Near-Seabed Velocity Modeling Techniques of Pre-Stack Depth Migration for Shallow Water Marine Data

Wang Binggang[1], Ding Chengzhen[1], Yu Ming[1], Chen Xin[1], Song Jiawen[1], Chen Yingpeng[1], Hu Xin[1], Gao Jiangtao[1], Dong Qingyu[1], Zhang Dan[1], Cheng Hu[1], Zhang Ran[1], Wang Xi[1], Kang Xupeng[1]

[1]Bureau of Geophysical Prospecting, China National Petroleum Corporation

Extended abstract

Introduction

The quality of pre-migration seismic data, accuracy of the velocity model, and choice of migration algorithm are the main factors influencing the imaging results of pre-stack depth migration in petroleum seismic data processing[1-4]. Pre-stack depth migration involves continuously optimizing the velocity field in the depth domain to achieve accurate imaging. The accuracy of the shallow velocity model plays a crucial role in the entire migration profile, spanning from shallow to deep layers. It significantly impacts the imaging quality during the velocity iteration and optimization process. The structure and imaging quality of the entire depth migration profile are particularly sensitive to the influence of the shallow velocity model. Conversely, errors in the deep velocity model have relatively minor effects on the imaging quality of the depth migration profile. Therefore, establishing and optimizing the shallow velocity models, especially near-seabed velocity models, are of utmost importance in depth migration processing. These tasks are considered top priorities, as they directly contribute to the success of depth migration and ultimately enhance the overall imaging quality.

The initial velocity field for pre-stack depth migration is typically derived by converting the root mean square (RMS) velocity from pre-stack time migration to interval velocity in the depth domain. However, accurate RMS velocity analysis in the shallow layers, especially near-seabed areas, is challenging due to the limited availability of mid to long offset information. As a result, the reflection events in these regions are not sufficiently clear for reliable RMS velocity analysis during pre-stack time migration processing. Consequently, the RMS velocity in the shallow part and near-seabed areas may not be accurate. Similarly, the reflection events in common reflection point (CRP) gathers obtained through pre-stack depth migration are also not sufficiently distinct for reflection tomography, which is a primary method for updating the velocity model for pre-stack depth migration. Therefore, conventional methods fail to produce an accurate velocity model in the shallow part and near-seabed areas. Over the years, researchers worldwide have proposed various modeling methods to address this challenge[5-8]. These methods make use of different sources of information to establish initial velocity models for the shallow part and near-seabed area, such as micro-logging, small refraction seismic surveys, vertical seismic profiling (VSP) logging, acoustic logging, tomography inversion, gravity exploration, magnetic exploration, and electrical exploration, etc. In traditional pre-stack depth migration approaches, the pre-migration seismic data usually undergo static correction, where the near-seabed velocity model is replaced by a replacement velocity. However, recent studies have shown promising results by utilizing the First-Break Tomography Inversion Velocity Model (FBTIVM) to establish near-seabed velocity models in mountainous and Gobi regions[9-11]. This paper focuses on the shallow water region of the Caspian Sea and proposes a novel method for establishing the near- seabed velocity model based on FBTIVM. This study demonstrates successful pre-stack depth migration outcomes using this approach.

General Modeling Strategy for Near-seabed Velocity Model

In conventional pre-stack depth migration techniques, the seismic data used typically undergoes tomographic static correction, which involves replacing the velocity value between the sea-bed and the High Velocity Layer (HVL) with a constant replacement velocity. This approach is employed to address the challenge of complex variations in the near-seabed velocity model by simplifying it through static correction. However, this method represents a compromise solution that neglects the lateral and vertical variations in the near-seabed velocity. The drawback of this approach is that the wave field in the near- seabed area does not accurately reflect the actual subsurface conditions. As a result, errors introduced in the near-seabed region can accumulate and propagate to deeper layers, ultimately impacting the quality of the migrated image for the entire seismic profile.

The approach presented in this research paper involves integrating the First-Break Tomography Inversion Velocity Model (FBTIVM) with the initial velocity model at the High Velocity Layer (HVL) interface. This method offers several advantages compared to conventional techniques. Firstly, it ensures that the wave field in the near- seabed area is more representative of the actual subsurface conditions, allowing for a more accurate restoration of the true propagation path of seismic waves. By doing so, it effectively avoids travel time errors in the near- seabed regions and prevents the accumulation of these errors in deeper layers. Through a series of velocity updating iterations, the proposed method achieves a more refined pre-stack depth migration imaging outcome. Importantly, this approach eliminates the need for the compromise solution of applying tomographic static correction and directly addresses the complexities of the near-seabed velocity. As a result, it provides a more scientifically and logically solution. The effectiveness of this new method has been demonstrated through successful application in the shallow water regions of the Caspian Sea, yielding favorable results.

By incorporating the First-Break Tomography Inversion Velocity Model (FBTIVM) instead of a replacement velocity value, adjustments need to be made to the pre-migration seismic data that has already undergone tomographic statics correction. There are two approaches to perform the necessary time shift on the pre- migration seismic data. The first approach involves directly applying the inverse of the tomography static correction value to the data. The second approach, also called the Equivalent Time Shift (ETS) method, involves scaling the HVL from the depth domain to the time domain using the FBTIVM and the replacement velocity respectively. The difference between these two scaled values is calculated. This difference is then divided by two and matched to the source and receiver points based on their coordinates. Finally, the corresponding values are applied to shift the pre- migration seismic data. Comparing these two methods, the ETS method yields superior migration imaging results. The migration imaging obtained using the former method exhibits some structural distortion in the shallow portion. Therefore, the ETS method is preferred as it provides better accuracy and reduces potential distortions in the shallow part of the migrated image.

Merging the FBTIVM to the Top of Initial Velocity Model

In near-seabed velocity inversion, the process involves utilizing first-break values to perform iterative tomography inversion. The first arrivals considered in this context encompass direct waves, refraction waves, and turning waves. The iteration process of first-break tomography inversion is built upon the seismic travel time equation:

$$t = \int \frac{dl}{v(x,z)}$$

Firstly, calculate the time field function T(x, z) based on the functional equation outlined in formula (2):

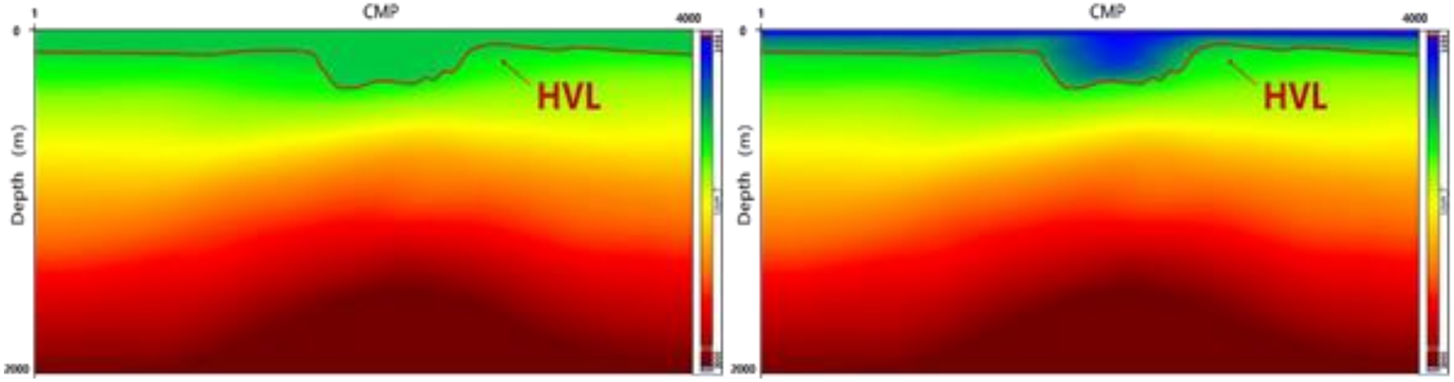
$$\left(\frac{\partial t}{\partial x}\right)^2 + \left(\frac{\partial t}{\partial z}\right)^2 = \left(\frac{1}{v(x,z)}\right)^2 \tag{2}$$

Subsequently, the ray path is traced to generate a travel time residual equation that is computationally straightforward:

$$\Delta t = A \cdot \Delta s \tag{3}$$

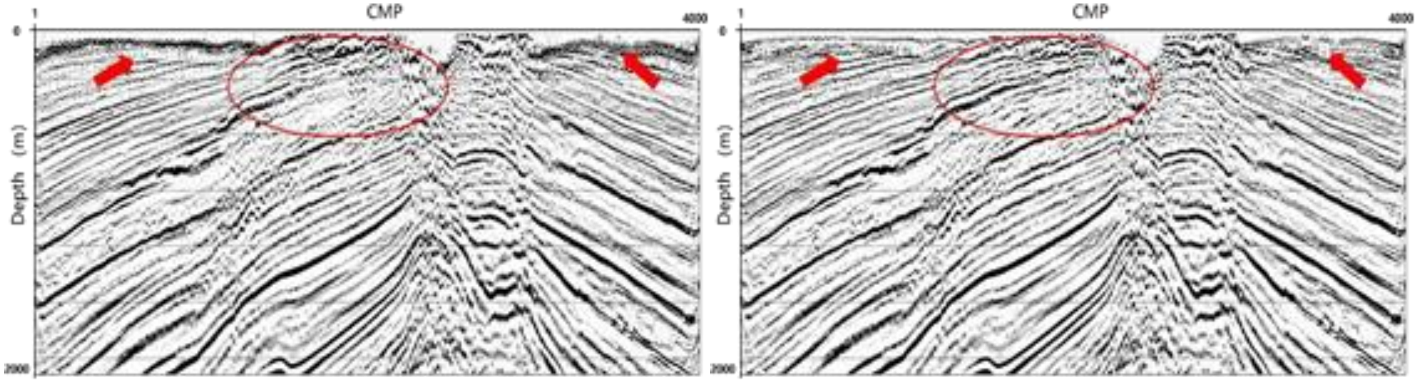
In equation (3), the travel time residual vector is represented by Δt, A denotes the geometric path matrix of the seismic wave ray, and Δs represents the slowness increment vector. Through collaborative solving of the travel time residual equation with specific constraints, the velocity model of the near-seabed can be obtained by an iteratively computation. To enhance the accuracy of the inversion process, constraints are typically applied using micro-logging data. These constraints serve as additional information that aids in achieving improved outcomes during the iterative operations.

The velocity model derived from the first-break tomography inversion method for near-seabed exploration is not entirely precise. However, it is relatively closer to the actual velocity field when compared to the replacement velocity. Typically, it is necessary to smooth the First-Break Tomography Inversion Velocity Model (FBTIVM) and subsequently integrate it into the initial velocity model at the interface of the High Velocity Layer (HVL). The smoothed FBTIVM exhibits a velocity variation trend that is more consistent with the actual velocity field while avoiding abnormal changes that could result in structural deformation in deeper layers.



(a) (b)

Figure 1. (a) Replacement velocity merged to initial velocity model at the interface of HVL.
(b) FBTIVM merged to initial velocity model at the interface of HVL.



(a) (b)

Figure 2. (a) Pre-stack Depth Migration Image with replacement velocity merged to initial velocity model at the interface of HVL. (b) Pre-stack Depth Migration Image with FBTIVM merged to initial velocity model at the interface of HVL.

In Figure 1, two velocity models were utilized for migration testing. One model involved integrating the replacement velocity model at the interface of HVL into the initial velocity model, while the other model integrated the FBTIVM at the same interface. Figure 2 displays the resulting migration images from the two velocity models. The image quality of the latter velocity model is superior to that of the former velocity model. There is a higher level of resolution and clarity in the shallow area in Figure 2(b). This improvement is due to the FBTIVM providing more accurate velocity values when compared to the replacement velocity, which ultimately leads to more precise pre-stack depth migration imaging.

Time Shift Method of the Pre-migration data

After integrating the FBTIVM into the initial velocity model, the next crucial step before migration is to perform time shifting on the pre-migration data. The purpose of this time shift is to align the data with the velocity model. Since the pre-migration data has already undergone tomography static correction using the replacement velocity, it is necessary to apply a time shift to ensure proper alignment. There are two methods for conducting the time shift. One way is directly applying the inverse of tomography static correction, the other way is utilizing the Equivalent Time Shift (ETS) method. In the specific survey analysed in this study, the source and receiver points were positioned at sea level after the tomography static correction. The detailed process for performing the time shift involves four steps:

Step One: Shifting the source and receiver points from sea level to the seabed using the water velocity.
Step Two: Shifting the source and receiver points from the seabed to the HVL using the replacement velocity.
Step Three: Shifting the source and receiver points from the HVL to the seabed using the FBTIVM.
Step Four: Shifting the source and receiver points from the seabed back to sea level using the water velocity.

To simplify the above four steps, they can be condensed into the following two steps:

Step One: Scaling the HVL from the depth domain to the time domain using the replacement velocity and FBTIVM respectively, resulting in two corresponding layers, H_1 and H_2 correspondingly.
Step Two: Calculating the difference between H_1 and H_2 and dividing it by two, as shown in Formula
(4). This yields the value of H_{mis}. Matching the H_{mis} values to the source and receiver points by theirs coordinates and subsequently shifting the seismic traces accordingly.

By following these steps, the pre-migration data can be properly aligned with the velocity model for accurate migration. The simplified two-step approach described above is called the Equivalent Time Shift (ETS) method, which is essentially equivalent to the four-step method mentioned previously.

$$H_{mis} = \frac{1}{2}(H_2 - H_1) \tag{4}$$

The main difference between directly applying the inverse tomography static correction method and utilizing the ETS method lies in their respective abilities to preserve high-frequency values in the tomography statics correction. The ETS method is particularly advantageous as it ensures the retention of these high-frequency static correction values, which ultimately contributes to the generation of superior pre-stack depth migration images. Figure 3 illustrates the calculated H_{mis} within the survey area. The map exhibits a relatively smooth distribution without any noticeable high-frequency values.

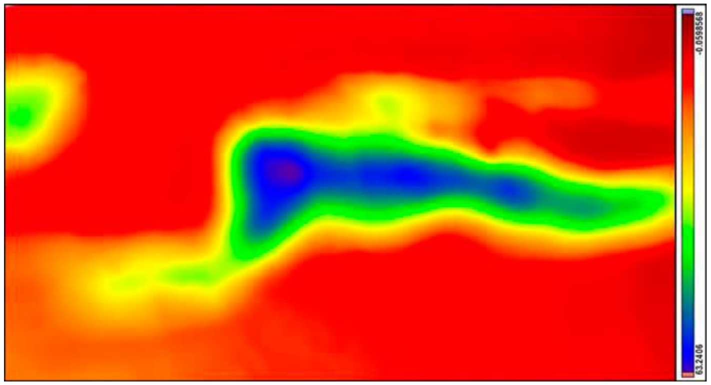
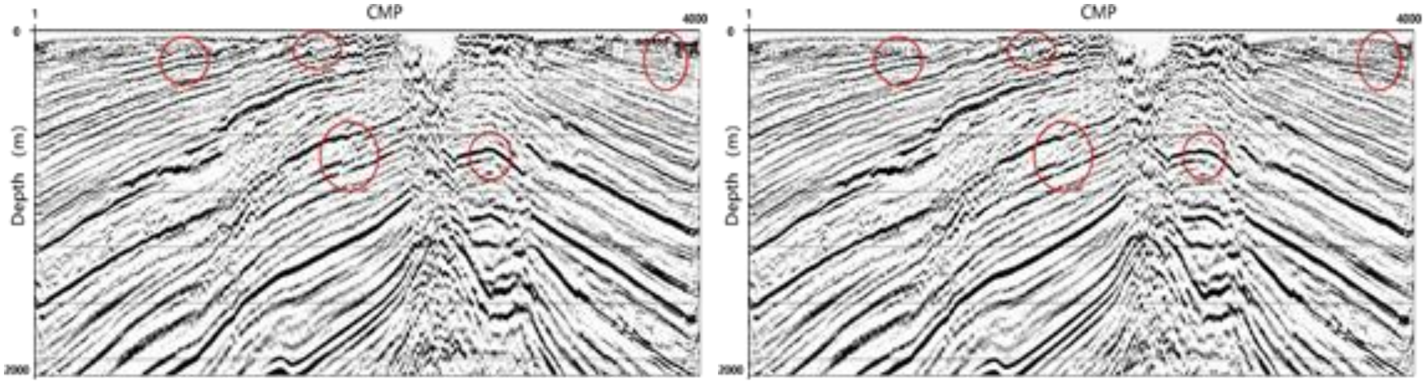


Figure 3. H_{mis} map calculated in the survey area.



(a) (b)

Figure 4. (a) Pre-Stack Migration Image with time shift method directly applying the inverse of tomography static correction (b) Pre-Stack Migration Image with ETS method

The migration results of the pre-migration data using two different time shift methods are depicted in Figure 4. The velocity model employed is the same as the one with the FBTIVM integrated into the top of the initial model at HVL. Upon comparing the two migration images presented in Figure 4, it is evident that the migration result obtained with the ETS method shown in Figure 4(b) exhibits reduced structural distortion in the shallow section and overall superior migration quality compared to Figure 4(a). This comparison outcome serves as evidence for the advantage of utilizing the ETS method.

Conclusions

The quality of pre-stack depth migration imaging heavily relies on the accuracy of the velocity model. Particularly, the accuracy of the velocity model in the shallow section and near-seabed area has a more significant impact compared to the deeper sections. However, constructing and updating a near-seabed velocity model has long been a challenging task. This study focuses on seismic data analysis in the shallow water region of the Caspian Sea. To obtain an optimal underground layer image through pre-stack depth migration, an innovative technique for building the near-seabed velocity model is proposed.

The proposed technique involves merging the First Break Tomography Inversion Velocity Model (FBTIVM) with the initial velocity model at the High Velocity Layer (HVL). Consequently, the pre-migration seismic data is adjusted using the Equivalent Time Shift (ETS) method. Two sets of tests were conducted to evaluate the effectiveness of the technique. The first set of tests demonstrated that the FBTIVM model outperformed the replacement velocity model, as it produced a migration image with clearer events and higher resolution in the shallow section. The second set of tests confirmed that employing the ETS method for time shifting the pre- migration seismic data yielded better results than directly applying the inverse of tomography static correction. The ETS method resulted in a migration image with reduced structural distortion in the shallow section. Overall, the technique proposed in this study effectively addresses the challenges associated with the near-seabed velocity model of pre-stack depth migration for shallow water marine data in the Caspian Sea.

Reference

[1] SU Qin, LV Bin, TIAN Yan-can, et al. Application of Floating Datum Pre-stack Dpeth Migration Method to Piedmont Complex Structure Imaging [J]. XINJIANG PETROLEUM GEOLOGY, 2009, 30(5):560-562.

[2] Ma Yanyan, Li Guofa, Zhang Xingyu, et al. Strategy of velocity model building in pre-stack depth migration [J]. OIL GEOPHYSICAL PROSPECTING, 2014, 49(4): 687-693.

[3] PAN Xing-xiang, QIN Ning, QU Zhi-peng, et al. Tomography velocity modelling and application of pre- stack depth migration. Progress in Geophys, 2013, 28(6): 3080-3085.

[4] Zhang Qiaoling, Dai Haitao, Gu Faming, et al. Research and application of velocity modelling technology in complex structural areas [C]. Proceedings of the 2022 Geophysical Exploration Technology Seminar of the Chinese Petroleum Society, 2022: 724-726.

[5] Yang Qinyong, Fang Wubao. A study on seismic imaging techniques in complex surface and subsurface areas [J]. Oil and Gas Geology, 2008, 29(5): 676-682.

[6] WANG Hong-qi, LU Lie-qing, LIU Wen-qing. Application of 3D Pre-stack Depth Migration in Complex Area [J]. XINJIANG PETROLEUM GEOLOGY, 2004, 25(5): 498-499.

[7] Fang Wubao. The model building technology in 3D pre-stack depth migration [J]. GEOPHYSICAL PROSPECTING FOR PETROLEUM, 2002, 41(2): 132-135.

[8] Bevc, D. Flooding the topography: wave-equation datuming of land data with rugged acquisition topography. Geophysics, 1997, 62(5):1558-1569.

[9] Fang Yong, Yu Liang, Li Xue, et al. The Application and Effectiveness of 3D “Ture” Surface Sequential Pre-stack Depth Migration Processing Technology in the Kelasu West Section [C]. SPG/SEG Nanjing 2022 International Geophysical Conference.

[10] YAO Xiaolong, ZHANG Yongsheng, QI Peng, et al. TTI anisotropic velocity modelling based on a smoothed surface for a piedmont zone [J]. Geophysical Prospecting for Petroleum, 2020, 59(4): 539-550.

[11] LUO Yong, YANG Xiaohai, TUO Junjun, et al. Reverse unified construction and application of approximate true surface processing datum: a case study of the Anjihai anticline in southern margin of Junggar basin [J]. Progress in Geophysics. 2021, 36(6): 2531-2539.