Discussions on resolution limit in seismic inversion

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Summary

Inversion of acoustic impedance has been an important and powerful tool for seismic prediction of reservoir. Based on practical experiences and theoretical analysis, seismic inversion can precisely determine the top, bottom and thickness of one geobody within a resolvable window from a quarter to two thirds of apparent wavelength. When a geobody’s thickness goes out of resolvable window, it can also be delineated. In the later case, errors of thickness may occur in the procedure of seismic inversion. Fortunately these errors can be eliminated with relationship of seismic-well tie and structural analysis in order to obtain the true thickness of a geobody.

Key word: seismic inversion, resolution, apparent wavelength.

Introduction

The resolution quality plays an important role in seismic exploration. In this paper, we just refer to vertical seismic resolution which is defined as the ability to separate two close reflecting interfaces.

Seismic resolution often suffers from interfering effects of wavelets, so one more strictly defined resolution is that seismic resolvability means their envelopes are completely separable.

Evidently according to this definition, the resolution of seismic data we interpret everyday is very low, which is not the fact consistent with resolution level of our seismic data at present.

For a long period, Rayleigh criteria proposed by Rayleigh and Ricker has generally been accepted. According to the criteria, the vertical resolution limit is \( \frac{\lambda}{4} \), viz. a quarter of wavelength based on the fact that two wavelets are separable when time displacement of two wavelets reflected from the top and bottom of a thin bed is greater than or is equal to half a duration of the wavelet.

This paper starts with Rayleigh’s criteria, and goes further on vertical resolution in reservoir geophysics. In reservoir geophysics, the vertical resolution means the minimum thickness of a formation that can be delineated exactly, so there should be a supplement for Rayleigh’s criteria.

With comparison of seismic inversion and well data in shallow formations of Bohai Oilfield, and modeling tests, we draw a conclusion that the reservoir thickness predicted from seismic inversion is faithful when reservoir thickness is in the scope of \( \frac{\lambda}{4} \sim \frac{2\lambda}{3} \) (here \( \lambda \) is apparent wavelength and \( \lambda = 0.78\lambda \)), and together with the condition that the thicknesses of surrounding beds above and over the reservoir of interest are great than \( \frac{\lambda}{4} \).

Dominant wavelength and apparent wavelength

Seismic motion we record is a kind of wave propagation that obeys principles of physical seismology. Seismic wavelet is not an impulse, but a function with a period of duration, which is the reason why seismic vertical resolution is limited.

Seismic resolution depends considerably on the properties seismic wavelet, including band width, duration and waveform of the wavelet. The wavelet used in this paper is Ricker wavelet which is composed of one peak and two troughs, or two lobes. The dominant frequency \( F_m \) of Ricker wavelet is the frequency at which the amplitude
spectrum reaches its maximum value. Dominant period is defined as $T_m = 1/F_m$ (Figure 1).

Ricker wavelet is formulated as,

$$s(t) = \left[1 - 2(\pi f)^2\right]e^{-\left(\pi f^2\right)^2}$$

After applying first order derivative on equation (1),

$$s'(t) = \pi^2 f^2 e^{-\left(\pi f^2\right)^2} \left(4\pi^2 f^2 t^2 - 6\right)$$

Setting $s'(t) = 0$ we obtain the points where equation (1) has local minimums and maximums,

$$t_1 = 0 \quad \text{and} \quad t_{2,3} = \pm \sqrt{6/(2\pi f)}$$

$t_1$ corresponds to the local maximum, and $t_{2,3}$ two local minimums, namely two troughs. Thereby, we define the apparent period of the wavelet as,

$$T_a = 2|t_{2,3}| + |t_1| = \sqrt{6}/(\pi f)$$

Inserting $F_m$ into equation (4), we get apparent period,

$$T_a = \sqrt{6}/(\pi F_m) \approx 0.78T_m$$

From above analysis and equation (5), obviously we underestimate the resolution of seismic inversion if we define vertical resolution using dominant wavelength in Rayleigh criteria. At present, vertical resolution is defined using apparent wavelength in reservoir delineation in Bohao oilfield.

$$V = \frac{0.78 V}{4 F_m}$$

**Modeling tests**

At first, we define a model with three bodies of interest, 2 meters layer, a wedge and a 20 meters layer from top to bottom (Figure 2). In this model, the three bodies have the same velocity, $v = 2100m/s$. Assuming a wavelet with a dominant frequency $f = 60Hz$ and using equation (6), we can calculate the resolution limit is 7 meters, namely a quarter of apparent wavelength in this situation.

![Geological Model](image)

Figure 2 - geological model, reservoirs in yellow and surrounding bed in cyan.

Normal incidence synthetic section of this model and inverted relative acoustic impedance can be calculated and displayed (Figure 3 and Figure 4).

For layer thickness less than a quarter of the apparent wavelength, for example 2 meter, thickness estimated from inverted acoustic impedance is larger than that of true model. While for 20 meters layer, two false thin layers above and below the 20 meters layer appear. In these two cases, we can not exactly determine the top, bottom and thickness of the reservoir of interest.

![Synthetic Section](image)

Figure 3 - zero-offset synthetic section of the model, with a wavelet of dominant frequency at 60 Hz.
For the wedge body in this model, we find when reservoir thickness ranges in the scope \( \frac{\lambda_s}{4} \sim 2\frac{\lambda_s}{3} \), i.e. 7-18 meters, inverted acoustic impedance can be used to define the top and bottom of the reservoir, and thus the thickness. For thinner end where thickness is less than 7 meters, inferred reservoir thickness is overestimated, while for thicker end where thickness is larger than 18 meters, inferred reservoir thickness is underestimated (Figure 5).

**Application in filed data**

The reservoirs of interest in Bohai oilfield are encased in Lower Minghuazhen Formation, at the depth range of 1500-2000 meters and with a rapid lateral thickness change from 1-15 meters. The seismic data here are characterized with a 60 Hz dominant frequency, and the reservoir velocity is 2100 m/s, the same as those of the model. Figure 9 illustrates the thickness distribution of the sandstone reservoir and vertical resolution window in this oilfield.

We verify our inverted thicknesses of sandbodies with adjacent well data. In A well, sandbody 1 is 8.2 meter thick, and sandbody 2 is 18 meter thick (Figure 6). In B well, sandbody 3 is 13 meter thick, and sandbody 4 is 3 meter thick (Figure 7). In C well, sandbody 5 and 6 are 16 and 25 meter thick respectively (Figure 8).

Observing the inversed results, we can see that we obtain reliable estimations of the thicknesses of No. 1, 2, 3, and 5 sandbodies ranges from \( \frac{\lambda_s}{4} \) to \( 2\frac{\lambda_s}{3} \), i.e. vertical resolution window of 7-18 meters. When surrounding bed thickness is larger than \( \frac{\lambda_s}{4} \), inverted acoustic impedance can be used to determine top and bottom of one single sandbody. For a sand group made of several thin sandbodies, we can only identify the geometry of the sand group in inverted acoustic impedance section. We get an overestimated thickness of No. 4 sandbody thinner than 7 meters, and an underestimated thickness of No. 6 sandbody thicker than 2 thirds of apparent wavelength.

In resolution window, we compare the estimated thicknesses with those from well data of the reservoirs of Minghuazhen Formation in Bohai oilfield. The error distribution is illustrated (Figure 10), horizontal axis for reservoir thickness error range, and vertical axis for frequency.
Conclusions

The theoretical analysis, modeling tests and practical experiments arrive at the same conclusion that, we can determine the thickness of a reservoir accurately only when reservoir thickness is ranges from $\frac{\lambda_r}{4}$ to $\frac{2\lambda_r}{3}$, i.e. vertical resolution window.

Out of this window, there are two cases. When the thickness of one geobody is less than $\frac{\lambda_r}{4}$, estimated thickness is larger than the true thickness; and the true thickness can be approached with corrections from well data. While for thickness of geobody larger than $\frac{2\lambda_r}{3}$, inferred thickness may be smaller than the true thickness. In the later situation, first we often perform a comprehensive with well data and regional geological data, then we tune to the true top and bottom location of the geobody. Therefore a quantitative interpretation of a subsurface geobody can be obtained with higher accuracy.

Reference


