The imaging resolution analysis for complex models applied in seismic survey design

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Summary

In this paper, based on a complex seismic-geolocial model, the Time-Spatial Domain Acoustic Equation Finite-Difference Forward Modeling with given seismic geometries and wavelets are used to get the Point Spreading Function (PSF) at different analysis positions, on the basis of which, we further calculate the illumination spectrum and the envelope of a point scatter. In order to provide an useful tool for seismic survey design and optimization, in the numerical experiment, with the maximum offset unchanged, we use variable source interval or receiver interval to analyze the influences of different geometry parameters to the PSDM resolution.

Introduction

Nowadays more and more seismic survey design technologies have been used before seismic acquisition for giving a balance between the cost and the quality of seismic data. We all hope that we can get good enough seismic data with minimum cost. The wave equation modeling based and the wave equation illumination analysis based seismic survey designs have been used nearly throughout each large seismic survey design project. The seismic imaging resolution has been the highest goal of the seismologist, but the methods are mostly based on the ray tracing theory (Gelius et al., 2002; Lecomte, 2008;). Such high frequency asymptotic approximation based ray tracing theory cannot deal with the model for complex structures, but it has its unique characterisitcs, i.e. it can get the ray-path from the source through the subsurface interface to the receiver, such that it can easily get the local open angle of incident wave and reflect wave at the reflection position. This open angle is necessary for either imaging resolution or PSDM amplitude of the target. In other words, the angle domain illumination is closely related with the imaging resolution. Xie et al., (2005, 2006); Wu et al., (2006) expanded the above methods to the one way wave equation, which required to calculate a large number of frequencies due to the application of the wave equation operators in the F-K domain. In this way, it is very difficult to meet the require for a broadband seismic wavelet. In addition, the angle limit of one way propagator is also a flaw. Although the local incident angles at different scatter points can be calcualted, the calcualtion amount is enormous, especially when the broadband wavelet is used as the input source.

There are several ways to get seismic illumination based on full-wave equation (Xie and Yang, 2008; Yang et al., 2008; Cao and Wu, 2009; Yan, et al., 2014), but the computation are unbearable. Xie, et al. (2005, 2006), Wu, et al. (2006); and Mao and Wu (2011) calculated the relationship among the PSFs, the pre-stack depth migration and the PSDM resolution based on the one way propagator, and thus the seismic wave equation illumination, the seismic migration imaging and the imaging resolution analysis are connected. Cao, et al. (2013), Chen, et al. (2015) proposed a new method which can directly calculate the angle based seismic wave illumination through PSDM imaging.

In this paper, we further develop this method and apply it to the seismic survey design. We use different geometries, seismic wavelets of different frequencies and different maximum offsets to compute the PSFs at different position in a complex model, compute the envelopes of the PSFs, which indicates the PSDM resolution, and compare the different results to provide reference for the choice and optimization of different geometry parameters.

Methodology

For PSDM, many factors affect the seismic imaging resolution, even though an accurate velocity model cannot ensure to get a good PSDM image because some effects such as limited acquisition geometry aperture, insufficient acquisition sampling, bandwidth-limited seismic wavelets and the wave propagation itself in complex models will also affect the seismic resolution.

General speaking, seismic imaging is just as follow:

$$I=R*m \tag{1}$$

where *I* means the seismic PSDM image, * means the convolution and *m* is the velocity model. When *R* is a pulse function, the best seismic resolution will be achieved. But due to the limited geometry aperture, different source and receiver distance or different source wavelets will not allow *R* to become a pulse. It will spread out correspondingly at the imaging point, which we called the Points Spreading Functions (PSF). The PSF carries the full information, including the information regarding the model, such as complex model structure; the wave propagation information such as the multiple reflection of seismic waves, the type conversion of seismic waves and the noises generated by random media; and the geometry parameters such as the receive apertures of each shot, the offset variations and the bandwidth of source wavelets.

After the 2D Fourier transform, the 2D wavenumber spectrum will be generated from the PSF at the interested position in the complex model. The physical meaning that the 2D wavenumber spectrum is that the illumination vectors of all the source and receiver pairs sum up at the interested position, which, based on the ray tracing theory, can be expressed as follow for a source point (S) and a receiver point (R) within a local range (see Figure 1):

$$I_{SR}=p_S-p_R \tag{2}$$

where p_S and p_R are the slowness vectors of the incident wave and the scatterd wave fields respectively within the local subsurface range, which can be obtained by solving Eikonal equation; I_{SR} is the illumination vector; and wavenumber vector $k_{SR}=f \cdot I_{SR} =f(p_S-p_R)=k_R-k_S$, through which you can see that k_{SR} is a function closely connected with frequency.

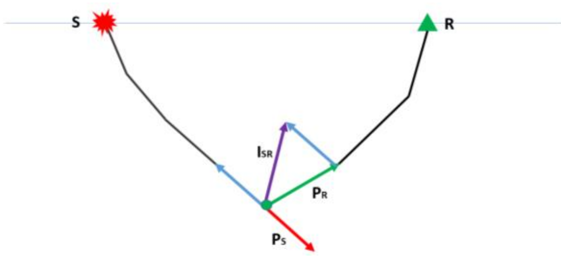


Figure 1: The local illumination vector

The wavenumber vector from the same point underground are supperpositioned multiply using different source and receiver pairs to get a wavenumber spectrum (see Figure 2); and the wavenumber specturm achieved from the PSFs through Fourier transform is just the superposition of the k_{SR} that makes up of all the source-receive points of the entire geometry, where the length of k_{SR} indicates the resolution:

$$R_x=\frac{2\pi}{\Delta k_x}$$
$$R_z=\frac{2\pi}{\Delta k_z} \tag{3}$$

where R_x and R_z are the horizontal and the vertical size of imaging resolutions respectively at the corresponding interested point, i.e. the range of the PSF reflects the size of resolution, and its amplitude reflects the intensity of illumination, which is closely relative with the migration imaging resolution.

The size and the sharpness of PSF directly indicate the imaging resolution of the target for different geometry parameters. In order to further quantify them into the imaging resolution, we can simplify it into an envelope computation process. For a local point, we can obtain its envelope through Hilbert transform. The size of its envelope indicates the size of resolution and the amplitude of its envelope indicates the sharpness of the imaging point. The bigger the amplitude of envelope, the sharper the image will be. By the quatification, we can compare the effects of different geometry parameters to the imaging resolution.

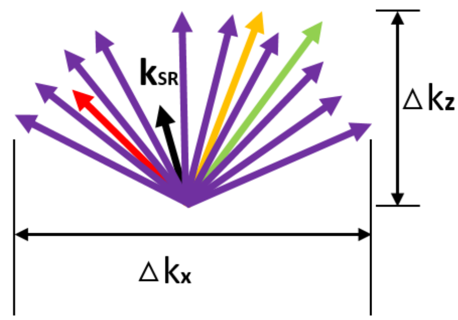


Figure 2: Wavenumber spectrum of different source-receiver points after multiple superposition processing

Numerical example

Here, we used a 2D model with a very complex structure (Figure 3). The length of the model is 10 km; the depth of model is 5 km; both the lateral and the vertical grid sizes are equal, 5m; and the velocity ranges from 2,000m/s to 5,000m/s.

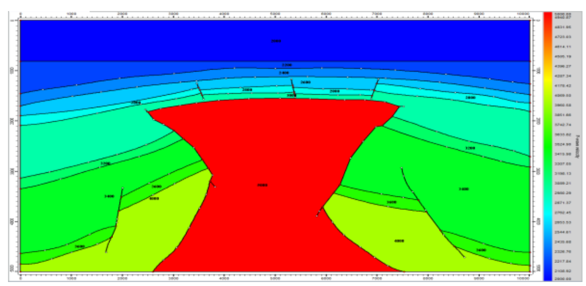


Figure 3: A velocity model: length × depth = 10km × 5km.

In order to avoid the interaction between the target points, the distance between the perturbation points are enlarge to 500m, i.e. we embed a 10% perturbation every 500m in both lateral and vertical direction in the model to compute the PSFs and their wavenumber spectrums so as to compared the effects of different geometries and wavelets to the imaging resolution.

Firstly we lay out 300 shot points. The first source is located at 2 km and the last one at 8 km from the beginning of the model; the source interval is 20m; each shot contains 801 receivers and the receiver interval is 5m; the maximum offset for each shot is 2 km; the dominant frequencies of ricker wavelets used are 16 Hz, 24 Hz and 32 Hz respectively. Figure 4 are the PSFs computed using these three wavelets. The data windowed by the red squares are chosen for resolution comparison (Figure 5). We can see that with the decrease of the wavelet frequency, the size of PSF for the same geometry changes, the higher the wavelet frequency, the smaller the size of PSF.

Figure 6 and 7 are the wavenumber spectrums achieved from the PSFs in Figure 4 and 5 respectively by Fourier transform. With the increase of the dominant frequency of wavelet, the distribution range of the wavenumber spectrum is increasing. The size of the spectrum in Figure 7 (right) is twice as that in Figure 7 (left), similar to the case of the dominant frequency of wavelet used; while the size of imaging point is inversely proportional to that of wavenumber spectrum, indicating that the higher the dominant frequency of wavelet, the better the PSDM resolution will be. This conclusion coincides with our common sense, namely, wavelet of high dominant frequency is more beneficial to PSDM imaging resolution.

As we know that the imaging quality is not only controlled by the dominant frequency of wavelet, it is also affected by many geometry parameters such as the maximum offset, the source and receiver intervals. We use the above method to compare the influence of different source or receiver interval to imaging resolution.

Similarly, we also lay out 300 shot points. The first source is located at 2 km and the last one at 8 km from the beginning of the model; the source interval is 20m; the maximum offset for each shot is 2 km; the receiver interval is 5m, 10m, 20m, 40m and 50m. The dominant frequency of Ricker wavelet is 32Hz. Figure 8 shows the zoom in of the PSFs at the same position in Figure 5. It can be seen that when the different receiver intervals 5m, 10m or 20m is adopted, the distribution range of PSF is almost unchanged, in another word, the variation of receiver interval does not affect the size of imaging point. With the continuously increasing of the receiver interval, the noise in the PSDM image increases gradually, but you can see if you check carefully that the size of PSF is still unchanged except that the noise blurs the image of the PSFs, leading to the decrease of imaging S/N ratio. Hence, we can get an initial conclusion that when other factors are unchanged, the change of receiver interval does not affect the size of imaging resolution, but the sharpness of the imaging resolution at the imaging point.

Then we fix the receivers in each shot, the maximum offset is also 2 km, the source intervals are 20m, 40m, 50m, 100m and 200m. The dominant frequency of Ricker wavelet is also 32 Hz. The analyzed position in Figure 9 is identical with that in Figure 8. So does its distribution when the receiver interval changes, and similarly the change of source interval does not affect the size of image much except the sharpness of PSDM image. After that, we compute the envelopes of PSFs in Figure 8 and 9 using Hilbert transformation.

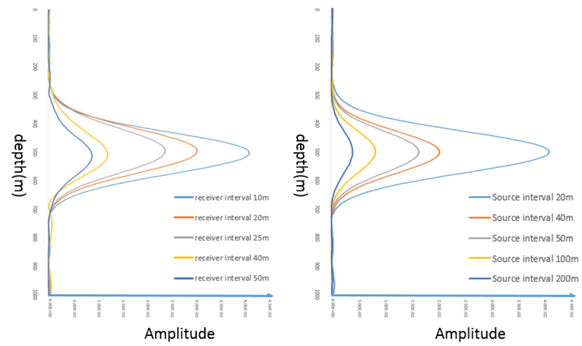


Figure 10: The envelopes of PSFs computed with the geometry parameters in Figure 8 and 9.

Figure 10 is the envelopes of PSFs drawn using different geometry parameters. The amplitudes of the envelopes indicate that with the increase of source or receiver interval, the amplitude will decrease gradually, which also indicates that the sharpness of its image will also decrease gradually.

Conclusions

In this paper, a time-spatial domain acoustic finite difference forward modeling method is used on the basis of any complex seismic-geological model to compute the PSFs of different geometry parameters at different interest positions as well as their wavenumber spectrum and envelope, and thus compare the PSDM imaging resolutions of different parameters. The method is mainly implemented in 2D complex model in this paper and it can be extended to 3D cases easily.

It is observed that seismic wavelet is the most import element that affects the seismic PSDM resolution; and the S/N ratio of seismic data and the geometry parameters are other very important elements that affect the sharpness of resolution. Using this method, we can change the input wavelet, the source or receiver interval and the maximum offset, and thereby compare the influences of different geometry parameters to the imaging resolution and provide a method for seismic survey design and optimization. In the seismic survey design process, the dominant frequency of wavelet must be ensured firstly to meet the requirement of resolution size; and then reasonable geometry parameters must be used to ensure the S/N ratio of data according to the sharpness of imaging resolution.

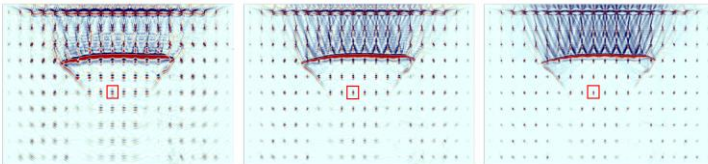


Figure 4: PSF of different Ricker wavelets. Left: 16 Hz; middle: 24 Hz; and right: 32 Hz.

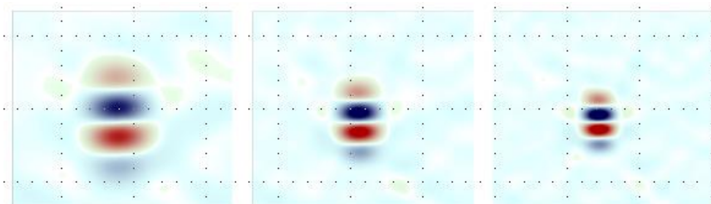


Figure 5: Zoom in of the PSFs in Figure 4. Left: 16 Hz; middle: 24 Hz; and right: 32 Hz.

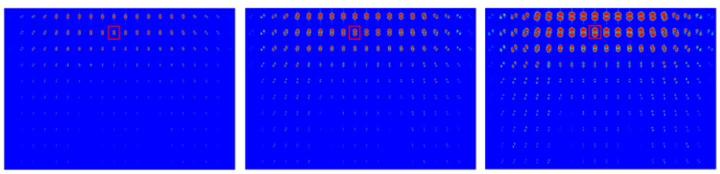


Figure 6: The wavenumber spectrums achieved from the PSFs in Figure 4 by Fourier transform. Left: 16 Hz; middle: 24 Hz; and right: 32 Hz.

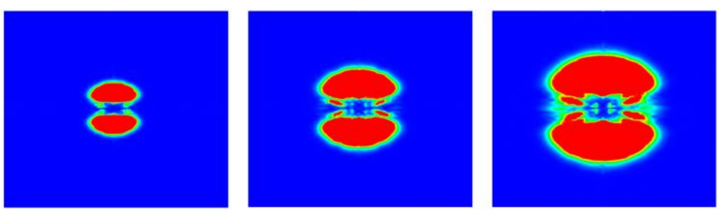
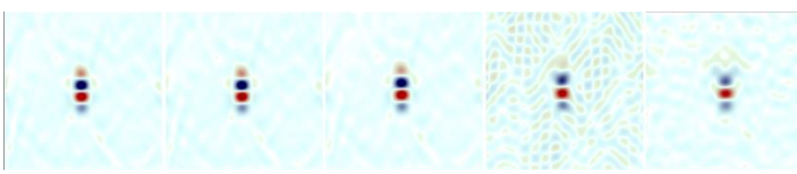
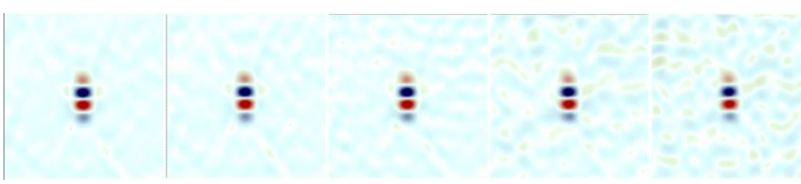


Figure 7: The zoom in of the wavenumber spectrums in Figure 5. Left: 16 Hz; middle: 24 Hz; and right: 32 Hz.



(a) (b) (c) (d) (e)

Figure 8: The zoomed in PSFs of different receiver intervals: (a) 5m; (b) 10m; (c) 20m; (d) 40m; and (e) 50m.



(a) (b) (c) (d) (e)

Figure 9: The zoomed in PSFs of different source intervals: (a) 20m; (b) 40m; (c) 50m; (d) 100m; and (e) 200m.

EDITED REFERENCES

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