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Study on the Velocity Analysis Method of Low SNR Seismic Data

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Abstract

When the signal to noise ratio of seismic data is very low, velocity spectrum focusing will be poor., the velocity model obtained by conventional velocity analysis methods is not accurate enough, which results in inaccurate migration. For the low signal noise ratio (SNR) data, this paper proposes to use partial Common Reflection Surface (CRS) stack to build CRS gathers, making full use of all of the reflection information of the first Fresnel zone, and improves the signal to noise ratio of pre-stack gathers by increasing the number of folds. In consideration of the CRS parameters of the zero-offset rays emitted angle and normal wave front curvature radius are searched on zero offset profile, we use ellipse evolving stacking to improve the zero offset section quality, in order to improve the reliability of CRS parameters. After CRS gathers are obtained, we use principal component analysis (PCA) approach to do velocity analysis, which improves the noise immunity of velocity analysis. Models and actual data results demonstrate the effectiveness of this method.

Keywords: SNR, velocity analysis, CRS super gathers, ellipse evolving stacking, PCA

1. Introduction

At present, the focus of seismic exploration has shifted to the areas with strong interference, such as complicated topography areas. But the signal-to-noise ratio of seismic data obtained in these areas is very low, the reflection phase axis on the common center point (CMP) gather can not be distinguished completely, the focusing of velocity spectrum is poor, the error of the extracted stacking velocity is quite large, and it is difficult to establish an accurate velocity model, which leads to the poor effect of subsequent migration imaging. How to establish a more accurate velocity model for low SNR seismic data has become an urgent problem to be solved.

The CRS method was proposed by Professor hurbal (1983). It has takeen into account the local characteristics of the underground reflector and all the reflection information in the first Fresnel zone, and makes more effective use of the information of multiple coverage reflection data (G. hocht et al., 1998; R. J ager et al., 1998; Jurgen Mann et al., 2000; Wang Hua-zhong et al., 2004; Tian Wen-hui et al., 2006; sun Xiao-dong et al., 2007). However, traditional CRS stack only improves the quality of post stack time profile. and the partial CRS stack method studied in this paper inherits many advantages of CRS stack. as the partial CRS stack method utilizes the information about the local inclination and curvature of each reflection unit to stack the gathers that contribute to the reflection unit, making full use of the potential of multiple coverage data, which can improve the quality of prestack data and is more conducive to our subsequent processing, such as velocity analysis, stack and migration imaging.

By analyzing the search process of CRS parameters, we find that the exit angle of zero offset ray and the curvature radius of normal wavefront in CRS parameters are searched on the zero offset profile, and high quality zero offset profile can improve the reliability of CRS parameters. Compared with the conventional CMP stack method, the ellipse expansion CRP method abandons the traditional idea of common center of CMP, and stack in the original shot domain directly. Since this method makes full use of all kinds of effective information (strong or weak reflection information and diffraction information) to realize interference stack. The stack profile obtained by the ellipse evolving CRP method is bound to be better than the conventional CMP stack method (Zhou Qing-chun et al., 2009). Therefore, we can search CRS parameters on the elliptical stacking section to improve the accuracy of the parameters.

After the CRS super gathers are obtained, we can use the conventional velocity analysis method to obtain the stacking velocity. However, the conventional velocity analysis method is based on the assumption that the horizontal layer of underground medium and the time distance curve of reflected wave are hyperbolic, so it will cause large error when the stratum is inclined or the offset is large, and the noise on CRS gather will also have a great impact on the velocity analysis. In this paper, principal component analysis (PCA) is introduced into velocity analysis to enhance the anti noise and accuracy of velocity analysis.

2. Theory and Method

2.1 Partial CRS Stack Method

Partial CRS stack method is based on multi parameter CRS travel time formula, described bythree parameters (α、R_{NIP}、R_N):

$$t^2(x_m,h)=\left[t_0+\frac{2\sin\alpha}{v_0}(x_m-x_0)\right]^2+\frac{2t_0\cos^2\alpha}{v_0}\left[\frac{(x_m-x_0)^2}{R_n}+\frac{h^2}{R_{NIP}}\right] \tag{1}$$

In which t_0 is the zero offset reflection time, x_0 is the zero offset shot check midpoint position, x_m is the shot receiver center position, h is the half offset, v_0 is the surface seismic wave velocity at the point x_0 .The three stacking parameters are the exit angle α of zero offset ray, *NIP* wave andcurvature radius R_{NIP}、R_N of wave front emitted to the earth surface of N wave.

Different from the conventional CRS stack, partial CRS stack is to stack the same offset within the stacking aperture to build a high SNR prestack gather. We use CMP stack, ZO stack, CRS stack and optimization algorithm to search three wave field attribute parameters, and then use the travel time formula (1) based on partial common reflection surface stack to determine the stacking surface (as shown in Figure 1).

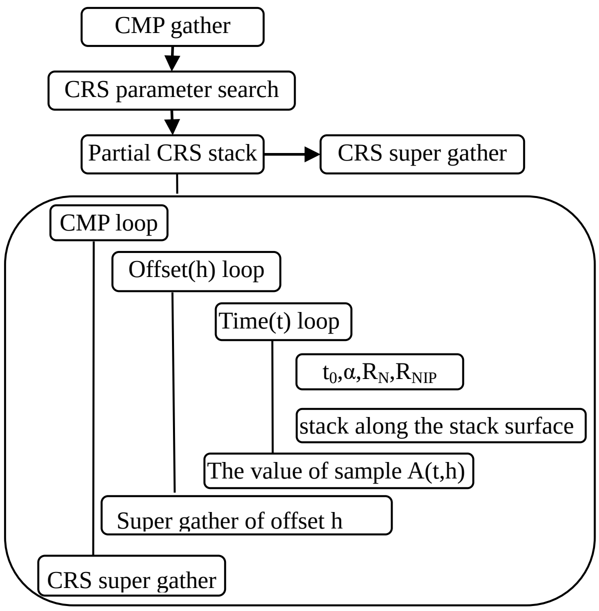


Figure 1. Flow chart of partial CRS stack

Firstly, we use the Sigsbee2a model data released by SMAART JV in 2001 to verify the correctness of the above method. The model has 45.72m offset, 348 channels receiving, 22.86m trace spacing, 87 maximum coverage times, 8ms sampling interval and 12S sampling length. We add S / N = 20 Gaussian noise to the original data. We select 1100 CMP from CMP 200 to 1299 to do the test, and construct CRS super gathers following the flow in Figure 1. It can be seen that only the strongest common phase axis is visible in CMP gathers (Fig. 2 (a)) But in CRS gathers, the reflection layer is clearly visible and the signal-to-noise ratio is significantly improved (Fig. 2 (b)).

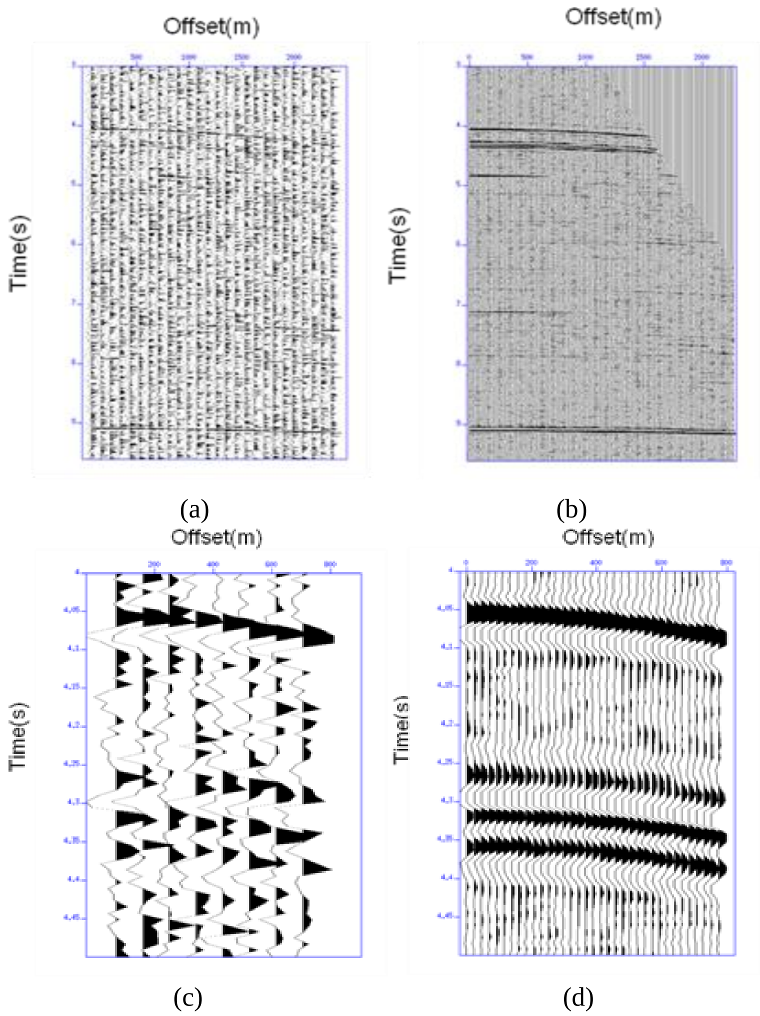


Figure 2. (a) Original CMP gather, (b)CRS gather, (c) partial enlarged drawing of (a), (d) partial enlarged drawing of (b)

2.2 Ellipse Evolving CRP Method

It can be seen from the geometric relationship in Figure 3 that the seismic wave ray excited from any focus of the ellipse must pass through another focus after being reflected by any point of the ellipse. For the homogeneous medium, the path distances and travel times of these rays are exactly the same. Given a common shot point record, the elliptic equation focusing on shot point ES and receiver point RS is:

$$\frac{z^2}{\frac{(vt)^2}{4}-\frac{l^2}{4}}+\frac{(x-\frac{l}{2})^2}{\frac{(vt)^2}{4}}=1 \tag{2}$$

In which t is the total travel time along the downward and upward rays, v is the propagation velocity in homogeneous isotropic media, offset $l = x_r - x_s$, shot point coordinate x_s , receiver point coordinate x_r .

Suppose that l_0 represents the distance between the normal of the reflection point and the shoot point on the ground, and t_0 represents the two-way travel along the normal direction, then

$$l_0 = x + z\frac{dz}{dx} \tag{3}$$

$$t_0 = \frac{2z}{v}\sqrt{1+(\frac{dz}{dx})^2} \tag{4}$$

Bringing formula (3) and (4) into (2) can get the formula of transformation from seismic record to (l_0 , t_0)domain:

$$\frac{t_0^2}{t^2-\frac{(x_r-x_s)^2}{v^2}}+\frac{(l_0-\frac{x_r+x_s}{2})^2}{(\frac{x_r-x_s}{2})^2}-1=0 \quad (5)$$

By expanding common shot gathers at time t according to formula (5) (that is to say, by projecting the normals of all possible reflection points into the zero offset time profile) we can obtain an elliptical arc AB in the zero offset profile domain, which reflects all possible positions of underground reflection points in the zero offset profile.

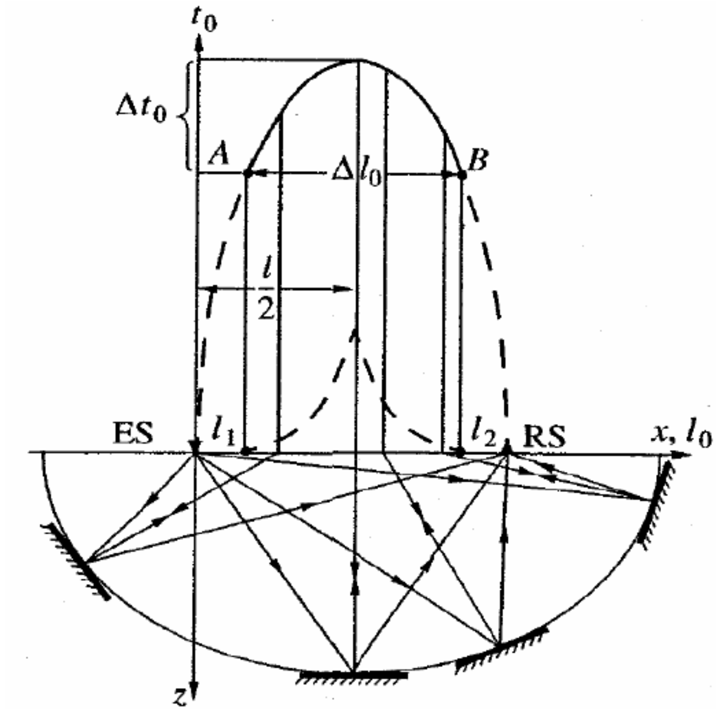


Figure 3. principle diagram of ellipse evolving

Figure 4 (b) is the ellipse evolving stacking section of the above-mentioned sigsbee2a model. Compared with Figure 3 (a), it can be seen that the signal-to-noise ratio of the ellipse evolving stacking section is higher and the structure is clearer. Figure 4 (c) is the CRS gather constructed by searching for CRS stack parameters on the obtained ellipse evolving stacking section (the stacking aperture parameters remain unchanged). Compared with Figure 2 (b), it can be seen that the common phase axis of CRS gather obtained by ellipse evolving stacking is more obvious, which indicates that the CRS parameters obtained by elliptical stacking section are more accurate.

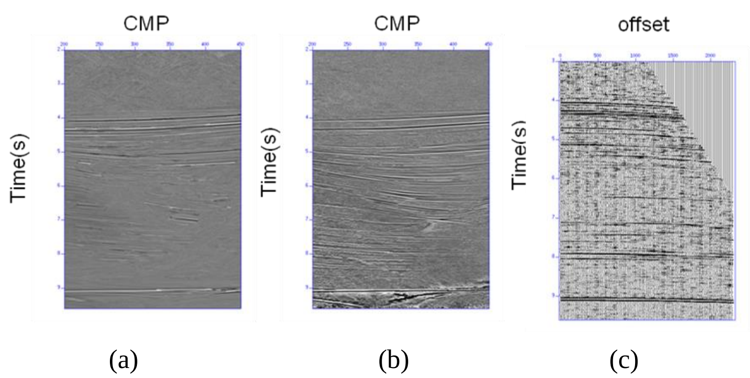


Figure 4. (a) stacking profile of CMP, (b)stacking profile of ellipse evolving, (c) CRS gather based on ellipse evolving

2.3 Principal Component Analysis (PCA) Method

Principal component analysis is a process of recombining the original P variables into a set of new independent variables. In order to make the first linear combination F1 reflect the original variable information as much as possible, the common method is to maximize the variance F1. Because the first linear combination F1 has the largest variance among all linear combinations and contains the most original variable information, it is called the first principal component. If F1 can not reflect all the information of the original variable, then we consider to choose the second principal component F2, so that F2 has the largest variance in the remaining linear combination and is not related to F1. By analogy, we can find all the P principal components, and their variance is decreasing. In practice, the first several major components should be selected for analysis to simplify the data (Sun Xiang-e et al., 2006; sun xiang-'e, 2007). By using the energy direction difference between signal and noise in seismic data, we apply PCA method to velocity analysis. By calculating the eigenvalue of covariance matrix of data volume, , we can find the effective signal in the data volume as well as the correct hyperbolic track based on the change rule of eigenvalue. The operation flow chart is as follows:

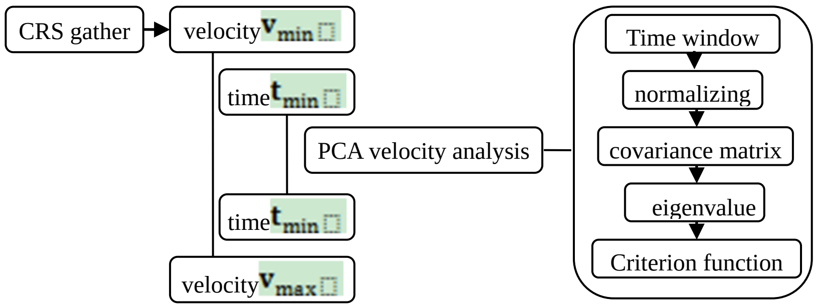


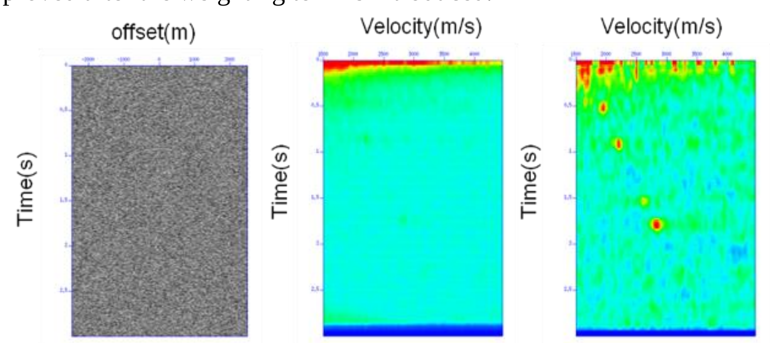
Figure 5. Flow chart of PCA velocity analysis

When the signal-to-noise ratio of seismic data is too low, the difference between signal component and noise component decreases, and the commonly used principal component analysis criterion becomes invalid. We substitute the energy term into the original function as the weighting factor:

$$Cc = \sum_{j=i-M}^{i+M} \sum_{k=1}^{N} q[j,k]^2 * \frac{\lambda_1 - \sum_{j=2}^{N} \frac{\lambda_j}{N-1}}{\sum_{j=2}^{N} \frac{\lambda_j}{N-1}} \tag{6}$$

Where M is the time window width, N is the number of seismic traces, $q[j,k]$ is the amplitude value of the jth sampling point on the kth trace, and λ_j is the eigenvalue of the covariance matrix.

Fig. 6 (b) and (c) are the PCA velocity spectrum of a CMP gather. It can be seen that the noise immunity of the method has been improved after the weighting term is introduced.

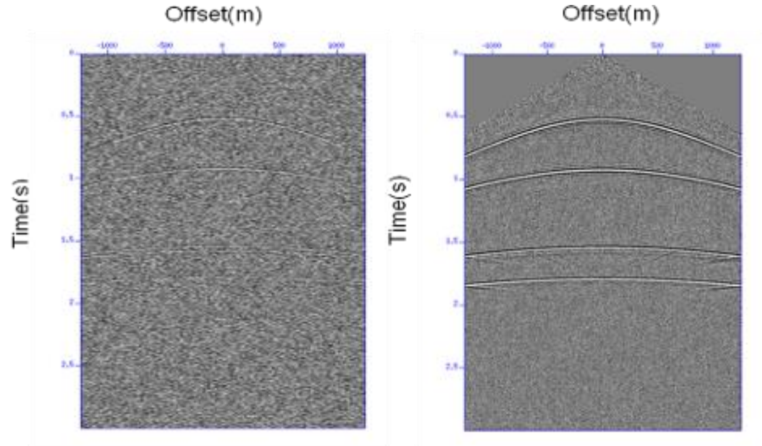


(a) (b) (c)

Figure 6. PCA velocity spectrum of (a)CMP gather, (b)the conventional method, (c) method discussed in this paper

3. Model Test

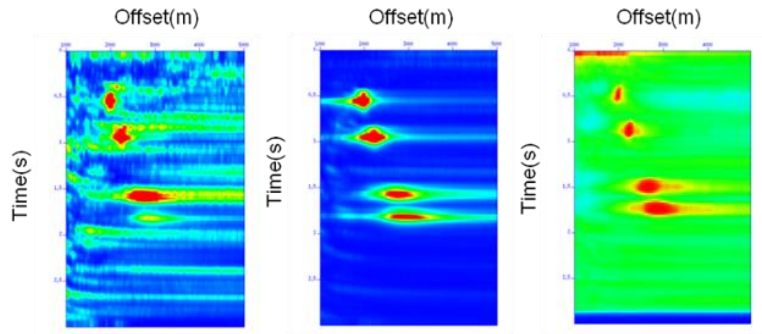
We use a four-layer depression model to test and verify the effectiveness of this method. Firstly, the model is simulated in forward modeling. The middle shot is adopted and there are 650 shots in total. 501 channels are received by each shot, with a trace spacing of 5m, CMP spacing of 2.5m, CMP ranging from 250 to 3346, sampling interval of 2ms and sampling points of 1500. After the result of forward modeling is obtained, the random noise of s/n=2 is added. We selected 800 CMP gathers from cmp1400 to 2199 for the test. Firstly, the ellipse evolving stacking profile is obtained, and then CRS gathers are constructed by searching on the ellipse evolving stacking profile based on the CRS parameters. Figures 7 (a) and (b) are CMP gathers and CRS gathers at cmp1500 respectively. It can be seen that the SNR of CRS gather has been improved significantly, and the event of reflected waves of the deep interface can be recognized by naked eyes.



(a) (b)

Figure 7. (a) Original CMP gather, (b) CRS gather

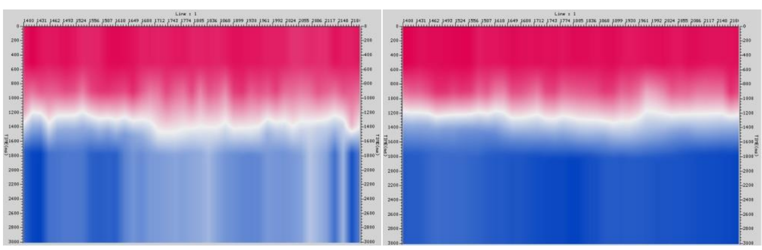
After the CRS gathers are obtained, we use the conventional velocity analysis method and PCA method to analyze the velocity respectively. The results are shown in Figure 8 (b) and (c), from which we can see that the energy of the velocity spectrum based on PCA is more focusing and the resolution is higher.



(a) (b) (c)

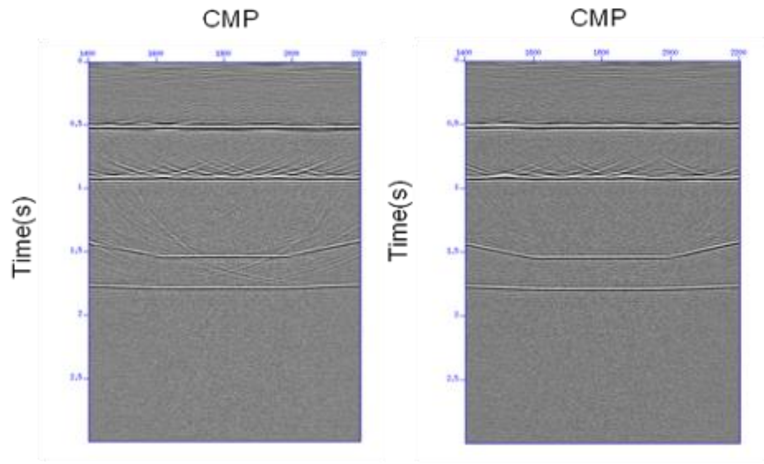
Figure 8. Velocity spectrum of (a) original CMP gather, (b) CRS gather, (c) method discussed in this paper

We use PCA method to analyze the velocity of the obtained CRS gathers and get the velocity model (Fig. 9 (b)). Then, this velocity model is used to carry out Kichhoff prestack time migration, and the results are shown in Fig. 10 (b). It can be seen that the migration profile structure of the velocity model based on this method is more continuous, and the diffraction wave convergence is better, which indicates that the velocity model based on this method is more accurate.



(a) (b)

Figure 9. Velocity model (a) conventional method, (b) method discussed in this paper



(a) (b)

Figure 10 Prestack time migration profile based on (a) original velocity model, (b) velocity model discussed in this paper

4. Conclusions

For low signal-to-noise ratio seismic data, in order to extract more accurate stacking velocity, improving the signal-to-noise ratio is the key. Through the study of this paper, we can draw the following conclusions:

(1) Partial CRS stack uses all the traces that contribute to the reflection unit, which makes full use of the potential of multiple coverage data and can generate CRS super gathers with high quality and high signal-to-noise ratio;

(2) Ellipse evolving stacking method abandons the traditional idea of CMP and realizes the true common reflection point stacking. When the layer is inclined, the stacking effect is obviously better than the conventional CMP stacking. It is more reliable to search CRS parameters based on ellipse evolving stacking section;

(3) PCA method can detect the target phase axis to the maximum extent by utilizing the numerical difference between the principal component and the minor component. After the weighting term is introduced, the noise immunity of velocity analysis is enhanced, and the clear velocity spectrum with focused energy is obtained.

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