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Three-component polarization migration of channel waves for prediction ahead of coal roadway

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ABSTRACT

When excavating roadways in coal mining, it is critical to predict any geological anomalies that lie ahead of the excavation in advance. Channel waves can be used for this purpose; however, the mirror imaging artefacts in the diffraction migration of channel waves must be overcome. When mixed with a Rayleigh channel wave, the polarization migration of a two-component Love channel wave is no longer possible. In this paper, the polarization situations in three-dimensional channel waves are comprehensively summarized and a new three-component channel wave polarization migration technique is proposed to remedy the deficiencies in current migration methods. The proposed technique has directional selectivity and filters out other interfering waves during the migration process, eliminates the artificial mirror phenomenon, and provides a higher imaging accuracy than other methods. However, the polarization of three-component channel waves is very complex. For example, the fundamental mode of a Rayleigh channel wave in the center of a coal seam is vertical-linearly polarized instead of elliptically polarized. In addition, the Love and Rayleigh channel waves mix easily as the group velocities of their fundamental modes are similar, and separating these necessitates the use of a special polarization filter. When two types of channel waves mix, a suitable polarization filter can be applied to suppress one or the other; however, this can produce two migration images of Love and Rayleigh channel waves. The most economical and practical means to overcome this is to record the two horizontal components at the center of the coal seam using a Love channel wave polarization migration that is independent of the Rayleigh channel wave. The proposed method was validated by way of a numerical simulation, and the results confirmed its superiority over conventional methods.

1. Introduction

In underground coal mining, roadway excavation is an important step that directly determines the safety and efficiency of the mine. The primary challenge in such excavations is to overcome the risk of encountering geological anomalies, such as faults, collapsed columns, crushed zones, and so on (Ghosh and Sivakumar, 2018), as these anomalies increase the complexity of roadway excavation due to the associated safety issues, for example, roof collapses, water invasion (Yin et al., 2016a; Yin et al., 2016b), and gas leaks (Liu et al., 2017). If the existence of geological structures can be predicted ahead of the roadway face, then precautions can be taken to prevent disaster. For these reasons, it is critical to be able to predict the existence of such structures ahead of the roadway face.

In-seam seismic method generally refers to the application of channel waves in the coal seam to detect the structure of the seam (Dresen and Rüter, 1994). This method provides better results than electrical prospecting and support a longer exploration distance relative to other geophysical methods used in underground coal mining. However, due to the crowded heading face, less reflection information is received from structures in front. In addition, as the reflection channel wave field is complex and the signal is typically weak, it is difficult to process the data. Consequently, the quality of the predictions obtained using these methods is generally poor.

Over the past few decades, researchers have investigated the reflected channel wave from the side coal channel for imaging ahead of a coal roadway. Mason et al. (1980) proposed the delay lag sum imaging method based on the Kirchhoff migration, which is similar to diffracted wave imaging. Buchanan (1981), Buchanan, 1983) modified this method to propose dynamic trace stacking and self-adaption delay lag sum imaging. Millahn and Marschall (1980) considered the orientation of an SH-wave to determine the actual reflection point, then used the two horizontal components of the Love channel wave in the polarization migration. Other scholars (Dresen and Rüter, 1994; Wang et al., 2014; Yancey et al., 2007) applied envelope stacking and Love channel wave polarization to image the channel waves in experiments in coal mines. Hu and McMechan (2007) applied reverse-time prestack elastic

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migration to image mining hazards within coalbeds using reflected body waves. Wang (2007) and Ge et al. (2008) applied an elliptical mapping method to the reflected channel wave for void delineation.

Zhang et al. (2007) applied diffracted P-wave scanning migration imaging for prediction ahead of a coal roadway. Wang (2015) evaluated the suitability of the reflected channel wave for predictions ahead of an excavated roadway, and proposed a reflected channel wave strength algorithm based on the least squares deconvolution and radial trace transformation methods to deal with the reflected channel wave being significantly contaminated. Lüth et al. (2005) applied Fresnel zone migration based on the polarization orientation to simulated vertical seismic profiling (VSP) and real field data. When compared with standard depth migration, this method was found to improve the imaging quality. Han et al. (2018) demonstrated that wavelength-dependent Fresnel beam propagator can provide accurate wave propagating directions and developed a wavelength-dependent Fresnel beam migration method for VTI media. Wang et al. (2016) studied the full space seismic polarization migration technique in a mine and filtered the body waves using three-dimensional polarization filtering during migration to eliminate the artificial phenomenon related to the transverse zygomorphy of the fault. In terms of the numerical simulation of channel waves, Essen et al. (2007) simulated Rayleigh channel waves in a model containing a fault and variations in the thickness of the coal seam and the results indicate that a reflected channel wave with a smaller amplitude is generated when a channel wave encounters a disturbance. It was also noted that there was no reflected channel wave in a furcated coal seam. Yang and Cheng (2012) and Yang et al. (2016) investigated the characteristics of the channel wave field reflected from structures in front of the roadway heading face and found that the Rayleigh channel wave exhibits enough energy to make it suitable for detection ahead of the face. The Love channel wave has a weak energy distribution that may not be suitable for prediction ahead of a roadway. Li et al. (2015) applied numerical techniques to investigate channel wave propagation in a fluctuant roadway and qualitatively analyzed the wave properties in complex roadway models. He et al. (2017) studied the theoretical basis for applying a vertical z-component channel wave in mining exploration and found that the normal mode of a Rayleigh channel wave is always present. In addition, it is highly possible that both the fundamental and first modes of channel waves can be recorded.

Although the transmitted channel wave method is well understood, research supporting prediction ahead of a coal roadway is lacking and many challenges remain. The channel wave envelope stacking method has low resolution, and the results of diffracted channel wave migrations include artificial migration arcs and mirror fault images. Although the two-component Love channel wave provides good polarization migration results, the wave field is complex and the two components may also contain the Rayleigh channel wave, which is not SH linearly polarized. Thus, if the two components are recorded, then the full wave field of the channel wave cannot be comprehensively analyzed. In addition, the polarized filter accuracy of two components is less than that for three components. These problems can be overcome via three-component channel wave polarization migration. The difficult is that three-component channel wave polarization is very complex and has not been adequately studied.

In this paper, we analyze the polarization properties of three-dimensional (3D) channel waves, investigate a channel wave polarization filter, and propose a three-component polarization migration method. The proposed method was validated by way of a numerical simulation.

2. Theory

2.1. Diffracted channel wave migration

Kirchhoff migration is commonly applied to body waves as channel waves are interference waves, which conflicts with the assumptions underlying the Kirchhoff integral equation. As an alternative, diffracted wave migration can be used instead of directly applying Kirchhoff migration. The weighed factors of channel waves can be considered for modifying the diffracted wave migration in the diffracted amplitude stacking step.

According to the Huygens' principle, each diffraction point can be assumed to be a wavelet source. In addition, each grid point can be considered to be a reflection point in the diffracted scanning migration and each recorded trace can be assumed to be the stacking of these diffraction events. These definitions can also be applied to channel waves. Because channel waves only propagate in the coal seam, the diffracted migration of a channel wave generally completes in the seam layer (Wang, 2015). The stacking amplitude energy at (x, y) is:

$$P(x,y)=\sum_{i=1}^{N}\sum_{j=1}^{M}\left|w_{ij}A(t_{ij})\right|^2=\sum_{i=1}^{N}\sum_{j=1}^{M}\left|w_{ij}A\left(\frac{r_{ij}}{v_g}\right)\right|^2, w_{ij}=r_{ij}^{5/6}cos\theta \qquad (1)$$

where N is the total number of shots, M is the number of receivers, w_{ij} is the weighting factor, $A(t_{ij})$ is the amplitude at time t_{ij} of trace j in shot i, v_g is the group velocity of the channel wave, r_{ij} is the sum of the distances from point $P(x, y)$ to receiver point j and source i, $\cos\theta$ is the tilt factor, and $r^{-5/6}$ is the attenuation coefficient of the channel wave with distance. The instantaneous amplitude of the channel wave can be calculated via the Hilbert transformation, and the weighting factor is specific to our unique requirements. It is equivalent to the amplitude-preserving processing of the channel wave.

There are several advantages of using diffracted wave migration on channel waves versus surface seismic waves: 1) the group velocity of a channel wave is almost constant and can be calculated directly, while the velocity of a surface seismic must be computed at every layer (Lin et al., 2013); and 2) channel waves propagate in a coal seam, which can be seen as an approximately two-dimensional (2D) plane and are therefore easy to process without a 3D model. However, this method also has a significant deficiency in that all points on the elliptical path will be assigned during amplitude stacking while there may only be one or two actual reflection points. Consequently, the resolution of this method is low.

2.2. Principles of channel wave polarization migration

Channel waves can be divided into Rayleigh and Love channel waves based on their physical elements and polarization features. Rayleigh channel waves are generated by interference between P- and SV-waves when particles vibrate in a plane that is perpendicular to the coal seam and parallel to the direction of wave propagation. Because both horizontal and vertical components can be observed, the vibration trace generally appears elliptical (Fig. 1). A Love channel wave is generated in a coal seam due to the interference of SH waves when particles vibrate perpendicular to the direction of wave propagation in the horizontal plane.

Take a Love channel wave as an example, the reflected Love channel wave is received when encountering a fault (Fig. 1). A single three-

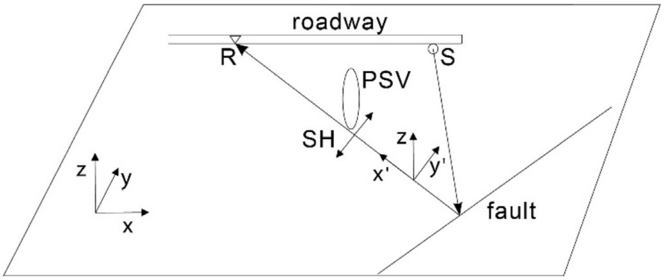

Fig. 1. Principles of channel wave prediction ahead of the face and particle vibration.