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Research paper

Seismic attenuation estimation using a complete ensemble empirical mode decomposition-based method

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ABSTRACT

The frequency attenuation gradient method can provide important information for hydrocarbon detection. In this paper, a method using Complete Ensemble Empirical Mode Decomposition (CEEMD), Hilbert transform and the least-squares curve-fitting is proposed for seismic attenuation estimation as an effective frequency attenuation gradient estimation approach. We first use CEEMD to obtain the different Intrinsic Mode Functions (IMFs), which have a narrow band and can enhance the physical meaning of instantaneous attributes trace by trace. The time-frequency spectrum, which is computed using a Hilbert transform of each IMF, is represented as a spectrum with a single-peak that has narrow side lobes, which is conducive to frequency attenuation gradient estimation. Second, for each time sample, the frequency-amplitude spectrum of each IMF trace is extracted from the time-frequency spectrum to conduct the attenuation gradient computation. Then, the logarithm operation is performed for each IMF trace. Due to the very narrow bands of some IMFs in some seismic traces, a variable frequency window is adopted along the IMF trace according to the local data characteristics. Finally, the attenuation gradient for each IMF in a seismic trace can be computed using least-squares fitting. A different IMF reflects a seismic trace with a different spatiotemporal scale and can highlight different geologic and stratigraphic information. The correlation weighted average operation is used to highlight some useful details in seismic trace and obtains the attenuation gradient for each seismic trace. Field data examples demonstrate our method and its effectiveness. The proposed method can stably estimate the frequency attenuation gradient.

1. Introduction

Seismic attenuation refers to the loss of energy that occurs during seismic wave propagation in an underground medium and is intrinsic to a medium. With the exception of wavefront divergence during seismic wave propagation in rocks, the imperfect elastic characteristics of rocks can also cause seismic energy attenuation. Because the elastic energy of a seismic wave is irreversibly converted into heat and then dissipated, the total energy of seismic wave is attenuated (Toksöz and Johnston, 1981). There are many factors affecting seismic wave attenuation. However, in a relatively stable stratum structure with few changes in the vertical and horizontal lithology, the attenuation of seismic waves is mainly caused by the properties of any fluids (Anderson and Hampton, 1980; Dvorkin and Nur, 1993; del Valle-García and Ramírez-Cruz, 2002; Castagna et al., 2003; Korneev et al., 2004; Duchesne et al., 2011). In a decoupled system that is formed by a rock matrix and its filled fluids, the physical properties of the rock matrix and the composition of the fluids filling the rock matrix will determine the energy dissipation degree and the possible dissipation frequency range (Mitchell et al., 1996).

The energy attenuation of seismic waves can sensitively detect the presence of fluid in a formation and can be used as a direct hydrocarbon indicator (see Winkler and Nur, 1982; Clark et al., 2001; del Valle-García and Ramírez-Cruz, 2002; Castagna et al., 2003; Maultzsch et al., 2007; Duchesne et al., 2011). The overall effect of energy attenuation on a seismic trace is that higher frequencies are suppressed more rapidly than lower frequencies in gas-prone sediments. Thus, attenuation anomalies will be present in the signal. The physics of seismic attenuation can be used for

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reservoir detection (e.g., Winkler and Nur, 1982; Clark et al., 2001; Castagna et al., 2003; del Valle-García and Ramírez-Cruz, 2002; Maultzsch et al., 2007; Reine et al., 2009; Duchesne et al., 2011; Xue et al., 2014a,b; Xiong et al., 2011).

The Energy Absorption Analysis (EAA) method, which was proposed by Mitchell et al. (1996), computes the absorption coefficient to estimate the high-frequency energy absorption by the media to detect hydrocarbons. Due to the effective estimation of the high-frequency attenuation information, the EAA method has been widely used in hydrocarbon detection (see, for example, Martin et al., 1998; Xiong et al., 2011). Accurate calculation of the absorption coefficient or attenuation gradient is key to the EAA method. The conventional EAA method, which uses a two-point slope, is only suited for smooth spectra with very few or nearly no side lobes or seismic data having a high Signal-to-Noise Ratio (SNR) (Xue et al., 2014b). Today, the attenuation gradient is commonly calculated in the wavelet transform domain to guarantee that the attenuation gradient has a strong anti-noise performance and to analyse the instantaneous properties on different scales (Martin et al., 1998; Xiong et al., 2011; Xue et al., 2014b). However, there are some limitations to this algorithm. The fixed length of the analysis time window will influence the accuracy of the results. For an irregular spectrum, the curve fitting of two points will decrease the accuracy dramatically. For some weak hydrocarbon responses or low SNR seismic data, the effectiveness of the EAA method based on wavelet transform is reduced sharply. To improve the effectiveness of the attenuation gradient in the indication of hydrocarbons, a time-frequency analysis method with a higher time-frequency resolution and aggregation and an improved linear fitting method are the current research foci.

The Empirical Mode Decomposition (EMD) method that was proposed by Huang et al. (1998) can decompose a nonlinear and non-stationary signal into a finite number of Intrinsic Mode Functions (IMFs), which are gradual single-frequency sub-signals. Compared to other Fourier-based and Wavelet-based conventional time-frequency methods, such as short time Fourier transform, Stockwell transform (Stockwell, 1996), and continuous wavelet transform, EMD-based time-frequency methods have higher temporal and spatial resolutions (Huang et al., 1998; Hassan, 2005). However, the mode-mixing problem, i.e., different intrinsic time scales are contained in one IMF or different IMFs distributed in similar intrinsic time scales, will cause two adjacent IMF waveforms to alias and produce an obscure physical meaning for some of the IMFs that were obtained from an EMD. To overcome mode mixing, Wu and Huang (2009) proposed the Ensemble EMD (EEMD), which still has reconstruction problems. Then, Torres et al. (2011) proposed an alternative method that can handle mode mixing, achieving almost perfect reconstruction by summing the individual IMF components. As gradual, single-frequency signals, IMFs with smooth spectra with narrow side lobes are suitable for obtaining more accurate attenuation gradients. Different IMFs with different spatiotemporal scales can highlight different geologic and stratigraphic information.

In this paper, we present a method for attenuation gradient estimation using complete ensemble empirical mode decomposition (CEEMD) with the Hilbert transform (HT) and least-square curve fitting methods. CEEMD combined with HT as one time-frequency analysis method is first demonstrated to have high time and frequency resolutions and better energy aggregation than other conventional time-frequency methods, such as short-time Fourier transform, Stockwell transform, and continuous wavelet transform. Then, we apply the CEEMD-based attenuation gradient estimation method for frequency attenuation analysis of the seismic data that were acquired over a tight sandstone reservoir in PengLai gas field in Central Sichuan, China. We show the success of the proposed method in providing more precise absorption coefficient estimation and better hydrocarbon-prone interpretations than those of the conventional frequency attenuation gradient method.

2. Principle and methods

2.1. Energy absorption analysis (EAA)

When a seismic wave propagates in an underground medium, some of the elastic energy of the seismic wave is irreversibly converted into heat due to the imperfect elastic characteristics of the rocks, thus resulting in amplitude attenuation and high frequency loss. Due to the different physical properties of rocks and the different properties of the contained fluids, the amplitude attenuations of elastic waves will also differ. When the rock contains oil or gas, the amplitude attenuation of the elastic wave is significantly increased. It has been demonstrated that 5% or less gas present in porous media can dominate the acoustic characteristics of the sediments and significantly increase the reflection amplitude (Anderson and Hampton, 1980; Domenico, 1974). Therefore, the degree of amplitude attenuation of elastic waves by rocks can sensitively detect whether hydrocarbons exist in the formation and can effectively enhance the accuracy of the interpretation in vertical and horizontal reservoir prediction.

The EAA method uses the function $exp(-a\omega)$ to estimate the spectrum that is affected by absorption (Mitchell et al., 1996), where ω is the angular frequency. a is the absorption gradient or the absorption coefficient. The conventional EAA method uses a linear curve fitting of two points (65% and 85% of the total energy) to estimate the line slope, which is the absorption gradient as shown in Eq. (1)

$$a = \left|\frac{\ln(E_{85}) - \ln(E_{65})}{f_{85} - f_{65}}\right|, \tag{1}$$

where E_{85} and f_{85} represent 85% of the total energy and its corresponding frequency, respectively. E_{65} and f_{65} represent 65% of the total energy and its corresponding frequency, respectively. The energy at 65% and 85% is the cumulative energy that arrived at 65% and 85% of the total energy, respectively.

Fig. 1 shows a schematic diagram of the EAA method. If the spectrum of seismic data $x(n), n = 1,2,\cdots,M$ is $X(k), k = 1,2,\cdots,N$, that is, $X(k) = \sum_{n=1}^{N} x(n)\exp(-2njk\pi/N),$, the power spectrum is $P(k) = |X(k)|^2$. Then, the total energy S is the sum of the square of the amplitude spectrum, that is, the sum of the power spectral energy: $S = \sum_{k=1}^{N/2+1} P(k)$. As shown in Fig. 1, the dominant frequency is the frequency at the maximum energy. Using the dominant frequency as the initial attenuation frequency, the frequencies at 65% and 85% of the total energy can be calculated. In the frequency range $f_{65} \sim f_{85}$, according to the corresponding energy, the frequency absorption gradient can be obtained by fitting two points.

EAA works on a trace-by-trace basis. The absorption gradient for each trace is computed by carrying out a continuous spectrum analysis in a series of small time windows that move by the chosen increment for the analysis along the trace. The length of the analysis is generally small (e.g., 40 ms) and constant for all of the traces. EAA is used to detect a sudden increase in the rate of exponential decay in the higher-frequency portion of the spectrum (Mitchell et al., 1996).

2.2. Complete ensemble empirical mode decomposition (CEEMD)

EEMD is a noise-assisted data analysis method that was