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CBM Reservoir Rock Physics Model and Its Response Characteristic Study

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ABSTRACT The rock physics model of coalbed methane (CBM) reservoir is significant for the study of CBM content. However, because of the adsorption and dissociation of the CBM reservoir, it is difficult to establish models. In addition, the studies on rock physics modeling of the CBM reservoir are scarce. This paper proposes the basic modeling process. First, the coal rock minerals and methane in adsorbed state are used to calculate elastic parameters of coal rock matrix. Then, the differential equivalent medium model is used to get elastic parameters of the dry rock skeleton. The free methane is mixed with water, and finally the Gassmann equation is applied to obtain elastic parameters of the CBM reservoir model. The study on the CBM reservoir rock physics model's response characteristics has found that there is a sensitive negative correlation between CBM content and P-wave velocity and density. The higher CBM content goes with larger absolute values of intercept, gradient, and seismic amplitude, because their seismic attributes are more sensitive to higher CBM content, whereas the response characteristics are opposite with the lower CBM content. The relationship among the CBM content and absolute values of intercept, gradient, and seismic amplitude in the real data of Qinshui Basin is largely consistent with the response characteristics of the established rock physics model, indicating that the CBM reservoir rock physics model proposed in this paper has a certain feasibility, and the response characteristics of its intercept, gradient, and seismic amplitude are more sensitive to predicting CMB reservoirs.

INDEX TERMS CBM reservoir, rock physics, intercept, gradient, amplitude attribute, sensitive.

I. INTRODUCTION

Coalbed Methane (CBM) is a kind of unconventional and self-generation and self-storage natural gas occurred in coal seams. China has the third largest CBM reserves in the world and has great potential for CBM development and utilization [1]. At present, much progress has been made in the studies on CBM reservoirs. For example, Peng *et al.* [2] proposed a theory for detecting enrichment areas targeting at cleats and fractures coalbed with the AVO technique. Wang [3] put forward a way to use changing patterns of seismic frequency spectral to analyze the reservoir characteristics and applied the method to predict CBM reservoirs, the changing patterns of seismic frequency spectral are sensitive to CBM content. Qi and Zhang [4] introduced seismic multi-attribute fusion based on D-S evidence theory to predict CBM enrichment areas. Wang *et al.* [5] carried out CSAMT exploration for the CBM enrichment areas in the north Qinshui Basin. Chen *et al.* [6] studied AVO response characteristics in CBM enrichment areas and proposed that the density is more sensitive to CBM content, which might indicate CBM content and shear elasticity indicated permeability. Gao *et al.* [7] studied the AVO response of CBM with small offset. Andrew and Randall [8] held that 3D seismic exploration could provide effective information for CBM reservoir identification.

The rock physics can be used as a vehicle to connect seismic data and reservoir parameters. A reasonable rock physics model can provide necessary data for seismic forward modeling and seismic inversion, and plays a very important role in inversion and interpretation of seismic data [9]–[12]. However, CBM is considerably different from conventional natural gas. More than 90% of CBM is absorbed in the internal surface of the coal pores and cracks and a small amount of methane exists as free state. Currently, there is lack of studies on CBM reservoir rock physics modeling. Liu [13] has verified the feasibility of using seismic techniques to predict CBM reservoirs through calculating the sensitive seismic velocity variation caused by CBM adsorption capacity. Chen *et al.* [14], [15] found that there was a sensitive negative correlation between methane content and its P- and S-wave velocity and density and held that such sensitive relationship was intrinsic, inherent and regular within reservoirs.

CBM occurrence is mainly in absorbed state and small amounts of methane are in free state. On this basis, this paper has put forward the modeling process of CBM rock physics. The results indicate that there is a sensitive negative correlation between methane content and P-wave velocity and density. When the methane content is higher, the CBM reservoir rock physics model has the sensitive characteristics of larger absolute values of intercept, gradient and seismic amplitude, while the lower methane content goes with the opposite response characteristics. The sensitive relationship between Qinshui Basin's actual methane content, absolute values of gradient and seismic amplitude is basically same with the model's sensitive response characteristics in this paper.

II. METHODOLOGY

According to CBM occurrence state characteristics, the CBM in absorbed state is taken as the mineral composition of coal and rock in this paper. The Voigt-Reuss-Hill average [16] is used to calculate elasticity modulus of rock and coal matrix. Then, the elasticity modulus of the dry rock skeleton can be obtained by differential equivalent medium (DEM) model [17]–[20] which selects coal and rock matrix as the main phase of the dry rock skeleton and gradually uses the fractures to fill the dry rock skeleton until the volume ratio of two-phase medium is satisfied. Next, the Reuss formula is used to mix the methane in free state with water to form pore fluid. Finally, the elastic parameters of CBM reservoir model can be calculated by Gassmann equation.

A. Voigt-Reuss-Hill AVERAGE

Voigt-Reuss-Hill average can get the equivalent elastic modulus of isotropic medium [16]. Since the methane in adsorbed state is assumed to be the mineral composition of coal and rock matrix, the model can be used to calculate the elastic parameters of coal and rock and the methane in adsorbed state. The formula is as follows:

$$M_{VRH} = \frac{M_V + M_R}{2} \tag{1}$$

In which, $M_V = \sum_{i=1}^{N} f_i M_i$ and $\frac{1}{M_R} = \sum_{i=1}^{N} \frac{f_i}{M_i}$. M_i refers to the elastic modulus of No. i component, f_i refers to the volume content of No. i and M_{VRH} refers to the elastic modulus of mixed minerals.

B. DIFFERENTIAL EQUIVALENT MEDIUM (DEM)

Differential equivalent medium theory is to add fillings to the solid phase to stimulate the two-phase mixture [17]–[19]. The filling process continues until the volume ratio of two-phase medium is satisfied. DEM model's equivalent modulus depends on the adopted ways. In general, the results are different when using No.1 material as the main phase and No.2 material as fillings and using No.2 material as the main phase and No.1 material as the fillings. Based on the formation process of CBM reservoir, the coal and rock matrix is chosen as the main phase and the fractures are used as the fillings to get the elastic modulus of the dry rock skeleton [20].

Berrymann [21] has built the coupled differential equations about bulk modulus and shear modulus, which are as follows:

$$(1-f)\frac{d}{df}[K^*(f)] = (K_2 - K^*)P^{(*2)}(f) \tag{2}$$

$$(1-f)\frac{d}{df}[\mu^*(f)] = (\mu_2 - \mu^*)Q^{(*2)}(f) \tag{3}$$

In which K^* is the bulk modulus of the main phase and μ^* is the shear modulus of the main. K_2 and μ_2 refer to the bulk modulus and shear modulus of the fillings respectively. f is the volume content of the filling. P and Q are shape factors. *2 indicates the filling's affecting factor in elastic modulus of matrix.

C. Gassmann EQUATION

In the rock physical analyses of seismic data, the key is to use one kind of fluid saturated rock seismic velocity to predict another kind of fluid saturated rock seismic velocity, or use the rock skeleton to predict fluid saturated rock seismic velocity and vice versa, which is called fluid substitution. Gassmann equation is the basis for fluid substitution. In this paper, the Reuss formula is used to mix the methane in free state with water to form fluid-saturated pore fluids. Then Gassmann equation can be used for fluid substitution in the dry rock skeleton with fractures and thus to calculate the elastic parameters of CBM reservoir model.

Considering the elastic modulus of the dry rock skeleton, the elastic modulus of solid particles and saturated pore fluid, Gassmann equation builds the formula to obtain the elastic modulus of fluid-saturated rock, which is as follows [22]:

$$\frac{K_{sat}}{K_m - K_{sat}} = \frac{K_{dry}}{K_m - K_{dry}} + \frac{K_f}{\phi(K_m - K_f)} \tag{4}$$

$$\mu_{sat} = \mu_{dry} \tag{5}$$

where K_{sat} refers to the bulk modulus of saturated rock, K_m refers to the bulk modulus of rock matrix and K_{dry} refers to the bulk modulus of the dry rock skeleton. ϕ refers to rock porosity. μ_{dry} and μ_{sat} refer to the shear modulus of the dry rock skeleton and fluid-saturated rock, respectively.

III. THE BUILDING PROCESS OF CBM RESERVOIR ROCK PHYSICS EQUIVALENT MODEL

As a type of double structure system, CBM reservoir is made up of pores and fissures and the porosity is usually lower

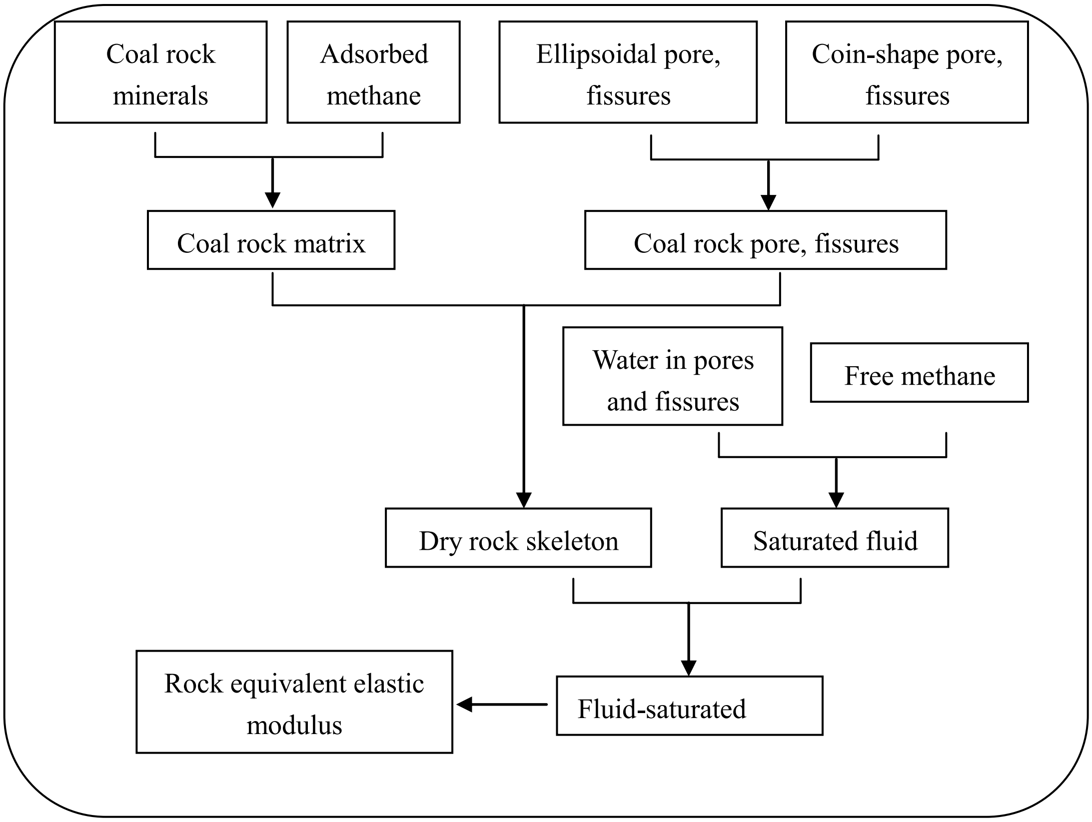

FIGURE 1. The building process of CBM reservoir rock physics.

than 10%. The methane is mainly stored in pores, and fissures are migration pathway of methane [22]. There are great difference between CBM and conventional natural gas. The conventional natural gas is storied in the reservoir in free state while the methane has adsorbed state and free state. About 90% of methane can be found in the internal surface of coal and rock pores and fissures in adsorbed state, and the methane in free state mainly exists in pores and fissures with better connectivity [2]. Therefore, this paper regards the methane in adsorbed state as the mineral composition of coal and rock and calculates the elastic modulus of coal and rock matrix equivalent medium. Then the methane in free state is mixed with water in fissures to form mixed fluid which will be filled into dry fissures. Finally, the fluid substitution is used for the model.

According to the above analyses of CBM reservoir characteristics, the CBM reservoir rock physics equivalent modeling process is given to obtain the equivalent elastic modulus of coal and rock matrix, dry rock skeleton and saturated rock. The detailed process is shown in Fig. 1.

The main steps of CBM reservoir rock physics modeling:

1) To take the methane in adsorbed state as the mineral composition of coal and rock and use V-R-H average to mix coal and methane in adsorbed state, the elastic parameters of rock and coal matrix can be obtained.

2) To add dry fissures of good connectivity to matrix by DEM model, the elastic modulus of dry rock skeleton can be obtained. The fissures are assumed to include ellipsoidal and coin-shaped fissures.

3) To fill the mixed fluid into dry fissures with good connectivity, the elastic parameters of fluid-saturated rock can be obtained. Then the CBM reservoir parameters such as P-wave velocity can be calculated, which are expressed by formula (6) and (7).

$$V_P = \sqrt{\frac{K + \frac{4}{3}\mu}{\rho}} \tag{6}$$

$$V_S = \sqrt{\frac{\mu}{\rho}} \tag{7}$$

In which V_P and V_S refer to P-wave and S-wave velocity, respectively. K, μ and ρ point to the volume content, shear modulus and density of fluid-saturated rock, respectively.

IV. RESPONSE CHARACTERISTICS ANALYSIS OF CBM RESERVOIR ROCK PHYSICS MODEL

The measured data of coal samples of Sihe Coal Mine in Qinshui Basin under high confining and high axial pressure in the laboratory are chosen as coal and rock parameters. The test instrument is MTS815 rock mechanics test system with the confining pressure of 14MPa and axial pressure of 10MPa. The results are as follows: the coal and rock bulk modulus $K_c = 5.21GPa$ and the density $\rho_c = 1.478g/cm^3$. The bulk modulus of the methane in adsorbed state

$K_g = 0.011GPa$ and the density $\rho_g = 0.065g/cm^3$. The shear modulus of coal and rock matrix $\mu = 2.27GPa$.

A three-layer geological model is designed whose roof and floor have the same rock elastic parameters that are common values of mudstone layer in coal measure strata. The P- and S-wave velocity and density are from the log information of several exploration wells in Qinshui Basin [23]. The middle layers are CBM reservoirs with different methane content. The geological model is shown in Table 1.

TABLE 1. CBM reservoir geological model.

Model	$V_p(km/s)$	$V_s(km/s)$	$\rho(g/cm^3)$
Roof	4.049	2.048	2.583
CBM reservoir			
Floor	4.049	2.048	2.583

The active porosity of main coal seams in Carboniferous-Permian in Qinshui Basin varies between 1.15% and 7.69%, mostly below 5% (Song et al., 2010). Therefore, the porosity of CBM reservoir is set as 5%. Based on CBM rock physics modeling process, the model is established to analyze the methane content's relationship with P-wave velocity, density, intercept, gradient and amplitude attribute.

A. THE RELATIONSHIP BETWEEN METHANE CONTENT AND P-WAVE VELOCITY AND DENSITY

Through the study of actual seismic data, Chen *et al.* [14], [15] have found that there is a sensitive negative correlation between methane content and its density and P-wave velocity, showing that the higher methane content goes with lower density and lower P-wave velocity, while the lower methane content goes with bigger density and bigger P-wave velocity. Fig. 2 shows the relationship between methane content and its P-wave velocity and density, which is obtained by the built CBM reservoir rock physics model. As shown in Fig. 2, the

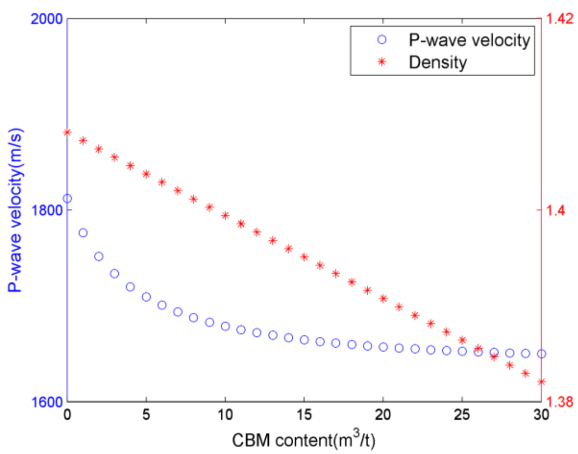

FIGURE 2. The relationship between methane content and P-wave velocity and density.

negative relationship between methane content and P-wave velocity and density is consistent with the above conclusion.

B. THE RELATIONSHIP BETWEEN METHANE CONTENT AND INTERCEPT AND GRADIENT

Shuey formula [24] is the simplified formula based on Zoeppritz equation, which is used to calculate different methane's corresponding CBM reservoir roof and floor reflective surface's intercept and gradient [25], [26]. The results are shown in Fig. 3. In Fig. 3(a), the roof reflective surface's gradient is negative, and the gradient is positive. As the methane content increases, the absolute values of intercept and gradient show an increasing trend. In Fig. 3(a), the floor reflective surface's gradient is positive and the gradient is negative. Their absolute values also increase with the increase of methane content.

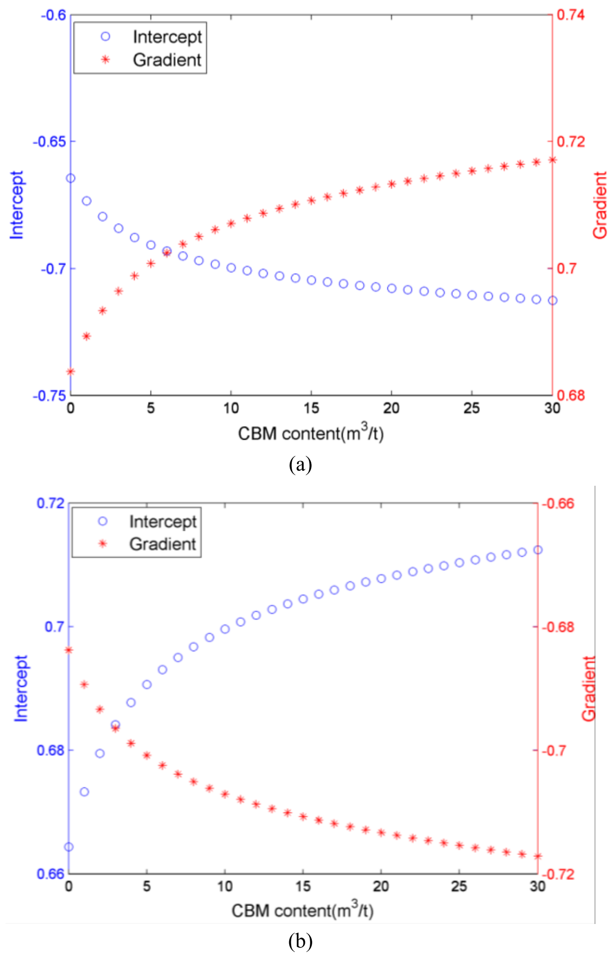

FIGURE 3. (a) The relationship between roof reflective surface's methane content and its intercept and gradient. (b) The relationship between floor reflective surface's methane content and its intercept and gradient.

C. THE RELATIONSHIP BETWEEN METHANE CONTENT AND AMPLITUDE

Because the geological model's roof and floor reflective surfaces [27]–[30] have same properties, this paper only discusses the roof reflective surface's AVO response characteristics. To set the methane contents of middle layers are 0,

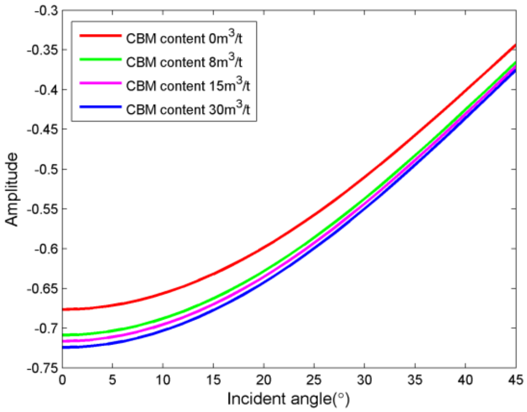

FIGURE 4. **The relationship between roof reflective surface's amplitude and incident angle.**

TABLE 2. **CBM drilling information of this exploration area.**

Well number	Inline	Xline	CBM content（m^3/t）
Well-1	244	265	18.9
Well-2	216	400	7.97
Well-3	190	710	13.39
Well-4	185	1212	10.27
Well-5	185	1038	12.66
Well-6	330	914	15.45
Well-7	326	1058	25.7
Well-8	330	1221	18.8
Well-9	185	874	25.5
Well-10	34	543	5.39

8, 15 and 30, respectively, AVO response characteristics of the roof reflective surface are shown in Fig. 4.

Fig. 4 shows that when the methane content is constant, the absolute value of seismic amplitude decreases as the incident angle increases. When the incident angle is same, the absolute value of seismic amplitude increases with the increase of methane content. Above all, the proposed CBM reservoir rock physics model's methane content is sensitive negatively correlated with P-wave velocity and density. The CBM reservoir with high methane is with the sensitive response [31]–[33] characteristics of bigger absolute values of intercept, gradient and seismic amplitude. When the methane content is low, these sensitive response characteristics are opposite.

V. CASE STUDY

A. WORK AREA OVERVIEW

Qinshui Basin lies in the mid-south of Shanxi province. It is one of the major coal distribution areas in North China and stores abundant CBM resources. The stable No.3 coal seam in this area is chosen as the research object. The No.3 coal seam is located in the Lower Permian Shanxi Formation (P1s). Its thickness is between 4.64m and 5.45m. The average thickness is 4.72m. The roof and floor are made up of mudstone and sandy mudstone. There are 10 CBM exploration wells in this area, its location and CBM content shown in Table 2.

B. RESPONSE CHARACTERISTICS OF INTERCEPT AND GRADIENT

The Well-10 with the minimum methane and the Well-7 with the maximum methane are selected to analyze the characteristics of the intercept and gradient by changing their CMP gathers into angle gathers, as shown in Fig. 5.

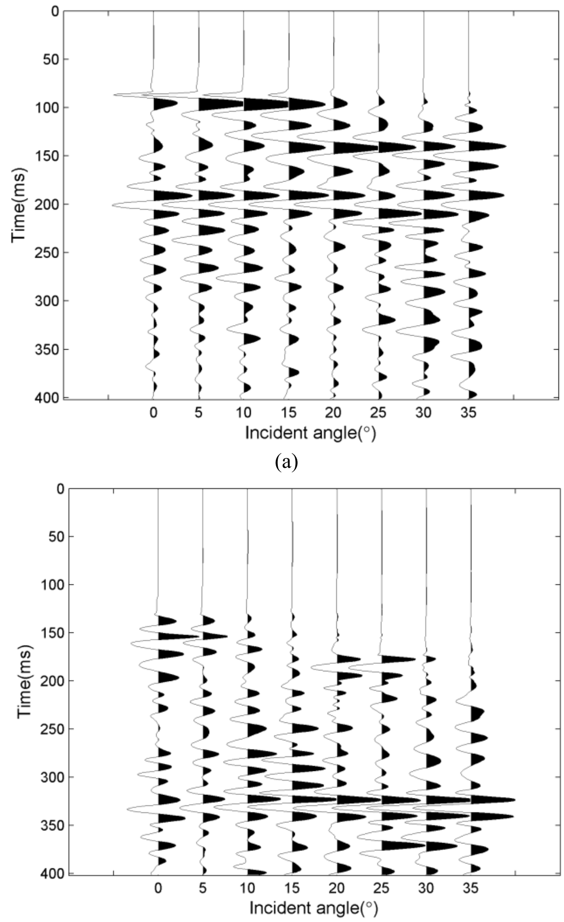

FIGURE 5. **(a) Angle gathers of Well-10. (b) Angle gathers of Well-7.**

Fig. 6 is the AVO response near the well. Well-10's absolute values of intercept and gradient are smaller while Well-7's absolute values of intercept and gradient are bigger. The sensitive response characteristics comparison indicates that when the methane content is lower in real seismic data, the absolute values of intercept and gradient are smaller. When the methane content is higher, the absolute values of intercept and gradient are bigger. Therefore, the sensitive response characteristics of intercept and gradient in the real seismic data are in consistent with the proposed CBM reservoir rock physics model's sensitive response characteristics.

C. AMPLITUDE CHARACTERISTICS

Fig. 7 shows the No. 3 coal seam's amplitude attributes. The higher methane content in CBM reservoir rock physics

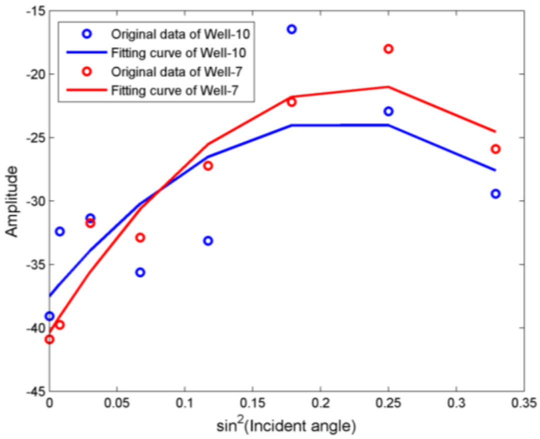

FIGURE 6. AVO response to Well10 and Well7.

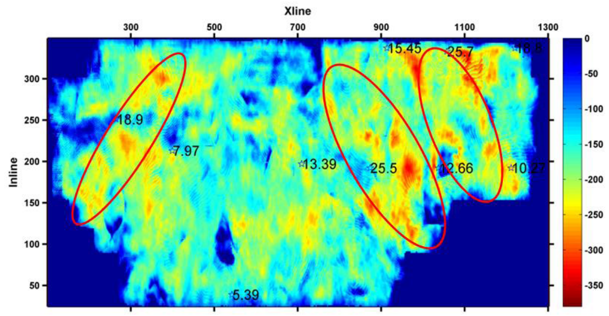

FIGURE 7. Amplitude attributes of No. 3 coal seam.

model, the bigger the absolute value of amplitude, the absolute value of amplitude is sensitive to CBM content. On this basis, the work area is fixed as the area with higher methane content, which is an elliptical area in Fig. 7.

Through comparison between the result and the known borehole data, there are eight wells whose methane contents are more than $10m^3/t$ and the absolute values of amplitude are bigger. The rest two wells' methane contents are less than $10m^3/t$ and the absolute values of amplitude are smaller. The amplitude sensitive response characteristics in real seismic data are in accordance with the sensitive characteristics of CBM reservoir rock physics model.

Above all, the sensitive response characteristic analyses of CBM reservoir rock physics model and the real seismic data indicate that the area with higher methane content is with higher absolute values of intercept, gradient and amplitude. Absolute values of intercept, gradient and amplitude are sensitive to CBM content. The application of Qinshui Basin's real data has verified the feasibility of the CBM reservoir rock physics model in the paper, and its sensitive response characteristics can be used as a reference to predict CBM reservoirs.

VI. CONCLUSIONS

(1) This paper has proposed the rock physics modeling process of CBM reservoir. Firstly, the coal and rock minerals and methane in adsorbed state are used to calculate the elastic parameters of coal and rock matrix. Then the elastic modulus of the dry rock skeleton is obtained by DEM model. Next, the methane in free state is mixed with the water. Finally, Gassmann equation is adopted to get the elastic parameters of the model of CBM reservoir.

(2) The study on the sensitive response characteristics of CBM reservoir model has found that there is sensitive negative correlation between methane content and P-wave velocity and density. That is, the higher methane content goes with larger absolute values of intercept, gradient and seismic amplitude. Absolute values of intercept, gradient and amplitude are sensitive to CBM content. When the methane content is lower, the sensitive response characteristics are opposite.

(3) For the real seismic data of Qinshui Basin, the sensitive relationship between methane content and the absolute values of intercept, gradient and seismic amplitude is basically consistent with the proposed model's sensitive response characteristics, verifying the feasibility of the proposed CBM reservoir rock physics model. Moreover, the sensitive response characteristics of intercept, gradient and seismic amplitude have certain guiding significance to CBM reservoir prediction.

(4) The use of DEM model to calculate the elastic modulus of the dry rock skeleton remains to be further improved for CBM reservoirs with complex pore types.

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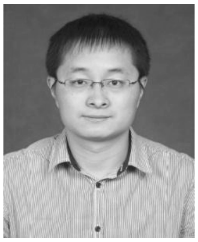

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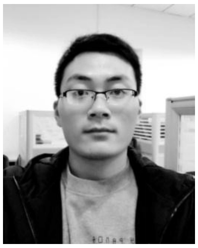

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