2011 Xi’an International Conference on Fine Geological Exploration and Groundwater & Gas Hazards Control in Coal Mines

AVO Modeling for Coal Seam Prediction

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Abstract

Amplitude versus offset (AVO) technology is an important tool and a leading skill to predict the fluid in reservoir and to identify the lithology. AVO was mainly used to predict the hydrocarbon reservoir. Its application in coal AVO identification technology is just beginning. The key to AVO technology is how to make a reasonable model for interpretation, and then to analyze the actual prestack seismic data. The conventional AVO forward model is based on two-layer model, and it cannot reflect thin interbed reservoirs or inhomogeneous medium. In order to interpret prestack seismic response of interbed coal seams, we construct AVO models by using the full well log data, which we compute the accurate reflection coefficient with different incidence angle, pick up the AVO Intercept and Gradient (I&G) with different frequency, and map the I &G cross-plot. This paper takes Gaojiabu coal field data as an example to make AVO forward models and AVO I&G cross-plots. Based on AVO cross-plots, we established a coal discriminator to distinguish the coal seam, carbonaceous-mud and argillaceous-carbon. Furthermore, we compared the AVO I&G cross-plot made from well log model and two-layer model.

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Selection and peer-review under responsibility of China Coal Society

Keywords: coal identification; AVO forward model; two-layer model; synthetic seismogram; Intercept & Gradient cross-plots

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1. Introduction

With the rapid growth of Chinese economy, the demands for oil and coal as the main consumer energy is increasing. With the increasing of deeper coal seam mining, the mining risk increases and the seismic resolution reduces gradually, which cause the loss of accuracy and effectiveness of available information. Then it urgently needs more advanced technology for predicting coal ranks, methane content, water flooding, temperature, pressure, etc. in coal seam, to guide coal mining. AVO is one of the advanced technologies for identifying lithology and predicting reservoir in energy resource exploration. Now AVO technique is applied to coal seam seismic exploration. Although the lithology identification research of coal seam has been set up (Zhang et al., 2009), the existent AVO method mainly based on two-layer model and approximate formula for reflection coefficient. This method doesn’t consider the thin interbed coal seam, and assumes that the elastic parameters of coal and its surrounding rock have little differences, which leads to the error of AVO forward modeling and inversion (Ma & Morozov, 2010). In this paper we use the full well log data and make a well log model to do AVO forward model. Our study focuses on identifying coal quality laterally, and finally we establish the discriminator to distinguish the varieties of coal ranks from AVO model. It finally provides the scientific method for identifying coal features and the fluid features in surrounding rocks.

2. Constructing two-layer model

This research starts from the three wells data of Well G1-4, Well G12-3 and Well G21-1 with measured S-wave logs, which come from Gaojiabu area of Binchang Coal Bureau in Shaanxi Province, China. The distance between Well G1-4 and G21-1 is 1.5 km. While the distance between G21-1 and G12-3 is 14.5 km. These three wells nearly located in a same 2D seismic line. The rank of coal varies among three wells. The depth of each well obtained from drilling is displayed in Table 1 (Zhang et al., 2009).

Table 1 The depth of coal seams

<table>
<thead>
<tr>
<th>Well name</th>
<th>Wellhead’s elevation/m</th>
<th>Depth range of coal seam/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1-4</td>
<td>888.07</td>
<td>668-680.5</td>
</tr>
<tr>
<td>G12-3</td>
<td>1136.28</td>
<td>992-998.6</td>
</tr>
<tr>
<td>G21-1</td>
<td>1054.82</td>
<td>845-858.5</td>
</tr>
</tbody>
</table>

To study the AVO attributes of two-layer model, it needs to pick up the P-wave velocity \(\alpha\) (km/s), S-wave velocity \(\beta\) (km/s) and density \(\rho\) (g/cm\(^3\)) firstly. It means pick up the data of blocked well logs (Table 2). We construct the two-layer model including the coal seam roof and floor from blocked well logs. Then we use Shuey’s proximate formula (Shuey, 1985) to calculate reflection coefficient \(R_{sh}\) and \(R_{zoe}\) with different incidence angle (0°-30°) and AVO intercept \(I_{sh}\) and gradient \(G_{sh}\). At the same time, we use Zoeppritz equation (Zoeppritz, 1919) to calculate exact reflection coefficient \(R_{zoe}\) within incidence angle 0°-30°, and get the \(I_{zoe}\) and \(G_{zoe}\) by linear fitting from \(R_{zoe}\)-sin\(^2\)\(\theta\) plot. Fig. 1 illustrates the relation of \(R\)-sin\(^2\)\(\theta\) by using Shuey’s approximation and Zoeppritz equation. Considering large contrast between coal seam and cap rocks, the use of Zoeppritz equation will get more accurate AVO intercept and gradient than that from Shuey’s formula. It can also be seen from Table 2 that the density of coal seam of G21-1, G1-4 and G12-3 decreases in turn, which means the coal ranks decreases in turn.

Table 2 The elastic parameters and AVO I&G for two-layer model
### Well name | Rock stratum | P-wave velocity/km·s^{-1} | S-wave velocity/km·s^{-1} | Density/g·cm^{-3} | Gradient | Intercept
--- | --- | --- | --- | --- | --- | ---
G1-4 | Overlying sandstone | 2.695414 | 1.476832 | 2.737750 | 0.808926 | -0.457607
| Underlying coal seam | 2.069191 | 0.488098 | 1.391043 | --- | --- |
G12-3 | Overlying sandstone | 3.035098 | 1.577157 | 2.532255 | 0.637499 | -0.383315
| Underlying coal seam | 2.396594 | 0.649521 | 1.468897 | --- | --- |
G21-1 | Overlying sandstone | 2.456991 | 1.191039 | 2.312882 | 0.630873 | -0.501684
| Underlying coal seam | 1.737208 | 0.245638 | 1.164952 | --- | ---

Fig. 1 The reflection coefficient versus the incidence angle \((R(\theta)-\sin^2\theta)\) for two-layer model by using Zoeppritz equation (black symbols) and Shuey’s approximation (blue symbols).

### 3. Constructing well log model and AVO attributes analysis based on accurate formula for reflection coefficient

When constructing well log model, we transform well log data from the depth domain into the time domain, and the sample interval is 0.1ms so that more detail information of logs can be kept in time domain. Then we calculate the reflection coefficient with different incidence angle based on Zoeppritz equation, and pick up the AVO gradient and intercept from the accurate reflection coefficient. In order to study how wavelet frequency influences the AVO attributes in the coal seam laterally, we convolve the reflection coefficients with 25 Hz, 30 Hz, 35 Hz, 40 Hz and 45 Hz Ricker wavelet respectively to get the synthesis seismogram. Fig. 3 compares the relation of accurate \(R-\sin^2\theta\) with different wavelet frequency in well log model and the relation of \(R-\sin^2\theta\) in two-layer model. It can be seen from the figure that \(R-\sin^2\theta\) of Well 1-4 and Well G21-1 maintain a good linear relationship. But for well G12-3, because of the existence of high-speed belt above the coal seam (Fig. 2), the elastic parameters have a significant
difference between the upper and lower layer of the interface. When the angle is relatively large, it no longer keeps the linear relationship. At this case, AVO intercept and gradient from Well G12-3 may not be compared with other two wells. So in order to rule out the influence of high-speed layer, we use the average data of the upper layer in two-layer model to replace high-speed belt data. Then make a calculation of the reflection coefficient and convolution, and compare it with the result of original data and the two-layer model (in Fig. 3, the colorized circles represent the result of changing high-speed belt data).

Fig. 2 Well log curves of P-wave velocity, S-wave velocity, density, sonic differential time and natural gamma, blocked curves and synthetic seismogram near the interface of coal seam (40Hz Ricker wavelet)

Comparing the three wells’ $R - \sin^2 \theta$ relations, it can be seen that the intercept decreases in order of G12-3, G21-1 and G1-4, which differs from the result of two-layer model completely. One of the advantages of well log model is that we may consider tuning effect at different wavelets, as the two-layer model doesn’t consider the effect of wavelet with different frequency or the effect of interlayer and thin
interbed layer. For example, for well G12-3, if we remove the high-speed belt in the model, it will cause a big change of the intercept and gradient, which also demonstrates the inaccuracy of two-layer model when it comes across the interbed layer. Comparing the effects of different wavelets in each well, we’ll find that the frequency of wavelet have little influence on the gradient, but have a great influence on intercept. The relation of $R \cdot \sin^2 \theta$ of well model also shows a great divergence in both intercept and gradient with the two-layer model. It indicates the error caused by two-layer model as well.

In the $I \& G$ cross-plot, on the basis of the varieties of coal ranks of the three wells, the coal discriminator is defined for distinguishing coal from carbonaceous-mud or argillaceous-carbon, which is marked with the black line in Fig. 4. It’s based on the Zoeppritz equation, and considers the effect of wavelet and the interlayer or thin interbed layer. It’s more accurate than the coal discriminator determined by two-layer model. Fig. 4 also shows the big difference of coal discriminators between two-layer model and well log model. Therefore, the use of two-layer model will lead to interpretation trap in coal and its wall rock discrimination.
4. Conclusions

The conventional AVO analysis is based on two-layer model. It doesn’t consider the effects of interlayer or thin interbed layer and the effect of wavelet with different frequency either. This caused large errors in the lithology prediction. While using the full well log data to make a well log model and calculate exact reflection coefficient, we may obtain more realistic and accurate AVO attributes. When making well log model, different frequency of wavelets should be used and sample rate should be small enough when converting well log from depth to time domain so that coal discriminator will be picked more accurate. By using well log AVO model, it is expected to provide solutions for the two problems arisen from thin interbed coal seam and the variation of coal quality laterally.

Acknowledgements

We appreciate Prof. Jianyuan Cheng of Xi’an Research Insitute of China Coal Technology & Engineering Group Corp for his valuable discussions. This work is supported by China 973 Program Grant 2006CB202208-4 and China NSFC Grant 40674041.

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