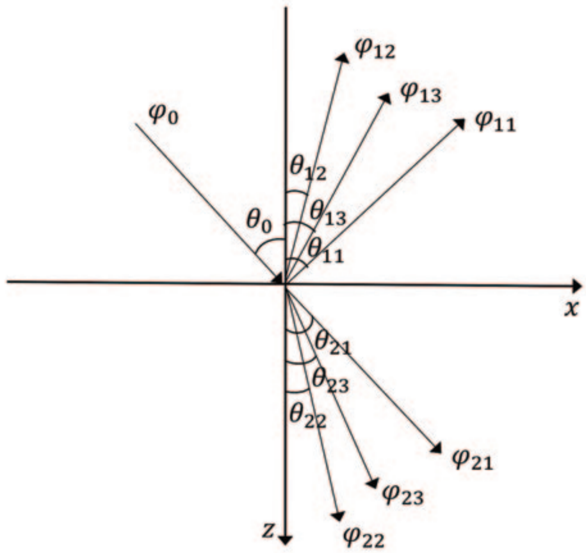

FIGURE 1. The reflection and transmission at the interface of porous medium saturated with an ideal fluid.

2.2 WAVE FUNCTIONS

Assuming that the incident wave φ_0 with its angle θ_0 is a fast P-wave (Figure 1), the functions of the incident, reflected and transmitted waves can be expressed as follows, respectively.

Incident seismic wave,

$$\varphi_0 = A_0 \exp\left\{i\omega\left(t - k_{11}x - p_{11}z\right)\right\}. \tag{1}$$

Reflected seismic waves,

$$\varphi_{1j} = A_{1j} \exp\left\{i\omega\left(t - k_{1j}x + p_{1j}z\right)\right\}, j = 1,2,3. \tag{2}$$

Transmitted seismic waves,

$$\varphi_{2j} = A_{2j} \exp\left\{i\omega\left(t - k_{2j}x - p_{2j}z\right)\right\}, j = 1,2,3, \tag{3}$$

$$k_{lj} = \frac{\sin\theta_{lj}}{vp_{lj}}, p_{lj} = \frac{\cos\theta_{lj}}{vp_{lj}} \quad l = 1,2, j = 1,2,3, \tag{4}$$

$$\mathrm{k} = k_{11} = k_{12} = k_{13} = k_{21} = k_{22} = k_{23}. \tag{5}$$

Where i, ω, k are the imaginary part, the frequency of incident wave and the horizontal slowness, respectively. A_0, A_{lj}, $l = 1,2, j = 1,2,3$ are amplitudes of the corresponding incident, reflected and transmitted waves, respectively. vp_{lj}, $l = 1,2, j = 1,2$ represent the velocities of P-wave, and vp_{l3}, $l = 1,2$ represent the velocities of SV-wave. $l = 1,2$ denote the top and bottom porous media, respectively. $j = 1,2,3$ denote the fast P-, slow P- and SV-waves, respectively.

3. REFLECTED AND TRANSMITTED THEORY

3.1 DISPLACEMENT AND STRESS

In the x-z plane, the wave's functions of fast P-, slow P- and SV-waves are used to describe the displacements of rock skeleton and pore fluids relative to rock skeleton (Equations 6, 7 and 8). The total stress forcing on rock skeleton is partly derived from the interaction force between rock skeletons, and the other part comes from the static pressure of pore fluids (Equations 9, 10 and 11).

$$u_{sx} = \sum_{j=1}^{2} \frac{\partial\varphi_j}{\partial x} - \frac{\partial\psi}{\partial z}. \tag{6}$$

$$u_{sz} = \sum_{j=1}^{2} \frac{\partial\varphi_j}{\partial z} + \frac{\partial\psi}{\partial x}. \tag{7}$$

$$w_{fz} = \sum_{j=1}^{2} \gamma_j \frac{\partial\varphi_j}{\partial z} + \Gamma_1 \frac{\partial\psi}{\partial x}. \tag{8}$$

Where φ_1, φ_2, ψ are wave functions of fast P-, slow P- and SV-waves, respectively. u_{sx} and u_{sz} represent displacements of rock skeleton along the directions of x and z, respectively. w_{fz} is the displacement of pore fluids relative to rock skeleton along the direction of z. $\gamma_j, j=1,2$, Γ_1 represent the ratios of seismic wave's amplitudes of pore fluids relative to rock skeleton corresponding fast P-, slow P- and SV-waves, respectively.

$$\boldsymbol{\tau}_s = \mathrm{K}\,(\nabla\cdot\mathbf{u}_s)\,\mathbf{I} + \mu\left[\nabla\mathbf{u}_s + (\nabla\mathbf{u}_s)^{\mathrm{T}} - \frac{2}{3}(\nabla\cdot\mathbf{u}_s)\,\mathbf{I}\right], \tag{9}$$

$$\mathbf{p} = [-\alpha M\,\nabla\cdot\mathbf{u}_s - M\,\nabla\cdot\mathbf{w}_f\,]\,\mathbf{I}, \tag{10}$$

$$\boldsymbol{\tau}_t = \boldsymbol{\tau}_s - \alpha\cdot\mathbf{p}. \tag{11}$$

Where, $\boldsymbol{\tau}_s$ is the stress tensor of rock skeleton, $\mathbf{p}$ represents the effective pressure of pore fluids, $\boldsymbol{\tau}_t$ denotes the total stress tensor acting on rock skeleton. K and μ are the bulk and shear moduli of rock skeleton, respectively. $\mathbf{u}_s = [u_{sx}, u_{sz}]^T$ is the displacement tensor of rock skeleton, and $\mathbf{w}_f = [w_{fx}, u_{fz}]^T$ is the displacement tensor of pore fluid relative to rock skeleton. α and M are the Biot parameters, and $\mathbf{I}$ is an identity tensor. Superscript T denotes the transposition of a matrix or a vector.

3.2 BOUNDARY CONDITIONS

The boundary conditions at the interface of porous medium are determined by the existing physical situations. The continuity equation for fluid-flow and the energy conservation at the interface are the fundamental requirements [Sharma, 2008]. The equation energy-conservation can be expressed as follows,

$$\begin{aligned} &\dot{u}_{1sz}\cdot\tau_{1tz} + \dot{u}_{1sx}\cdot\tau_{1tx} + \dot{\mathrm{w}}_{1fz}\cdot\bar{p}_{1z} = \dot{u}_{2sz}\cdot\tau_{2tz} + \\ &+ \dot{u}_{2sx}\cdot\tau_{2tx} + \dot{\mathrm{w}}_{2fz}\cdot\bar{p}_{2z}. \end{aligned} \tag{12}$$

Assuming that the interface of porous medium is welded contact, and the pores of up and bottom media are fully connected, the appropriate boundary conditions to be satisfied are,

$$\begin{aligned} &\dot{u}_{1sz} = \dot{u}_{2sz}, \dot{u}_{1sx} = \dot{u}_{2sx}, \dot{\mathrm{w}}_{1fz} = \dot{\mathrm{w}}_{2fz}, \\ &\tau_{1tz} = \tau_{2tz}, \tau_{1tx} = \tau_{2tx}, \bar{p}_{1z} = \bar{p}_{2z}. \end{aligned} \tag{13}$$

Where u_{lsx}, u_{lsz}, $l = 1,2$ are displacements of rock skeleton along the directions of x and z, respectively. w_{lfz}, $l = 1,2$ are displacements of pore fluids relative to rock skeleton along the direction of z, and the superscript '.' denotes partial time derivative. $\tau_{ltx}, \tau_{ltz}, \bar{p}_{lz}, l = 1,2$ are the total stresses tensor acting on rock skeleton along the directions of x and z, the effective pressure of pore fluids along the direction of z, respectively. $l = 1,2$ represent the porous media of the top and bottom layers, respectively.

3.3 COEFFICIENT EQUATIONS

Taking the functions of incident and reflected waves (equations 1 and 2) into the expressions of displacement and stress (equations 6-11), the boundary conditions for top medium can be expressed as equation 14. Similarly, that for bottom medium also can be obtained in the equation 15.

$$\mathbf{t}(\mathbf{0}) = \left[\dot{u}_{1sz}\ \dot{u}_{1sx}\ \dot{\mathrm{W}}_{1fz}\ \tau_{1tz}\ \tau_{1tx}\ \bar{p}_{1z}\right]^{T} = (i\omega)^2 \cdot \{\mathbf{Ip}\, A_0 + \mathbf{B}\cdot\mathbf{A}\}, \quad (14)$$

$$\mathbf{t'}(\mathbf{0}) = \left[\dot{u}_{2sz}\ \dot{u}_{2sx}\ \dot{\mathrm{W}}_{2fz}\ \tau_{2tz}\ \tau_{2tx}\ \bar{p}_{2z}\right]^{T} = (i\omega)^2 \cdot \mathbf{C}\cdot\mathbf{A}, \quad (15)$$

$$\mathbf{A} = \left[A_{11}\ \ A_{12}\ \ A_{13}\ \ A_{21}\ \ A_{22}\ \ A_{23}\right]^{T}. \quad (16)$$

Combining equations 13, 14 and 15, the equation of reflection and transmission coefficients represented by the ratio of seismic wave's amplitudes can be deduced,

$$(\mathbf{B} - \mathbf{C})\mathbf{R} = -\,\mathbf{Ip}, \quad (17)$$

$$\mathbf{R} = \left[\frac{A_{11}}{A_0}\ \frac{A_{12}}{A_0}\ \frac{A_{13}}{A_0}\ \frac{A_{21}}{A_0}\ \frac{A_{22}}{A_0}\ \frac{A_{23}}{A_0}\right]^{T}. \quad (18)$$

The coefficients solved above are relative to the amplitudes of seismic waves. Using the relation between the ratio of displacement amplitudes **r** and the ratio of seismic wave's amplitudes **R**, the equation of reflection and transmission coefficients can furtherly be modified as follows. For incident SV-wave, we only need to replace **Ip** with **Is** in the equation 19.

$$(\mathbf{B} - \mathbf{C})\mathbf{D}^{-1}\mathbf{r} = -\,\mathbf{Ip}, \quad (19)$$

$$\mathbf{D} = diag\left[\frac{vp_{11}}{vp_{11}}\ \frac{vp_{11}}{vp_{12}}\ \frac{vp_{11}}{vp_{13}}\ \frac{vp_{11}}{vp_{21}}\ \frac{vp_{11}}{vp_{22}}\ \frac{vp_{11}}{vp_{23}}\right]. \quad (20)$$

Where, the symbol diag[ ] denotes diagonal matrix, and the specific expression of the parameters B, C, **Ip**, **Is** in equation 19 can be referred to APPENDIX A.

4. POROUS MEDIUM MODEL

For furtherly analyze the influence of the porosity, pore fluids and incident anlge on reflection and transmission coefficients, a porous medium model and its equivalent model are established. The porous medium saturated with a fluid is separated by a plane surface with unconsolidated sandstone in the top layer and tight mudstone in the bottom layer. The detailed description is as follows.

4.1 ROCK SKELETON AND PORE FLUID PARAMETERS

For porous medium, the change of porosities will lead to the variation of the bulk and shear moduli of rock skeleton. The quantitative relationship among the porosity, the bulk moduli of rock skeleton and mineral grain are described by equation 21, and the similar relationship for the shear moduli is shown in equation 22 [Walton, 1987; Pride and Berryman, 2003; Zhao et al.,2015].

$$K_d = (1.0 - f)\ K_s \Big/ (1.0 + c\cdot f)\,, \quad (21)$$

$$\mu_d = (1.0 - f)\ \mu_s \Big/ (1.0 + c\cdot f)\,. \quad (22)$$

Where, K_s and μ_s are the bulk and shear moduli of mineral grain [Tosaya, 1982; Carmichale, 1989; Blangy, 1992], as shown in Table 1. K_d and μ_d are the bulk and shear moduli of rock skeleton, and f is porosity. The parameters c for sandstone and mudstone media are 6 and 4, respectively.

Properties	K_s (GPa)	μ_s (GPa)	ρ_s (kg/m^3)
Quartz (Up)	37	44	2650
Clay (Bottom)	25	9	2550

TABLE 1. Mineral grain parameters. Here, ρ_s denotes the density of mineral grains.

The bulk and shear moduli of rock skeleton varying with porosities are as shown in Figure 2. The red and green lines represent rock skeletons of porous media for sandstone in the top layer and for mudstone in the bottom layer, respectively.

The existence of pore fluids in underground medium will have an important effect on the propagation of seismic waves. In order to analyze the influence of different pore fluids on the characteristics of reflection and transmission coefficients, the bulk modulus and density of gas, oil and brine are given in Table 2 [Tuncay and Corapcioglu, 1996; Rubino and Holliger, 2012; Zhao et al., 2015].

Pore fluids	*Gas*	*Oil*	*Brine*
K_f (GPa)	0.012	2.1	3.0
ρ_f (kg/m^3)	78.0	940	1050

TABLE 2. Pore fluid parameters. Where, K_f and ρ_f represent the bulk modulus and density of pore fluids, respectively.

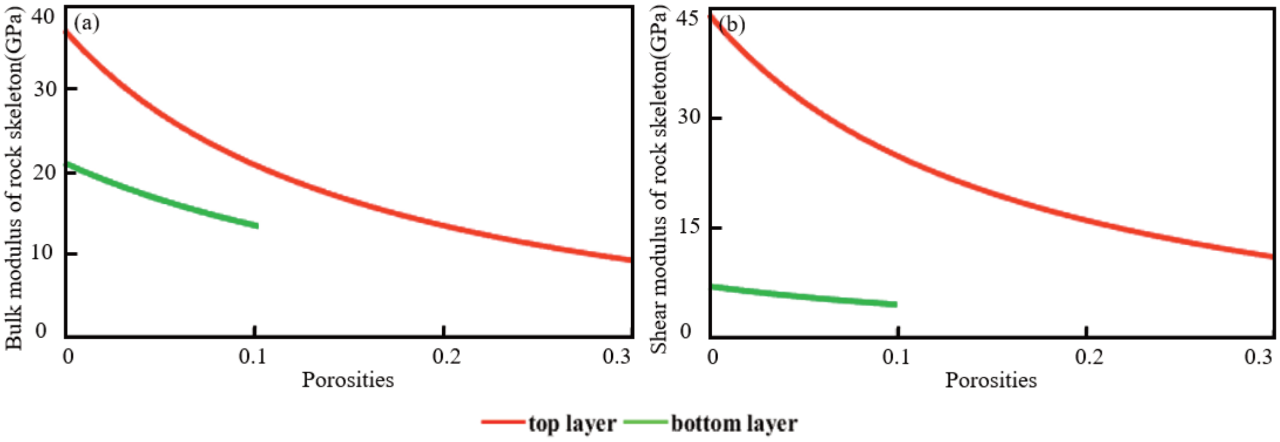

FIGURE 2. The variation of the bulk modulus (a) and shear modulus (b) of rock skeleton with porosities.

4.2 EQUIVALENT MODEL

For verifying the correctness of the equation and comparing the difference of the coefficients between the equivalent and porous media, a solid model which is equivalent to the porous medium model with sandstone (the porosity is 0.3) in top layer and mudstone (the porosity is 0.05) in bottom layer is established. The pore fluids filled in both top and bottom layers are all brine. The parameters are shown in Table 3.

Properties	vp (m/s)	vs (m/s)	ρ (kg / m^3)
Sandstone	5592	3767	2170
Mudstone	3390	1625	2523

TABLE 3. Equivalent medium model. Where, vp, vs and ρ represent equivalent P–wave velocity, S–wave velocity and density, respectively.

5. NUMERICAL RESULTS AND DISCUSSION

The pore shape, pore size and the properties of pore fluids all affect the propagation of seismic waves in porous medium. Studying and identifying pore fluids filling from underground medium is the ultimate aim of oil and gas exploration. Basis on this consideration, the characteristics of reflection and transmission coefficients at the interface of porous medium under different pore fluids filling and different porosities are analyzed, respectively.

5.1 DIFFERENT PORE FILLING

Based on the model established in the fourth part, the porosities are set 0.3 in the top layer, and 0.05 in the bottom layer. The pore fluids filling are gas, oil and brine in the top layer, and brine in the bottom layer, respectively. Figure 3 shows the variation of reflection and transmission coefficients with incident angle under the conditions of gas, oil and brine filling, respectively. In Figure 3, (a), (c) and (e) are reflection coefficients of fast P-, SV- and slow P-waves, respectively. (b), (d) and (f) are transmission coefficients of fast P-, SV- and slow P-waves, respectively. The red, green and blue lines represent reflection or transmission coefficients under the conditions of gas, oil and brine filling, respectively. The black line denotes the coefficients obtained from the equivalent model.

From Figure 3, we can draw the following conclusions. (1) Compared with reflection and transmission coefficients of the P- and SV-waves in the equivalent medium (black lines in Figures 3a-3d), the values of reflection and transmission coefficients of the fast P- and SV-waves in the porous medium (red, green and blue lines in Figures 3a-3d) are reduced, that is, the existence of pore fluids hinders the reflected and transmitted ability of seismic waves at the interface. (2) The bulk modulus (and density) of gas is quite different from that of oil or brine (Table 2), which leads to different characteristics of reflection and transmission coefficients at the interface of porous medium (Figures 3a-3d). This phenomenon can be used to identify gas bearing reservoirs. (3) The values of reflection or transmission coefficients of slow P-wave are very small, and the corresponding coefficients under the conditions of different pore fluids filling also have obvious differences (Figures 3e and 3f).

5.2 FFERENT POROSITIES

Based on the model established in the fourth part, we also set the brine filling in both top and bottom porous media. The porosities are, respectively, 0.1, 0.2 and 0.3 in the top layer, and 0.05 in the bottom layer.

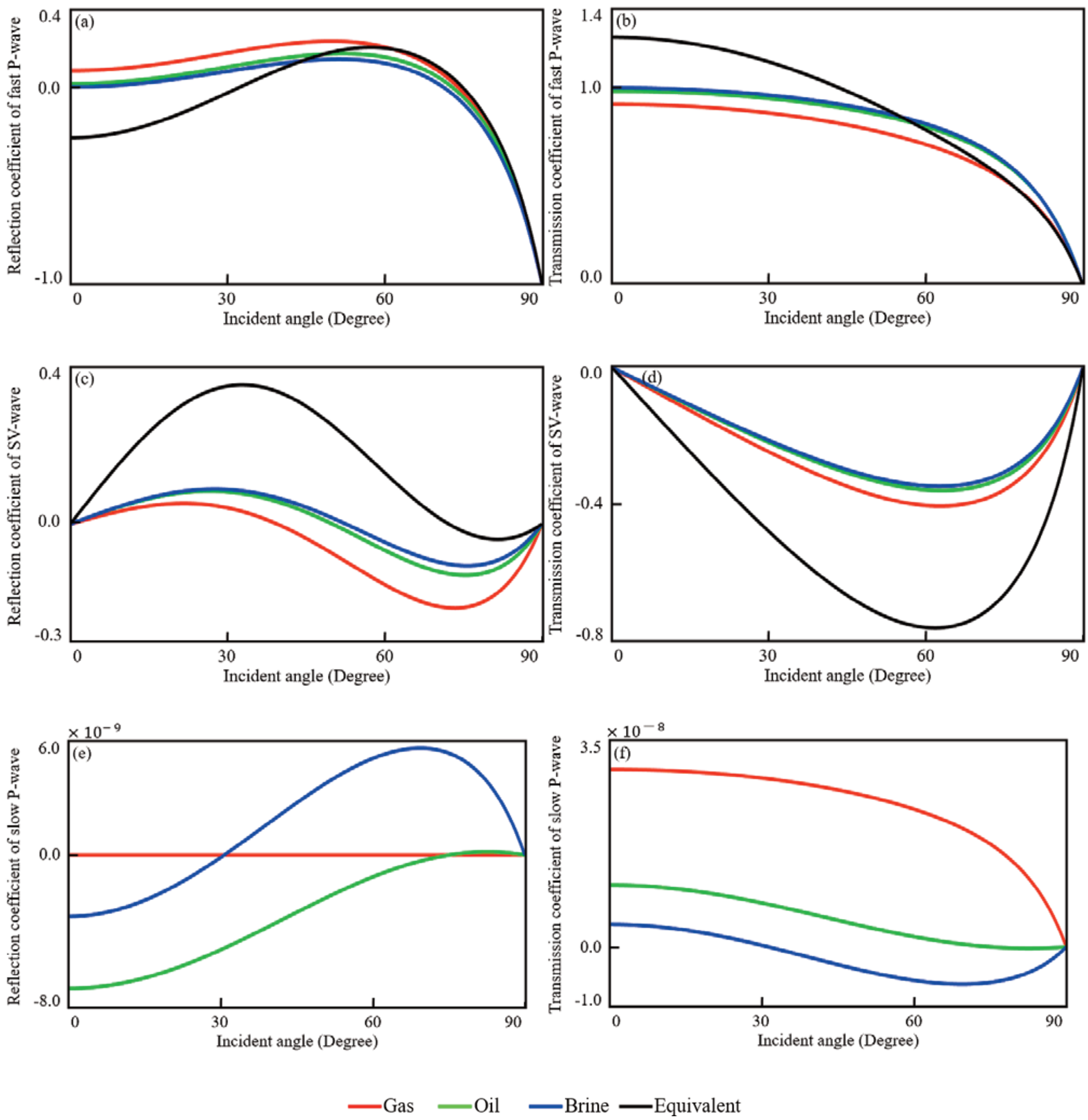

FIGURE 3. The variation of reflection and transmission coefficients with incident angle under the conditions of different pore fluids filling

Figure 4 displays the variation of reflection and transmission coefficients with incident angle at the interface of porous medium under the conditions of different porosities. In Figure 4, (a)-(f) are the same as in Figure 3. The red, green and blue lines represent the coefficients under the porosities of 0.1, 0.2 and 0.3, respectively. The black line denotes the coefficients obtained from the equivalent model.

According to Figure 4, some meaningful conclusions can be obtained. (1) The volume of pore fluids will expand and the absolute values of reflection and transmission coefficients of fast P- and SV-waves will decrease at the interface with the increasing of porosities (incident angles below 30 degree in Figure 4a). That is to say, higher porosities can further weaken the reflected and transmitted capability of fast P- and SV-waves, which again confirms the conclusions obtained in Figure 3. (2) Within the range of incident angle less than 45 degrees, the reflection coefficient of fast P-wave corresponding to the high porosity sandstone (blue line in Figure 4a) is basically unchanged, while that corresponding to the low porosity sandstone varies greatly (red line in Figure 4a) with incident angle, and the characteristics of the reflected SV-wave also have

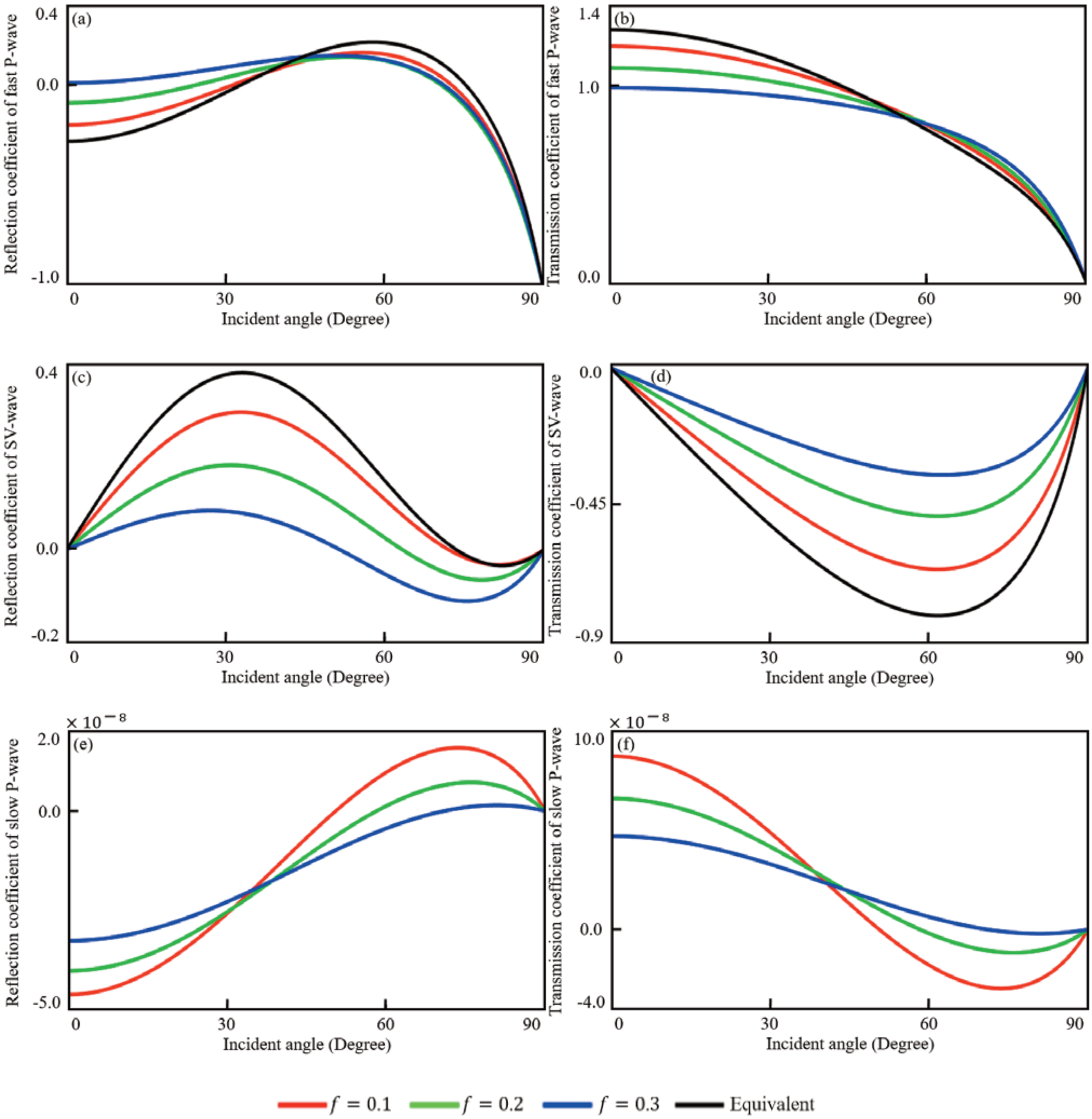

FIGURE 4. The variation of reflection and transmission coefficients with incident angle under the conditions of different porosities.

the similar phenomenon. We can qualitatively identify the porosities of sandstone porous medium using the variation characteristics of reflection and transmission coefficients of fast P- or SV-waves with incident angle. (3) Due to the existence of the pore and pore fluids, the reflected and transmitted slow P-waves are produced at the interface of porous medium. Although the values of reflection and transmission coefficients of slow P-waves are very small, the influence of porosities on that is relatively large (Figures 4e and 4f).

CONCLUSION

The variation characteristics of reflection and transmission coefficients with incident angle at the interface of porous medium saturated with an ideal fluid are studied. Considering the influence of porosities on the parameters of rock skeleton, a porous medium model, the bulk and shear moduli of rock skeleton of which vary with porosities, is established. The numerical analysis shows that the increase of porosity and the existence of pore fluids will reduce the values of reflection and transmission coefficients, and weaken the reflected and transmitted abilities of fast P- and SV-waves at porous medium interface. The characteristics of reflection coefficients of the fast P- and SV-waves corresponding porous medium saturated with gas or oil are obviously different, which can be used to identify gas and oil (or brine) bearing in the reservoirs. The porosities of porous sandstone medium can be qualitatively distinguished by reflected P- and SV-wave.

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