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How Small Is a Small 4D Signal - A Model Study for 4D Resolution

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SUMMARY

With the maturation of 4D seismic, legacy 3D data are replaced by purposely-shot conventional 3D surveys with multiple monitors and short time separation to follow the impact of production. Furthermore, permanent seismic installation like has been proven technically successful and economically feasible under the right condition. Naturally with a shorter cycle between 4D surveys, the need to detect smaller 4D signals, amplitude changes, and time shifts has become more critical in order to improve the dynamic characterization of reservoirs.

Since the motivation is to detect subtle 4D signals, in this paper we use the term 4D resolution to describe the detectability of 4D signals. If a small or subtle 4D signal can be detected by a seismic data of certain qualities, then such a seismic data is a high 4D resolution data. The idea is analogous to detecting thin beds with higher resolution data (Widess, 1973; Kallweit and Wood 1982). We test the impact of seismic bandwidth and non-repeatability and evaluate what kind of seismic characteristics a dataset would qualify it as a high 4D resolution dataset. Understanding these characteristics and qualifications would help us better design and process 4D seismic data and ensure the success of 4D application.

Introduction

The trend of 4D or time-lapse 3D seismic application is to acquire more monitor surveys with shorter time separation by conventional acquisition method or permanent seismic installation. Naturally with a shorter cycle between 4D surveys, the need to detect smaller 4D signals, amplitude changes, and time shifts has become ever critical in order to monitor the production, improve the dynamic characterization of reservoirs, and maximize the production.

We use “4D resolution” to describe how well a seismic dataset can detect a small 4D signal. If a smaller 4D signal is detected between a pair of 2 seismic datasets with different seismic characteristics; for example one pair has higher bandwidth and another pair has lower bandwidth which pair has higher 4D resolution to detect small 4D signals? The idea is analogous to that higher bandwidth or higher resolution data detects thinner beds (Widess, 1973; Kallweit and Wood 1982). In this paper, we investigate the influence of seismic bandwidth, non-repeatability, and time shift measuring technique and evaluate what seismic characteristics qualify a seismic dataset as a high 4D resolution dataset. Understanding these characteristics would help us design and process 4D seismic data for a successful 4D project. The results demonstrate that although higher frequency or broader bandwidth is important for being higher 4D resolution it becomes more complicated when considering the impact of tuning and non-repeatability

4D Tuning

Historically seismic resolution has been defined by different criteria (Rayleigh; Ricker 1953). Since Widess (1973) introduced the concept of thin beds, significant work has been published analyzing the thin bed detectability and tuning effect caused by the interference of bandwidth-limited seismic wavelet. Kallweit and Wood (1982) demonstrated that the tuning thickness decreases or temporal resolution increases with broader seismic bandwidth and higher frequency. It is entirely logical to make an analogy with the tuning concept for 4D effect analysis, in which the travel time changes due to production between two 4D surveys can also introduce a similar interference pattern. The travel time changes or shifts are created by velocity changes due to pressure changes and fluid replacements or by real depth changes due to compaction, dilation, and fluid contact movement. Figure 1 illustrates the evaluation of a 4D 2 ms time shift and amplitude differences for three Ricker wavelets of 20, 50, and 80 Hz. The well known peak-trough pattern or the derivative of Ricker wavelet shows that 80 Hz Ricker produces the maximum 4D amplitude difference and thus the most detectable 4D signal or we define it as highest 4D resolution, compared to that of 50 or 20 Hz wavelet.

When we increase linearly the time shifts from 2ms to 20ms and cross-plot the apparent time shifts (peak-to-trough time separation) and the maximum composite amplitudes (sum of the absolute maximum amplitudes of peak and trough) against the true time shifts in such a way similar to those of the classical tuning analysis (Kallweit and Wood, 1982). Figure 2 displays the 4D tuning phenomenon for the analysis of 4D resolution and 4D signal detectability. Clearly it demonstrates that the 80 Hz Ricker wavelet provides the highest 4D resolution to identify small 4D signals in terms of real time shift and amplitude detectability. The cross-plot of apparent time shift and true time shift shows that 80 Hz wavelet detects or resolve accurately down to 5 ms and then flattens out becoming un-resolvable. Meanwhile the 20 Hz Ricker can barely detect true 4D time shifts below 20ms. To the right of Figure 2, when the composite amplitudes reach the maximum caused by constructively-interfered at the 4D tuning thickness they further helps detecting visually small 4D time shifts and potentially can be used to approximate linearly the true time shift as the classical seismic tuning analysis does for resolving the real thin bed thickness below the tuning thickness.

4D Resolution - Tests, Results, and Observations

Bear in mind the 4D tuning concept describe above, it is beneficial to increase seismic bandwidth for better 4D resolution or how small is a small 4D signal that one can detect? Naturally one can achieve higher 4D resolution through new acquisition but it can be costly. A less expensive alternative is to use processing techniques to enhance the seismic resolution. Many processing techniques such as statistical deconvolution, signature deconvolution, and spectral whitening may increase the seismic resolution but also lower the signal-to-noise ratio (SNR). Other high resolution (HR) enhancement techniques, such as BE (Smith et al., 2008) reconstructing the missing low and high frequencies by continuous wavelet transform (CWT), may hold the potentials of increasing 4D resolution without deteriorating SNR.

We build a baseline reservoir model with an oil-water-contact (OWC) to study the impact of seismic frequency, turning, and non-repeatability. Figure 3 is the noise-free baseline model response with a 50 Hz of Ricker wavelet. A production scenario is simulated with a pore pressure depletion of 15 MPa in the oil leg by applying a linear relationship between velocity and effective stress (Eiken and Tøndel, 2005). It translates into a 9 to 0 ms time shift up from left to right for the OWC and 15 to 4 ms for the reservoir bottom. In Figure 4, we use three levels of 4D signal detectability (Janssen et al., 2006): (1) clear detectable in green color bar, (2) moderately detectable in orange color bar, and (3) non-detectable in red color bar and analyze the OWC (centered at 290 ms) movements and time shifts with three different frequencies of 20, 50, and 80 Hz. Furthermore, the non-repeatability impacts such as acquisition footprints and imperfect processing are modeled with two noise levels by adding band-limited random noises corresponding to NRMS of 0.14 and 0.44 as shown respectively in the upper row and lower row of Figure 4. For the higher repeatability or lower noise data, it shows that the clearest detectable zone in green increases progressively with higher frequency and detect smaller time shift from Figure 4a to 4c. Specifically, for 20 Hz it is clearly detectable until trace 32 or time shift of 5.4 ms, for 50 Hz, it is at trace 58 or time shift of 2.5 ms, and for 80 Hz it at trace 69 or time shift of 1.2 ms. It demonstrates that high frequency is better for high detectability and high 4D resolution if noise level is lower.

For the lower repeatability or high noise data for Figure 4d to 4f, it is more complex because the zone and its location of detectability vary with different frequencies. For example, the clearest detectability zone for 50 Hz is about in the first third of the section or in the larger time shift area, whereas the clearest detectability zone for 80 Hz moves to the right or smaller time shift area. This complex detectability phenomenon or 4D resolution variability can be explained by the 4D tuning effect when we cross-plot the composite amplitudes and the time shifts of the OWC in Figure 5. It is obvious that the clearest detectability zone is where the amplitudes are tuned to a maximum level above certain noise or non-repeatability level thus more visible to be detected for 50 and 80 Hz data. Conversely, the non-detectable zone in red is where the amplitudes are low relatively to the noise level for 20 Hz data.

Conclusions

The 4D tuning concept and 4D resolution tests demonstrate clearly that higher frequency is necessary for lower 4D tuning thickness and higher 4D resolution in terms of 4D signal detectability and measurement accuracy. Furthermore, in order to have better accuracy it is critical to increase the repeatability or decrease noise level as illustrated in Figure 4. Other tests not shown here also show that higher frequency enable better picking of the time shifts at least on the several picking algorithms tested.

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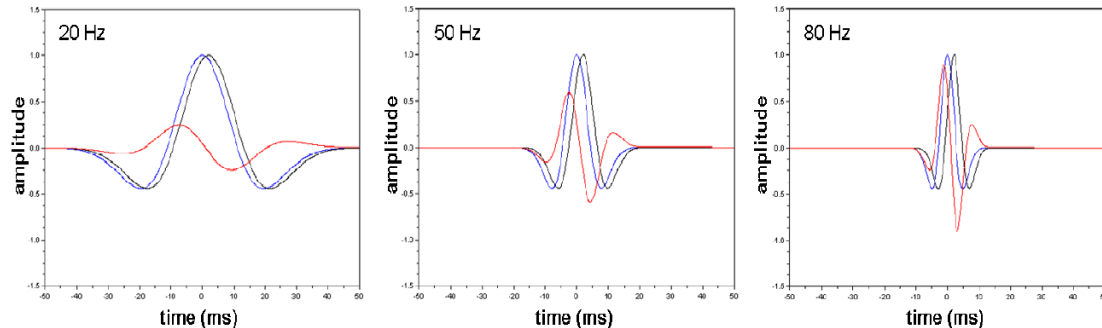


Figure 1: A simulated 2ms 4D time shift between two identical Ricker wavelets (in blue and black) and their 4D amplitude differences (in red) with a peak frequency of 20, 50, and 80 Hz respectively from left to right.

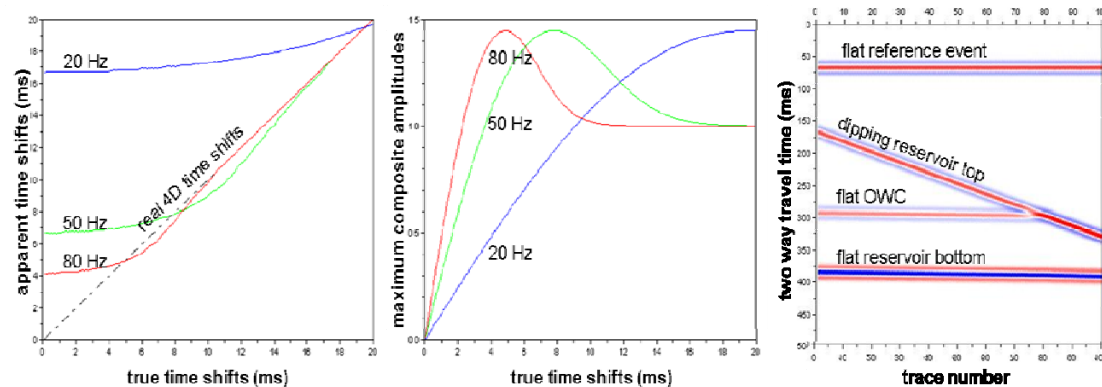


Figure 2: 4D tuning analysis to evaluate the 4D resolution using apparent time shifts and maximum composite

Figure 3: 2D model response of the baseline survey with

amplitudes for three Ricker wavelets of different bandwidths.

50 Hz Ricker and no noise

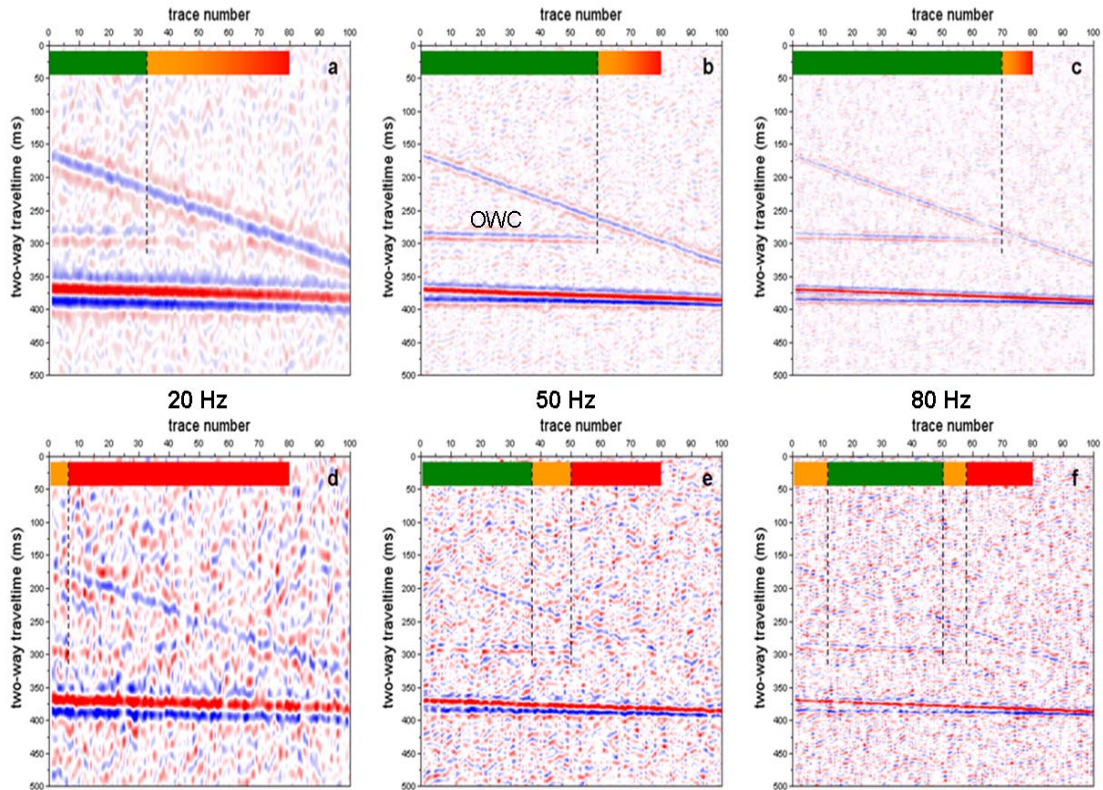


Figure 4: 4D differences to detect the OWC movement due to production with three different Ricker wavelets of 20, 50, and 80 Hz at two noise levels (top row and bottom row). The three levels of detectability are labeled with color bar: green for clearly detectable, orange for moderately detectable, and red for non-detectable.

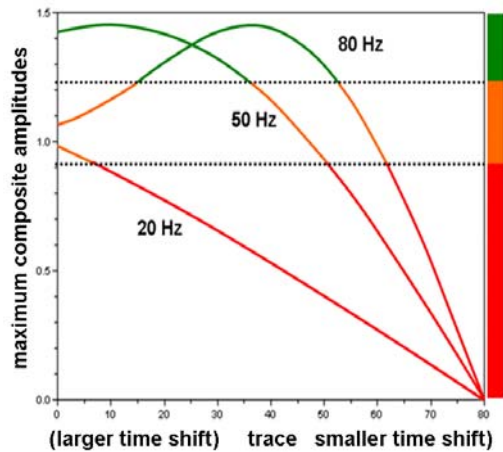


Figure 5: 4D tuning analysis with composite amplitudes and time shifts with higher non-repeatability in Figure 4.