Enhancement in Seismic Imaging using Diffraction Studies and Hybrid Traveltime Technique for PSDM

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Abstract. The accurate migration of seismic data is conditional on the parameters which are nominated. The effective velocity used in residual processing for migration is small compared to the original migration velocity. Considering traveltime computation is a significant part of seismic imaging algorithms. Conventional implementation of Kirchhoff migration is essential for precomputing a traveltime table from the categories involving traditional ray-tracing methods and finite difference eikonal solvers. In this paper, we examine the accuracy using, the eikonal solver and paraxial ray tracing traveltime computation in pre-stack Kirchhoff depth migration. This hybrid traveltime technique can be applied to a variety of problems related to faults, fractures, and complex region. To evaluate the relevance of this identical traveltime technique, we applied on a Marmousi data set.

1. Introduction

The expectation of a geophysicist about the subsurface is as complex as he/she can deliberate; this is, because real geology is undergone with dissimilar procedures and a long tenor to survive. So, information approached through seismic imaging will be more complex as the velocity is a multifarious structure. Marmousi is one of the complex and standard model which have been used to prove seismic imaging algorithms. The downward continuation of source and receiver by finite difference is relatively slow and dip-limited compared to the Kirchhoff integral implements migration, which has no dip inadequacy\cite{1}.

Migration is the one of primary seismic imaging tools; but, the earliest analogue seismic record was an illustration of a simple single-fold. These records were comprised of diffracted energy and random noise; but, those records still gave an interpretation of the earth’s subsurface. Mechanical migration removed the structural misrepresentation on early seismic data, and the CMP stack condensed the amount of random noise when diffracted energy was preserved. The subsequent development of DMO \cite{2} was used a method to expand the dip bandwidth of CMP stacking. Later on, the discovery of DMO (that is a procedure of pre-stack migration), led to a demand for migration methods with greater steep-dip imaging together with depth migration, leading to the wide range of migration techniques currently available \cite{3}.

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Traveltime computation plays an important role in seismic imaging. Several migration algorithms have been established on ray theory (high-frequency assumption). The lesser the curvature or the greater the radius of the curvature will give an improved quality of the ray-path. On the other hand, if the curvature of the ray is too big, the projecting point is not single, and also the Taylor series expansion is inaccurate; so, a poor migration result may suffer from the inaccurate calculation of traveltime [4].

In this paper, we have used a processing workflow including sorting into CMP order, NMO correction and stacking for diffraction studies. Using slope frequency filtering in f-k domain, separation of diffracted event and dipping reflector is done for diffraction studies. Kirchhoff PSDM is applied to the pre-stack data for imaging and traveltime is computed by paraxial ray-tracing and Eikonal solver which is a hybrid traveltime method for enhancement of imaging results.

2. Methodology

2.1. Theory and Method

Finite Difference Method

Here, for the modelling process, we took the velocity and density as the input, and the output was the seismic data. For the seismic inversion case, the input is traces and the out is the structural image. Both of these (Modelling and Inversion), common quantities are required to be calculated. These quantities consist of [4]:

- $\phi$ Propagation Angle
- $\tau$ Travel Time
- $\beta$ Incident Angle from Source or Receiver
- $\sigma$ Running Ray Parameter
- $\frac{\partial \beta}{\partial x}$ Geometrical Spreading Parameter

For each source or receiver, the above quantities satisfied the following equation [4]:

\[
\left( \frac{\partial \tau}{\partial x} \right)^2 + \left( \frac{\partial \tau}{\partial z} \right)^2 = \frac{1}{v(x, z)} \tag{1}
\]

\[
sin \phi = v \frac{\partial \tau}{\partial x} \tag{2}
\]

\[
\frac{\partial \sigma}{\partial x} \frac{\partial \tau}{\partial x} + \frac{\partial \sigma}{\partial z} \frac{\partial \tau}{\partial z} = 1 \tag{3}
\]

\[
\frac{\partial \beta}{\partial x} \frac{\partial \tau}{\partial x} + \frac{\partial \beta}{\partial z} \frac{\partial \tau}{\partial z} = 1 \tag{4}
\]

\[
\frac{\partial}{\partial x} \left[ \frac{\partial \beta}{\partial x} \right] + \frac{\partial}{\partial x} \left[ \mu(x, z) \frac{\partial \beta}{\partial x} \right] = 0 \tag{5}
\]

where $v(x, z)$ is the velocity and

\[
\mu(x, z) = \frac{\partial \tau}{\partial x} \left[ \frac{\partial \tau}{\partial z} \right]^{-1}
\]

Equation (1) eikonal equation, Equations (3) and (4) are derived by Pusey and Vidale (1991). Equation (5) follows from equation (3).
2.2. Travel time computation

Figure 1 describes the ray-tracing phenomena in a complex and heterogeneous medium with 100 rays. Paraxial optics can be defined as a ray-tracing accomplished in the limits of very small ray angles and heights. They allow us to make a number of simplified assumptions that make the arithmetic of ray-tracing considerably easier.

![Figure 1: Trajectories of 100 rays emitted by a source point in a heterogeneous medium. Shadow zone and multi-pathing effect can be seen [5].](image)

The eikonal differential equation is used for the elementary mathematical models which describe the traveltime (eikonal) propagation in a velocity model. The benefits of this method in comparison with ray tracing techniques comprise the capability to work on consistent model grids, a wide-ranging coverage of the receiver space, and a reasonable numerical robustness. A common implementation of the finite-difference eikonal equation is calculating the first-arrival travel times, though frequency-dependent enrichments.

The eikonal equation, describing the traveltime propagation in an isotropic medium, has the form:

\[ (\nabla r)^2 = n^2(x, y, z) \]

where \( r(x, y, z) \) is the traveltime from the source to the receiver point with the coordinates \( (x, y, z) \), and \( n \) is the slowness at that point (the velocity \( v \) equal to \( 1/n \)) [6].

This method calculates each traveltime table by paraxial ray-tracing, then in the shadow zone (Figure 1) the traveltimes are computed by solving the eikonal equation.

3. Results and Discussion

We have tested the above travel time calculation method to validate the results in a 2D Marmousi model. The Marmousi model has been considered as identical with the phrase complex media (Figure 2). The huge numbers of faults and folds induced in the model has created an interesting distribution of velocity anomalies and discontinuities. Thus, the Marmousi model has serve as a calibration tool used to test the various traveltime and migration algorithms. The data was produced using a 2-D acoustic finite-difference modelling programme.
Figure 2: Marmousi model, velocity range from 1650 m/sec to 4600 m/sec. 3 major faults, unconformity, anticline structure and overburden in the deeper section.

Figure 3: Seismic gathers before the NMO (Normal move out) correction (left). Seismic gather after the NMO correction. Events are slightly strait at the true reflection points (right).

Velocity analysis is a crucial job in processing; before the NMO correction we picked the correct velocity at different points. Figure 3 (left), we can see the move-out decreased when an increasing time and velocity; this is cause of poor resolution in deeper area. Figure 3 (right) shows selected shot points (17070, 17170, & 17270) from the section to illustrate the results after the NMO correction.
Figure 4: Stacked seismic sections after sorting the gathers to the CMP. Diffraction hyperbola can be seen at the faults, pinchouts and discontinuity.

Figure 5: Seismic Diffraction section by using the linear interpolation technique to determine the slope and amplitude on the dipping reflectors.

Figure 6: Seismic sections after the Kirchhoff PSDM using the hybrid traveltime calculation technique.
Figure 4 shows the stacked section before migration, in which we can recognise the diffraction hyperbolas where the faults and pinchouts are in the model (Figure 2). Migration aperture is one of parameters to stack the diffraction hyperbola. In this algorithm, we have used the 40 degree migration aperture to stack the hyperbola energy at the apex. Migration aperture smaller than the optimal size, will cause the destruction of the faults, fractures and pinchouts. More importantly, large apertures will degrade the migration quality in a poor signal-to-noise ratio and increase the cost of the computational power without any quality improvement [7]. After converting the shot gather to the CDP gather we applied the frequency dip filtering in the F-k domain to separate the diffraction and faults from the reflection (Figure 5). Figure 6 shows the final results of the Kirchhoff migration using a hybrid traveltine. Faults and pinchouts that make a complex velocity structure in deeper sections have been illuminated and can be interpreted properly. Amplitude spectrum is achieved by applying Fourier transform to the data in time domain (Figure 7), which is explaining the amplitude distribution with frequency and trace number. We can see the amplitude in the deeper section is affected by the faults and cause of poor amplitude recovery in the deeper section, both side on the corners amplitude is recovered.

4. Conclusions

We integrated two approaches to illuminate the subsurface structure using initial processing and migration. A hybrid traveltime computation method for PSDM has been studied in the imaging context. The propose study has validated that, the hybrid traveltime computation method for Kirchhoff migration is a tool for enhancement of imaging results in complex geological settings. In conventional data processing, either the eikonal solver or paraxial ray-tracing are used. The results demonstrate the significance of using hybrid traveltime computation, and provide more conceding results. We have used a Marmousi data set to prove this application algorithm, which is a complex geological model. On the processing side, sorting, CMP gathering, NMO correction, and stacking have been performed for the diffraction studies. Diffractions have been separated using dip frequency filtering in the f-k domain. The existence of a hyperbolic pattern is an indication of faults and/or fracture because of abrupt changes of velocity and acoustic impedance contrast. After application of the imaging algorithm with the correct aperture selection, each hyperbola was stacked at their apex. Overall, the hybrid traveltime imaging algorithm enables one to improve the imaging result for complex structures such as faults, fractures and structures below the complex velocity.
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