Monitoring Seismic Attenuation Changes Using a 4D Relative Spectrum Method in Athabsca Heavy Oil Reservoir, Canada

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Abstract

Heating heavy oil reservoirs is a common method for reducing the high viscosity of heavy oil and thus increasing the recovery factor. Monitoring these changes in the reservoir is essential for delineating the heated region and controlling production. In this study, we measure the changes in the seismic wave attenuation of a heavy oil reservoir by constructing time-lapse Q^{-1} factor maps using a 4D-relative spectrum method. This method estimates seismic attenuation from surface reflection seismic surveys by calculating, for each trace in each survey, the attenuation (Q^{-1}) using the spectral ratio (Toksoz et al. (1979)) between a reference reflector above the reservoir and a second reflector below the reservoir. The results of our study on a real data set exhibit alignment along the injection wells, indicating that seismic attenuation can be used to monitor changes in a heavy oil reservoir.

Introduction

In recent years conventional crude oil reservoirs have been in decline and heavy oil is becoming an important potential resource. The production of conventional cold heavy oil at depths between 50 m and 1000 m has a typical recovery factor of 5% to 10% (Clark (2007)). One method to increase recovery, is to heat a reservoir to above 200°C either by combustion of part of the heavy oil (Vendati and Sen (2009), Kendall (2009)) or by injecting steam into the reservoir (Clark (2007)). This procedure makes heavy oil less viscous and more mobile. Theoretical and experimental studies show that the properties of heavy oil are strongly dependent on temperature, frequency, and composition (Eastwood (1993), Das and Batzle (2008)). Behura et al. (2007) and Das and Batzle (2008) show that the shear modulus of heavy oil in general can be predicted by a frequency-dependent Cole-Cole visco-elastic model (Cole and Cole (1941)), which has both real and imaginary attenuative parts. The frequency where the strongest attenuation is observed is called the relaxation frequency, and is related to the temperature through the viscosity of the oil (Das and Batzle (2008)). From laboratory experiments, this peak attenuation is predicted to be at intermediate temperatures between 40° to 120°C. Because Batzle et al. (2006) indicates that heavy oils have different properties in the seismic, sonic, and ultrasonic frequency bands, these properties cannot be extrapolated from one band to another. Therefore, we need to have measurements in the seismic band in order to estimate attenuation for the intermediate temperatures.

The measurement of seismic attenuation in the field is, in general, a difficult task because of the difficulty in discriminating the decay of the signal from attenuation and that from geometric spreading or reflection. The spectral ratio method, a common technique to estimate the attenuation (Q - factor) of the medium which separates the effect of attenuation from geometric spreading, was first presented for laboratory measurements by (Toksoz et al. (1979)) and adjusted for vertical seismic profiles (VSP) by Hauge (1981). The advent of time lapse surface seismic acquisitions using permanent systems with fixed positions for sources and receivers in heavy oil fields (Byerley et al. (2008)), has made it possible to obtain high quality repeatable surface seismic data sets. Using such data we modify and adjust the standard spectral ratio method to the time-lapse surface reflection seismic data, and we show that changes in seismic attenuation due to the effect of steam injection can be monitored using this method. This paper is divided into two sections. In the first section, we present the 4D-Relative Spectrum Method (4DRSM). In the second section, we present results obtained with this method for a time-lapse reflection seismic data set from a heavy oil field in Athabasca, Canada.

4D-Relative Spectrum Method

The 4D-Relative Spectrum Method (4DRSM) is a time-lapse relative spectrum method for seismic wave attenuation estimation, which is an adaptation of the spectral ratio method (Toksoz et al. (1979)) to surface reflection seismic data. The method is derived by assuming a plane wave whose amplitude as a function of frequency is given by

$$A(f) = G(z)A_0 e^{-\alpha(f)z} e^{i(2\pi ft - kz)} \tag{1}$$

with magnitude

$$|A(f)| = G(z)A_0 e^{-\alpha(f)z} \tag{2}$$

where f is the frequency, k is the wave-number, z is depth, t is time, A_0 is the input source amplitude, $A(f)$ is the amplitude as a function of frequency, $G(z)$ is the geometrical spreading factor (assumed to be real as is standard in seismic processing), and $\alpha(f)$ is the frequency dependent attenuation coefficient. Although, for simplicity, we derive the method in one-dimension, it can be extended to two and three dimensions by defining $\alpha(f)$, z, and k as vectors.

By assuming that the attenuation $\alpha(f)$ is a linear function of frequency, we write

$$\alpha(f) = \tilde{\gamma}f \quad \text{or} \quad \alpha(f)z = \gamma f \tag{3}$$

with

$$\gamma = \tilde{\gamma}z = \pi z/(Qc) \quad \text{or} \quad \gamma = \pi t/Q \tag{4}$$

where Q and c are the frequency independent Q-factor and velocity, respectively. The assumption of a frequency independent (constant) Q is justified because in practice the heated reservoir would exhibit temperatures between those of the steam and the in-situ temperature. This means that the distribution of

relaxation peak frequencies will likely be relatively flat over a wide range of frequencies, resulting in a constant or nearly-constant Q-factor.

By taking the ratio between the magnitudes of two time windows on the trace (A_1 and A_2), which correspond to times t_1 and t_2 (figure 1), we adapt the method to be applied to surface seismic data. Then, by taking the logarithm, we obtain a linear function

$$\log\left(|A_2|/|A_1|\right) = -(\gamma_2 - \gamma_1)f + \log\left(G_2/G_1\right) \tag{5}$$

where $(\gamma_1 - \gamma_2)$ and $\log\left(G_2/G_1\right)$ are the slope and intercept, respectively. In practice, the spectral ratio $(|A_2|/|A_1|)$ will be ill-defined when the denominator is zero, and therefore a small number is added to the denominator to regularize the computation.
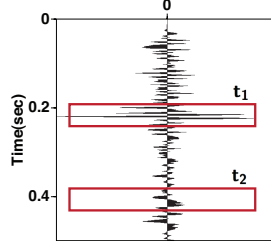

Figure 1: Representative trace for the relative spectrum calculation. The window around t_1 corresponds to the region which is not affected by the steam, whereas the window around t_2 corresponds to the steam-affected region.

From estimates of $\log\left(|A_2|/|A_1|\right)$, we calculate the relative Q-factor using

$$\tilde{Q} = \frac{1}{2}\frac{\pi(t_2 - t_1)}{(\gamma_2 - \gamma_1)} \tag{6}$$

where $\tilde{Q}$ corresponds to an estimate of the Q-factor for the region between t_1 and t_2. Note that the factor 2 in the denominator of eq. 6 is added to account for the two-way travel time. Note also that the geometric factor corresponds to the intercept and does not affect the estimate of the Q-factor.

In our analysis we assume that the attenuation γ_1 is the same for both the baseline and monitor data sets. Due to seasonal effects, γ_1 may not be the same potentially degrading the results. Nevertheless, if the spectra of t_1 is the same in both the baseline and monitor data sets, we expect this effect to be small. The workflow of the 4D relative spectrum method (4DRSM) is summarized by the following steps:

For each data set (Baseline or Monitor)

1. Choose the trace that corresponds to a certain offset.
2. Extract amplitudes within the windows at times t_1 and t_2.
3. Take the Fourier transform of the data in each window to calculate the spectrum (magnitude).
4. Calculate the ratio between spectra (preventing division by zero adding a small number to the denominator) and take the logarithm.
5. Fit the data as a function of frequency, and estimate the slope and the error-bar (the difference between the maximum and the minimum possible slopes with 95% confidence).
6. Calculate Q^{-1} from the slope.

Calculate $\Delta\left(1/Q\right) = 1/Q_B - 1/Q_{M1}$, where the subscripts B and M1 refer to the baseline and monitor data sets, respectively.

Real Data Example

We apply the 4DRSM to a three dimensional time-lapse reflection surface seismic data set from a heavy oil field in Athabasca, Canada; the two data sets were collected before and after steam injection. The total area of the surveys is 1700 m^2 with spatial and temporal sampling of dx = dz = 10 m, and dt = 0.001 s respectively. We refer to the two data sets as the baseline (before injection) and the monitor (after injection) data sets.

We use a single trace, from each time-migrated gather, that corresponds to the nearest offset of 16 m. The time window, which is tapered by 30% from each side and smoothed by a five point filter, is 0.04 s long. This window size corresponds approximately to the thickness of the reservoir, about 30-70 m as derived from the P-wave velocity of 2500 m/s.

Figure 2: Spectra from the windows at times t_1 and t_2 of baseline (a) and monitor (b) traces.

Figure 3: Relative spectrum as a function of frequency: baseline (a) and monitor (b).

In figure 2 we present the spectra separately calculated from the baseline and monitor traces for the window around time t_1, corresponding to the region above the reservoir (the portion of the signal which is not affected by the steam injection), and that around t_2, which is below the reservoir (the portion of the signal which is considered to be most affected by the steam injection). We observe that the spectra above the reservoir (blue lines) do not change significantly between the baseline and the monitor surveys, whereas the spectra that correspond to the reservoir (green lines) do change, primarily between 60 and 130 Hz .

In figure 3 we show the logarithmic ratio as a function of frequency, calculated from spectra shown in figure 2. The relative spectrum illustrates fairly linear behavior for the frequencies between 15 and 200 Hz (green fit to the blue data points in figure 3) giving us confidence that the assumption of constant Q is justified.

By computing the spectral ratio for each seismic gather in both the baseline and monitor surveys, we estimate the Q-factors by Eq. 5 and 6. Figure 4 illustrates the differential 1/Q ($1/Q_B$ - $1/Q_{M1}$) and its uncertainty $\Delta(1/Q_B - 1/Q_{M1})/(1/Q_B)$ calculated over the frequency range between 15 and 200 Hz, chosen based on figure 2, with reference reflectors at times t_1 and t_2, corresponding to regions above and below the reservoir, respectively. The uncertainty was derived from the error-bar of the fit, separately estimated for each data set ($\Delta(1/Q_B)$, $\Delta(1/Q_{M1})$). The black lines in figure 4 indicate the positions of the wells through which the reservoir is heated, and background color shows the estimated seismic attenuation.

In order to verify that the observed differences indeed correspond to the reservoir and not to the reflectors above it, we calculated two additional control results by the 4DRSM with different reference reflectors. In the first, figure 5(a), we kept t_2 below the reservoir and changed the position of t_1. This test results in a pattern of changes that is similar to that shown in figure 4(a). In the second test, the result of which is shown in figure 5(b), we set both t_1 and t_2 to reflectors above the reservoir. In this case we observe that the changes are not aligned with the wells (denoted by black lines). Therefore, we conclude that the observed changes in figure 4(a) are caused by the changes in the reservoir.

Conclusions

We adapted the spectral ratio method into 4DRSM to monitor time-lapse surface reflection seismic data. Using this method, we showed that the changes in the heated heavy oil reservoir can be detected and monitored using seismic wave attenuation. This result has the potential to establish a relationship

Figure 4: Differential 1/Q (a) and its uncertainty (b) between the baseline and the monitor data sets that were estimated using the 4DRSM with time t_1, corresponding to the region above the reservoir (the portion of the signal which is not affected by the steam injection), and time t_2, which is below the reservoir (the portion of the signal which is considered to be most affected by the steam injection). Black lines indicate the position of the wells through which the reservoir is heated.

Figure 5: Differential 1/Q between the baseline and the monitor data sets that were estimated using the 4DRSM with different reference times from those in figure 4(a): (a) time t_1 is set to another reflector while t_2 remains the same as in figure 4(a), (b) Both times t_1 and t_2 were set to reflectors that correspond to the region above the heated reservoir.

between the changes in seismic attenuation and those in the viscosity of heavy oil within the heated reservoir.

Acknowledgments

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