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Analysis of coal seam thickness and seismic wave amplitude: A wedge model

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ABSTRACT

Coal seam thickness is of great significance in mining coal resources. The focus of this study is to determine the relationship between coal seam thickness and seismic wave amplitude, and the factors influencing this relationship. We used a wedge model to analyze this relationship and its influencing factors. The results show that wave interference from the top and bottom interfaces is the primary reason for the linear relationship between seismic wave amplitude and wedge thickness, when the thickness of the wedge is less than one quarter of the wavelength. This relationship is influenced by the dominant frequency, reflection coefficients from the top and bottom boundaries, depth, thickness, and angle of the wedge. However, when the lateral shift between the reflected waves is smaller than the radius of the first Fresnel zone, the wedge angle and change in lithology at the top and bottom layers are considered to have little effect on the amplitude of the interference wave. The difference in the dominant frequency of seismic waves can be reduced by filtering, and the linear relationship between amplitude and coal thickness can be improved. Field data from Sihe coal mine was analyzed, and the error was found to be within 4% of the predicted seismic wave amplitude. The above conclusions could help predict the thickness of coal seam by seismic amplitude.

1. Introduction

Coal bed thickness is of great significance in mining coal resources. Coal thickness not only affects the evaluation of coal resources but also directly affects mine construction. Drilling interpolation is a common method used to predict coal seam thickness; however, this method produces inaccurate results between well locations (Peng et al., 2008; Mark et al., 2009). 3D seismic data provide dense horizontal sampling and abundant information on kinematics and dynamics (Zhong, 2001; Costain and Coruh, 2004; Li and Guo, 2007; Mark et al., 2009); therefore, seismic data is highly applicable to studying variations in coal seam thickness over large areas.

Many researchers have attempted to predict coal seam thickness using seismic data considering various aspects. Widess (1973) considered a zero-phase seismic wavelet and obtained the relationship between thin-bed thickness and reflection amplitude in a homogeneous medium. The amplitude of a reflection from a thin bed is, to the first order of approximation, equal to the wideness factor $4\pi Ab/\lambda_b$, where A is the amplitude of the reflection wave, b is the thickness of the bed, and λ_b is the (predominant) wavelength computed using the velocity of the bed. Kallweit and Wood (1982) proposed that the resolution limit of a seismic reflection wave is one quarter of the wavelength. If the thickness is less than the resolution, the wave amplitude shows a linear relationship with seam thickness. Tang (1987) proposed that the reflection coefficient of coal seams is larger than that of sandstone in oil field exploration, and therefore, the detection ability for coalbed thickness is higher. Tang's work serves as the basis for predicting seam thickness using amplitude attributes. However, the work ignores the influence of the angle of wedge. Dong et al. (2004) determined the relationship between coal seam thickness and seismic attributes according to forward simulation, including amplitude and frequency. When the thickness of the coal seam is 0–8 m, there is a monotone nonlinear relationship between amplitude and thickness. Meng et al. (2006) used a polynomial regression model to select attributes and predict coal seam thickness based on a back propagation artificial neural network. Four seismic attributes, average peak amplitude, kurtosis in amplitude, maximum absolute amplitude, and slope of instantaneous frequency, were selected to predict coal thickness. Peng et al. (2008) predicted coal seam thickness based on logging constrained seismic inversion and implied that impedance is close to coal thickness. Lu et al. (2016) used the P-wave impedance inversion to predict the thickness of a coal seam under the constraints of the horizons of the top and bottom interfaces of the coal seam. Yang et al. (2016) verified the approximation accuracy through numerical calculation and concluded that the errors in PP-wave reflection coefficients R_{PP} are generally

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smaller than 10% when the thin-bed thicknesses are smaller than one-eighth of the PP-wavelength.

These conclusions provide an important guide for the evaluation of coal seam thickness. However, not all methods agree and further analysis of the relationship between seismic wave amplitude and coal seam thickness is necessary. In practice, coal seam thickness cannot be easily derived using seismic data. In order to constrain the relationship between coal seam thickness and amplitude, we present a wedge model along with a staggered grid finite difference numerical simulation. We analyze the main factors effecting seismic wave amplitude. Then we predict coal seam thickness using seismic data from the Sihe Coal mine, and evaluate its validity.

2. Relationship between seam thickness and amplitude

2.1. Seismic wave propagation in a wedge model

The geometric parameters of the wedge model are as follows: the depth of the top interface, width, and maximum thickness of the wedge were 300 m, 500 m, and 60 m, respectively (Fig. 1). At the top of the model, 101 receivers were evenly distributed in the horizontal direction. The time discretization interval was 0.2 ms, and the grid spacing was 1 m in the horizontal and vertical directions. The source wavelet is a 50 Hz Ricker wavelet and medium parameters are shown in Table 1. A normal-incidence seismogram (Fig. 1) was simulated by staggered grid finite difference method. According to the normal reflection coefficient γ (Sheriff and Geldart, 1995), the reflection wave from the top interface has negative polarity. Similarly, a seismic wave incident to the bottom interface of the wedge results in a positive reflection coefficient, and hence the reflection wave polarity is also positive (Fig. 1). When the wavelet frequency *f* is 50 Hz, the seismic wavelength λ in the wedge is $\lambda = v_{p1}/f = 44$ m. When the thickness of the coal seam (11 m) is a quarter of the wavelength, the wave amplitude reaches maximum value as a result of mutual interference between reflection waves (Fig. 1). This phenomenon is known as the tuning effect, and thickness equal to a quarter of wavelength is also called the tuning thickness (Kallweit and Wood, 1982). When the coal seam thickness decreases, the superimposed amplitude also decreases.

Table 1
Properties of the wedge model. P-wave velocities and bulk densities were used for acoustic wave simulation. Since the reflected wave of the bottom interface is non-perpendicular, the reflection coefficient is not only related to the P-wave velocities and bulk densities, but also to the S-wave velocities.

Medium	Top	Seam	Bottom
P-wave velocity/$(\mathrm{m\cdot s^{-1}})$	$v_{p0} = 3000$	$v_{p1} = 2200$	$v_{p2} = 3400$
Bulk density/$(\mathrm{g\cdot cm^{-3}})$	$\rho_0 = 2.2$	$\rho_1 = 1.8$	$\rho_2 = 2.2$
S-wave velocity/$(\mathrm{m\cdot s^{-1}})$	$v_{s0} = 1730$	$v_{s1} = 1270$	$v_{s2} = 1962$
Acoustic impedance$(10^6\mathrm{Pa*s/m^3})$	$I_1 = 6.6$	$I_2 = 3.96$	$I_3 = 7.48$

We also simulated seismic records with different dominant frequencies, such as 30 Hz and 70 Hz. The reflected wave from the top interface has negative reflection coefficient. By extracting the minimum amplitudes of the reflection waves from the top interface of the wedge model, wave amplitudes could be observed to vary as a function of wedge thickness (Fig. 2). The relationship between wave amplitude and thickness is similar for wavelets with different dominant frequencies. With an increased dominant frequency, the tuning thickness becomes smaller. This result is also similar to that reported by Kallweit and Wood (1982). Other amplitudes show similar laws, such as the root mean square (RMS) amplitude, maximum amplitude, or average amplitude of troughs.

When the coal seam thickness is increased from 0 m to 11 m at a 50 Hz Ricker wavelet, the change in amplitude is monotonically decreasing. Most of the coal seams have thicknesses of less than 10 m, so the amplitude is sensitive to the thickness. When coal seam thickness is increased from 11 m to 21 m, the reflection amplitude gradually approaches a stable value, beyond which further increases in thickness have no effect. We established a wedge model (Fig. 3) to explain the phenomenon of interference and its influencing factors.

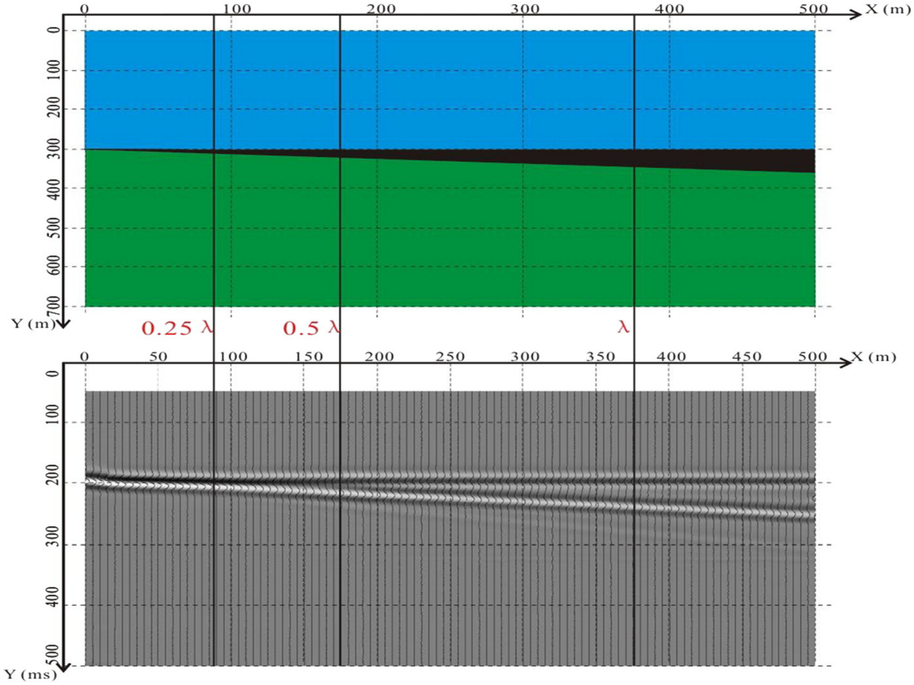

Fig. 1. A wedge model and its normal-incidence seismogram. The dominant frequency of the seismic wavelet is 50 Hz. When the thickness of the wedge is respectively equal to one wavelength (44 m), half of the wavelength (22 m) and a quarter-wavelength (11 m), the corresponding coordinates in the horizontal axis of the wedge model are 366 m, 183 m, and 91 m, respectively.