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Research Article

A New Method to Extract CSP Gather of Topography for Scattered Wave Imaging

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The seismic method is one of the major geophysical tools to study the structure of the earth. The extraction of the common scatter point (CSP) gather is a critical step to accomplish the seismic imaging with a scattered wave. Conventionally, the CSP gather is obtained with the assumption that the earth surface is horizontal. However, errors are introduced to the final imaging result if the seismic traces obtained at the rugged surface are processed using the conventional method. Hence, we propose the method of the extraction of the CSP gather for the seismic data collected at the rugged surface. The proposed method is validated by two numerical examples and expected to reduce the effect of the topography on the scattered wave imaging.

1. Introduction

The geophysical prospecting methods utilize the physical principles to investigate the properties of the earth. Seismic method, which is based on the principle of seismic wave propagation in solid earth, is the major geophysical tool for the oil and gas exploration [1, 2]. The reflection, refraction, diffraction, and the scattering properties of the seismic wave can be used to image the structure of the earth and obtaining the velocity distribution underground from the energy recorded at the surface in seismic traces.

Among these imaging methods, scattered wave imaging method is a relatively newly developed and promising imaging scheme. It has been proved useful for the investigation of the deep structures of crust, hydrocarbon, and metal mineral resources [3–6]. The principal imaging method for the scatter wave is the equivalent offset migration (EOM) method [7, 8]. It is based on the assumption that the earth subsurface consists of a large number of points (referred as scattering points), closely located on the interfaces. The EOM imaging is accomplished with two steps, the formation of the common scatter point gather (CSP), which is considered as a prestack partial and migration imaging. The processing of the CSP gather is similar to the conventional common middle point gather (CMP) in which the mapping of the input traces decides the correctness of the subsequent EOM imaging.

The CSP gather can enhance the signal-to-noise ratio effectively and increase the imaging precision greatly [9, 10]. The CSP gather is similar to CMP gather for both are formed by normal moveout (NMO) and stacking. However, compared with CMP, the CSP gather may contain much more traces. The extremely high fold for the CSP gather makes it possible to conduct an accurate velocity analysis at each migration position. On the other hand, the traces in the CSP gather summed only with the equivalent offset so that the stability of the CSP gather is ensured in the case of unknown velocity. A more accurate root mean square (RMS) type velocity can be recovered [11].

With the emphasis of the seismic exploration shifting to the area of complex geological setting, the seismic records collected at the rugged surface have placed a challenge for the scatter wave imaging tasks [12]. The procedure of the prestack migration using the equivalent offset concept and the CSP gather is based on the assumption that the earth surface is horizontal. When handling the data from rugged

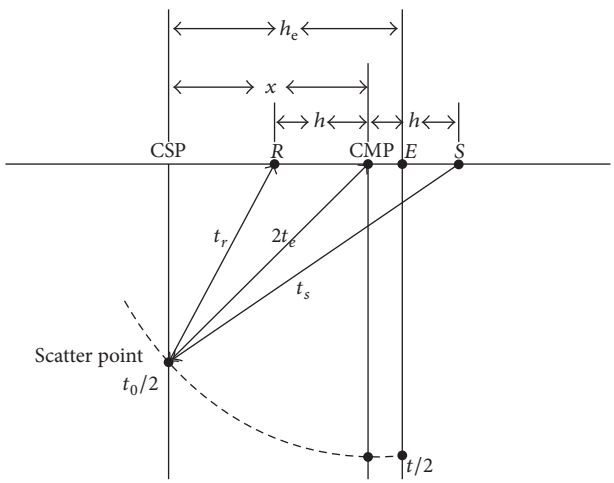

Figure 1: The sketch map to illustrate the geometrical concept of the equivalent offset (h_e). S is the source position, R is the receiver position, and E is the assumed collocated source/receiver position.

topography, the conventional processing using vertical elevation corrections will result in the increasing of the travel time to accommodate the elevation difference, introducing errors to the imaging result [13].

In this paper, the method to extract the CSP gather with topography is developed. Based on the equivalent offset for a horizontal surface, we derived the corresponding equivalent offset for the rugged topography case. The extraction of the CSP gather is based on the derived equivalent offset for the rugged topography. Finally, two numerical examples are given to verify the effectiveness of the developed method for refining the CSP gather.

2. Methodology

In this section, we give the derivation procedure for the proposed method. The equivalent offset for the horizontal surface follows the derivation given by Bancroft et al. [7].

2.1. The Equivalent Offset for Horizontal Surface. Firstly, we introduce the equivalent offset concept for a horizontal surface and the derived formula. Assuming that the ray paths between the source and the scatter point and between the scatter point and the receiver are straight line, the travel time of the scatter wave from the source to the receiver can be calculated as the sum of source to the scatter point time t_s and the scatter to receiver time t_r, as is shown in Figure 1.

$$t = t_s + t_r. \tag{1}$$

If we assume the velocity is constant, according to geometrical relationship in Figure 1, we can expand (1) into a double square root (DSR) equation,

$$t = \left[\frac{z_0^2 + (x+h)^2}{v^2}\right]^{1/2} + \left[\frac{z_0^2 + (x-h)^2}{v^2}\right]^{1/2}, \tag{2}$$

where z_0 is the scatter point depth, x is the x-coordinate of the middle point of source and receiver with the origin located at the scatter point, and h is half of the source-receiver separation. In order to adapt the DSR equation to the vertical velocity variation, the DSR equation can be modified as

$$t = \left[\left(\frac{t_0}{2}\right)^2 + \frac{(x+h)^2}{v_{\text{sq}}^2}\right]^{1/2} + \left[\left(\frac{t_0}{2}\right)^2 + \frac{(x-h)^2}{v_{\text{sq}}^2}\right]^{1/2}, \tag{3}$$

where the velocity v_{sq} here stands for the root mean square (RMS) velocity at $t_0 = 2z_0/v_{\text{ave}}$, which is the two-way zero-offset time calculated from the scatter point depth and the average velocity v_{ave} [14].

In order to simplify the DSR equation, we firstly set a collocated source and receiver point whose two-way travel time to the scatter point is equal to the travel time for the single sided ray path in Figure 1

$$t = 2t_e = t_s + t_r. \tag{4}$$

The travel times t_s and t_r so in (4) can be expanded for the case of varied velocity

$$2\left(\frac{{t_0}^2}{4} + \frac{{h_e}^2}{v^2}\right)^{1/2} = \left(\frac{{t_0}^2}{4} + \frac{(x+h)^2}{v^2}\right)^{1/2} + \left(\frac{{t_0}^2}{4} + \frac{(x-h)^2}{v^2}\right)^{1/2}, \tag{5}$$

where h_e denotes the equivalent offset which is defined as the offset of the collocated source/receiver position. h_e can be solved from (5)

$${h_e}^2 = x^2 + h^2 - \frac{(2xh)^2}{t^2 v^2}. \tag{6}$$

With the defined equivalent offset, the CSP gather can be formed without the DMO procedure. Although Fowler (1997) demonstrated that the DSR equation can be changed into different hyperbolic equation, the introduction of the equivalent offset is the only way that the sorting of the data into CSP gather can be achieved without time shifting.

2.2. The Equivalent Offset for Rugged Topography. In this section, we derive the formula of equivalent offset for the rugged surface. Firstly we assume that the rugged topography is analyzed in a 2D case, as is shown in Figure 2. We will utilize the configuration in the figure to illustrate the deriving procedure. The source position is located at the peak of the topography (S) while the receiver position is set at the hollow (R). To adapt the equivalent offset of the rugged topographical data to the horizontal case, we set a horizontal surface below the nadir of the hollow. Assuming that a zero-offset source and receiver are located at this horizontal surface and that the two-way travel time from this source/receiver position to the scatter point is equal to the original travel time from the source position (S) to the receiver position (R), we obtain the travel time equation

$$t_{\text{all}} = 2t_{SR} = t_S + t_R, \tag{7}$$

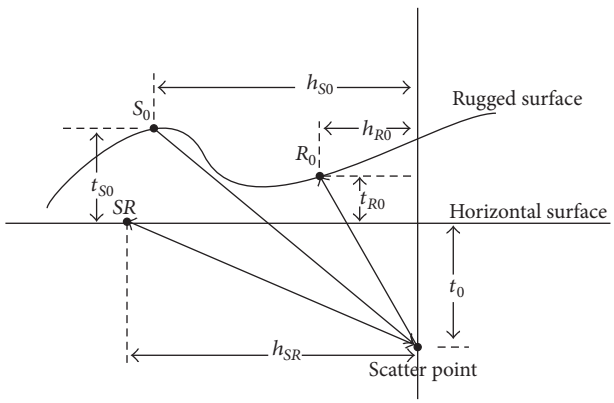

Figure 2: The sketch map to illustrate the equivalent offset for the rugged topography. S_0 is the source position, R_0 is the receiver position, and SR is the assumed collocated source/receiver position at the assumed horizontal surface.

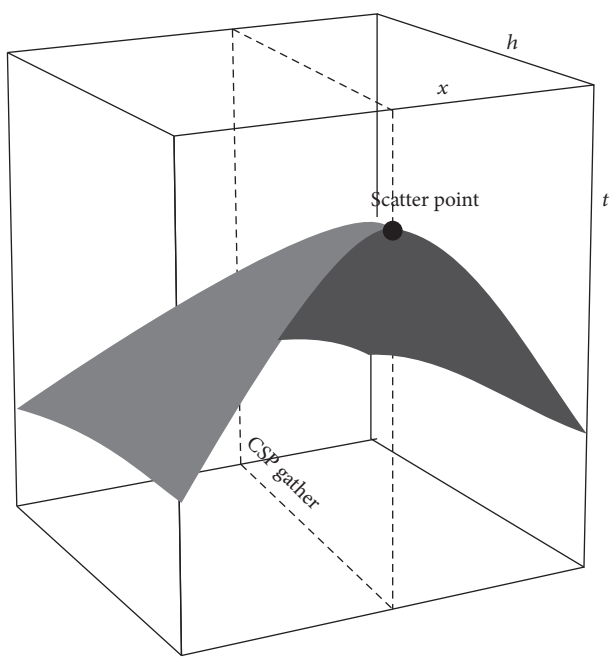

Figure 3: The sketch map to illustrate the mapping of the input data to the CSP gather. The shadowed surface is the Cheops pyramid and the dashed box is the plane where the CSP gather is formed.

where t_S denotes the travel time from the source position S to the scatter point, t_R denotes the travel time from the scatter point to the receiver position R, and t_{SR} denotes the two-way travel time from the source/receiver point t_{SR} to the scatter point. Equation (7) can be expanded based on the geometrical in Figure 3.

According to the geometrical relations in Figure 3, t_{SR} can be calculated with

$$t_{\text{all}} = 2t_{SR} = 2\left[{t_0}^2 + \left(\frac{h_{SR}}{v_{SR}(t_0)}\right)^2\right]^{1/2}, \tag{8}$$

where t_0 is the vertical travel time from the scatter point to the imagined horizontal surface, h_{SR} is the equivalent offset, and v_{SR} is the horizontal RMS velocity from the scatter point to the collocated source/receiver position (SR). Thus, the equivalent offset can be evaluated from (8).

$$h_{SR} = v_{SR}(t_0)\left[\left(\frac{{t_{\text{all}}}^2}{4}\right) - {t_0}^2\right]^{1/2}. \tag{9}$$

According to the travel time equation (7), the total travel time from the source position to the receiver position can be obtained with

$$\begin{aligned} t_{\text{all}} &= t_S + t_R \\ &= \left[(t_0 + t_{s0})^2 + \left(\frac{h_{S0}}{v_S(t_0 + t_{S0})}\right)^2\right]^{1/2} \\ &\quad + \left[(t_0 + t_{R0})^2 + \left(\frac{h_{R0}}{v_R(t_0 + t_{r0})}\right)^2\right]^{1/2}, \end{aligned} \tag{10}$$

where t_{S0} and t_{R0} are the vertical travel time from the source position (S) or the receiver position (R) to the imagined surface, respectively, h_{S0} and h_{R0} are the offset from the source or receiver position to the scatter point; v_S and v_R are the RMS velocity from the source position or the receiver position to the scatter point

$$\begin{aligned} v_s &= \left(\frac{\sum_{i=1}^{n+m} t_i v_i^2}{\sum_{i=1}^{n+m} t_i}\right)^{1/2} \\ &= \left(\frac{\sum_{i=1}^{n} t_i v_i^2 + \sum_{i=1}^{m} t_i v_{\text{S-surface-}i}^2}{t_0 + t_{s0}}\right)^{1/2} \\ &= \left(\frac{t_0 v_e^2 + \sum_{i=1}^{m} t_i v_{\text{S-surface-}i}^2}{t_0 + t_{s0}}\right)^{1/2}, \end{aligned} \tag{11}$$

$$\begin{aligned} v_r &= \left(\frac{\sum_{i=1}^{n+m} t_i v_i^2}{\sum_{i=1}^{n+m} t_i}\right)^{1/2} \\ &= \left(\frac{\sum_{i=1}^{n} t_i v_i^2 + \sum_{i=1}^{m} t_i v_{\text{R-surface-}i}^2}{t_0 + t_{r0}}\right)^{1/2} \\ &= \left(\frac{t_0 v_e^2 + \sum_{i=1}^{m} t_i v_{\text{R-surface-}i}^2}{t_0 + t_{r0}}\right)^{1/2}. \end{aligned} \tag{12}$$

With the derived formulas (9)~(12), we can calculate the equivalent offset for the rugged topography.

2.3. Mapping the Input Data to CSP Gather. When the CSP gathers have been formed, each CSP gather may be scaled and filtered or processed. Conventional algorithms such as noise and multiple removals, or velocity analysis, may also be used on the CSP gathers. The rugged topography is completed on the base of CSP gathers.

The seismic record collected at the earth surface contains the energy from arbitrary scattering point underground. The

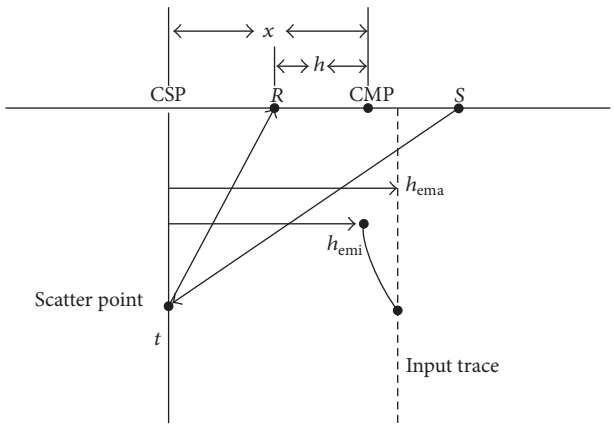

Figure 4: The mapping of the input trace to the CSP gather. The minimum equivalent offset h_{emi} and maximum equivalent offset h_{ema} are shown.

CSP gather is employed to concentrate these energies into a 2D (h, t) space and then place the scatter point at the optimal position for the following focusing process. As is illustrated in Figure 3, the energy from the Cheops pyramid is decomposed into the hyperbolic curve in the $x = 0$ plane and the corresponding scatter point is located.

For a given input trace in Figure 3, the x and h are definite variable. The record is mapped into the CSP gather from the first effective sampling point. Assuming the h_{emi} and h_{ema} represent the minimum and maximum equivalent offset which is related to the distance between the input trace and the scatter point at the earth surface ($x = 0$, $t = 0$) and the wave velocity at the earth surface. According to (6), h_{emi} and h_{ema} can be calculated as

$$h_{emi} = x,$$
$$h_{ema} = \left(x^2 + h^2\right)^{1/2}. \tag{13}$$

The mapping procedure is the relocation from the vertical input trace to the horizontal CSP gather, as is shown in Figure 4. With the increasing of the sampling time within input traces, the equivalent offset increases. The relationship between the sampling time and the equivalent offset is defined in (6) which is nonlinear. The earliest input trace corresponds to the minimum equivalent offset h_{emi} while the latest one corresponds to the maximum equivalent offset h_{ema}.

The location of the input traces is expressed by x and h. When $h = 0$ and $x \neq 0$, the source and the receiver are overlapped. It can be inferred from (6) that the equivalent offset for all samples in this case is equal to x without time shift. This is equivalent to self-excitation and self-receiving seismic records above the ramps of the scatter point. When $h = 0$ and $x = 0$, the source and the receiver are overlapped right above the scatter point without time shift.

It may appear from (6) that the equivalent offset needs to be calculated for each sample in an input trace. Bancroft et al. [7] demonstrate that only when the input samples shifted into a new offset bins did the equivalent offset need to be calculated again. The transition time of these bins can be found by rearranging (6)

$$t_i = \frac{(2xh)}{v\left(x^2 + h^2 - h_{SR}^2\right)^{1/2}}, \tag{14}$$

where i is the index of the offset bins. The transition time and the offset bins make the extraction of the CSP gather more efficient. Figure 5 gives the workflow of the forming of the CSP gather for the rugged surface.

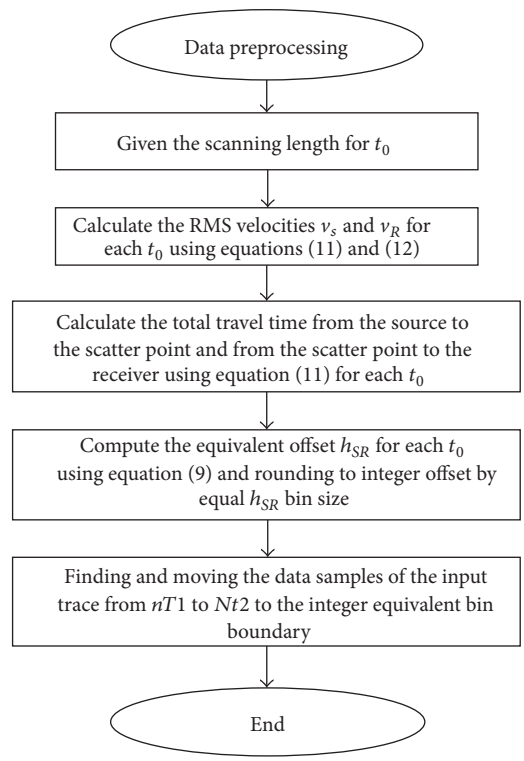

Figure 5: The workflow of the forming of the CSP gather for the rugged surface.

3. Examples

3.1. Single-Point Model. To validate the derived algorithm of the refined CSP gather of topography for scattered wave imaging, two numerical examples are given and compared. Firstly, a one-point model with homogeneous velocity structure was created to test the ability of the algorithm to handle simple model. As is shown in Figure 6, the range of the model is 800 × 800 m for the created coordinate and the single-point is located at (400 m, 200 m). The velocities of scatter point are v_p = 2500 m/s and v_s = 1380 m/s while v_p = 2000 m/s and v_s = 1110 m/s for the homogeneous half space.

We set 401 fixed receivers for the established single-point model so that the spacing between each receiver is 2 m. On the other hand, we put 21 shots along the designed survey line with a space of 40 m. There are 700 samples for each of the forwarded seismic records with a sampling rate of 2000 Hz.

Figure 7 gives an example of the forward traces. The CSP gather is formed with aperture 400 m with an increment

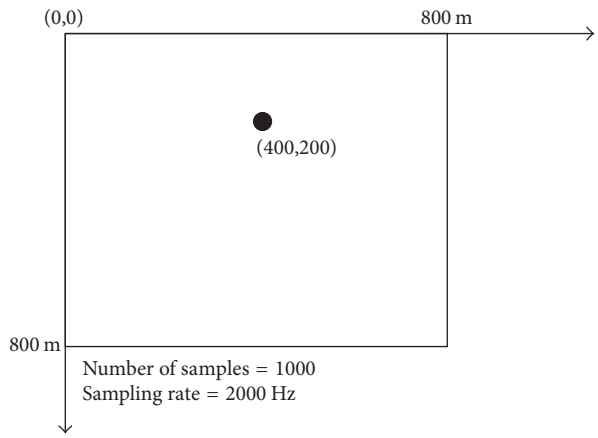

Figure 6: The single-point model with homogeneous velocity structure.

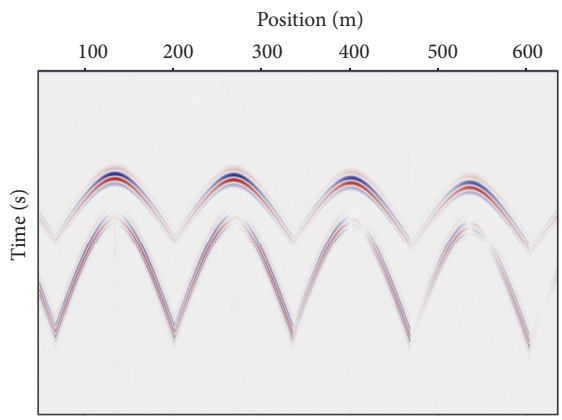

Figure 7: The synthetic traces from the single-point model.

of 2 m. Each input traces within the defined aperture will be mapped into each output CSP gather. Figure 8 gives the derived CSP gather. Figure 8(a) is derived from the algorithm based on the horizontal surface and Figure 8(b) is calculated using the algorithm based on the rugged surface. It can be inferred from the figure that the shape of the hyperbola is both well recovered. The consistency of the extracted CSP gathers from the two algorithms has validated the correctness of the derived method for refining CSP gather in rugged topography.

3.2. Inclined-Interface Model. After the validation of the developed algorithm on the single-point model, another 2D inclined-interface model is designed to test the effectiveness of derived algorithm. The inclined-interface model consists of two homogeneous mediums, the velocities are $v_p = 2500$ m/s and $v_s = 1380$ m/s for the upper layer and $v_p = 2000$ m/s and $v_s = 1110$ m/s for the lower layer. As is shown in Figure 9, the range of the model is 1200×800 m for the created coordinate. We set 601 fixed geophones for the established inclined-interface model so that the spacing between each receiver is still 2 m. On the other hand, we put 21 shots along the designed survey line with a space of 50 m. There are 1000 samples for each of the forwarded seismic records with a sampling rate of 2000 Hz.

Figure 10 gives an example of the forward traces. The CSP gather is formed with aperture 400 m with an increment of 2 m. Each input traces within the defined aperture will be mapped into each output CSP gather. Figure 11 gives the derived CSP gather. Figure 11(a) is derived from the algorithm based on the horizontal surface and Figure 11(b) is the calculated using the algorithm based on the rugged surface. On account that the horizontal inclined-interface model is a simplified case for the rugged topography, the examples given here only verified the ability of the developed method. It can be concluded from the figure that the derived CSP gather using the algorithm developed in this paper is consistent with the one derived from the horizontal case, which validates the effectiveness of the derived method.

4. Conclusions

The scattered wave imaging can be applied to the area of complex geological setting for the enhancement of signal-to-noise ratio by the extraction of CSP gathers. The forming of CSP gather is a critical step for the migration of the scattered

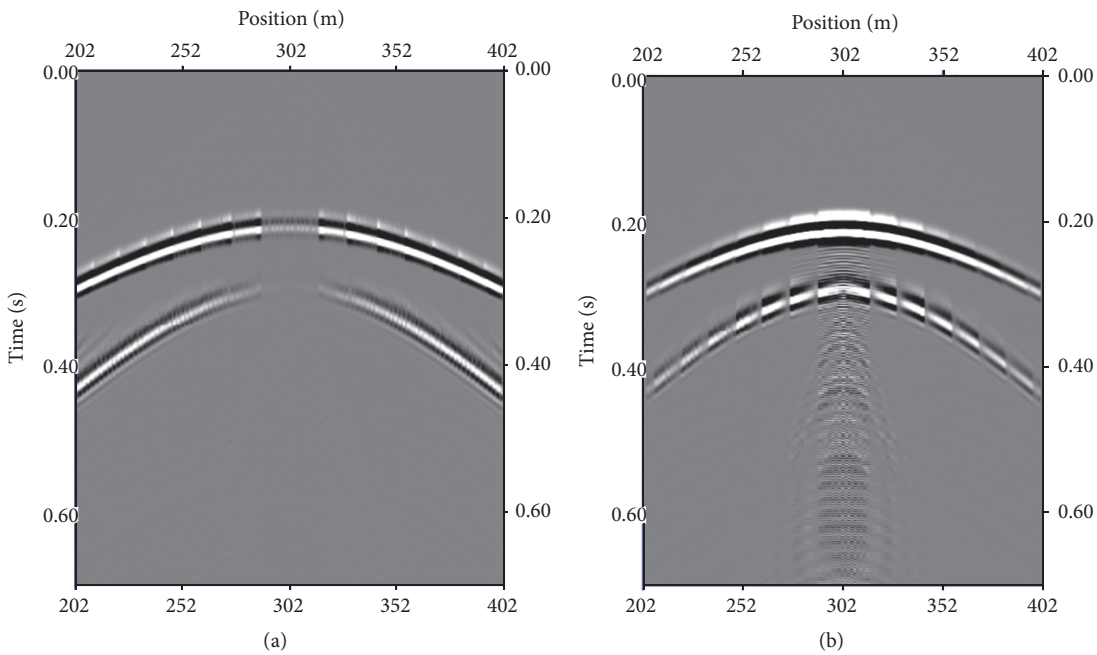

Figure 8: The extracted CSP gather: (a) the CSP gather at the scatter point using the algorithm for horizontal surface assumption; (b) the CSP gather at the same scatter point using the algorithm for the rugged surface.

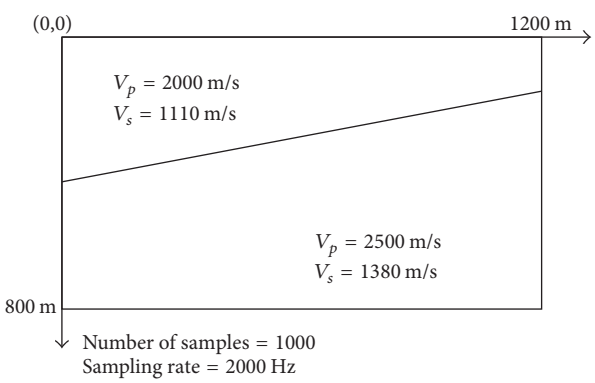

Figure 9: The parameter of the inclined-interface model.

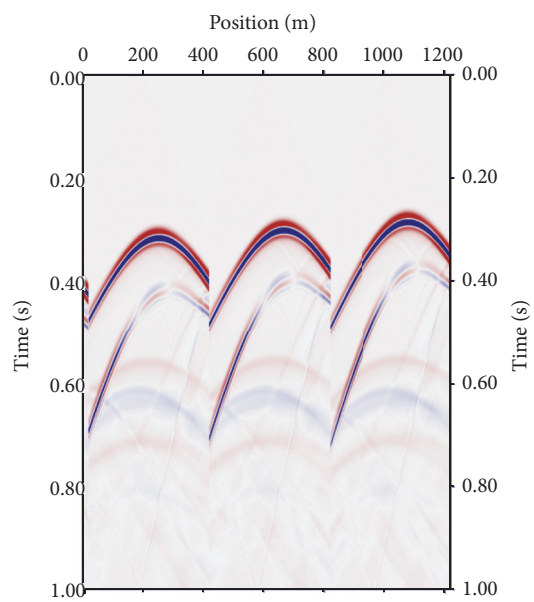

Figure 10: The synthetic traces from the inclined-interface model.

wave. However, it will seriously be affected by the topography of the survey area. The errors caused by the topography during the extraction of the CSP gather will be further introduced into the imaging result. To eliminate these errors, this paper adapts the equivalent offset from the horizontal surface to the rugged topography so that the accurate imaging for the scattered seismic data from the rugged surface is possible. The formula of the equivalent offset for the rugged surface has been derived and the subsequent procedure for forming the CSP gather has been conducted. Two numerical examples are given to validate the developed algorithm. The consistency of the CSP gather verified the effectiveness of the proposed method. The proposed algorithm can be further developed into the imaging scheme with scattered wave.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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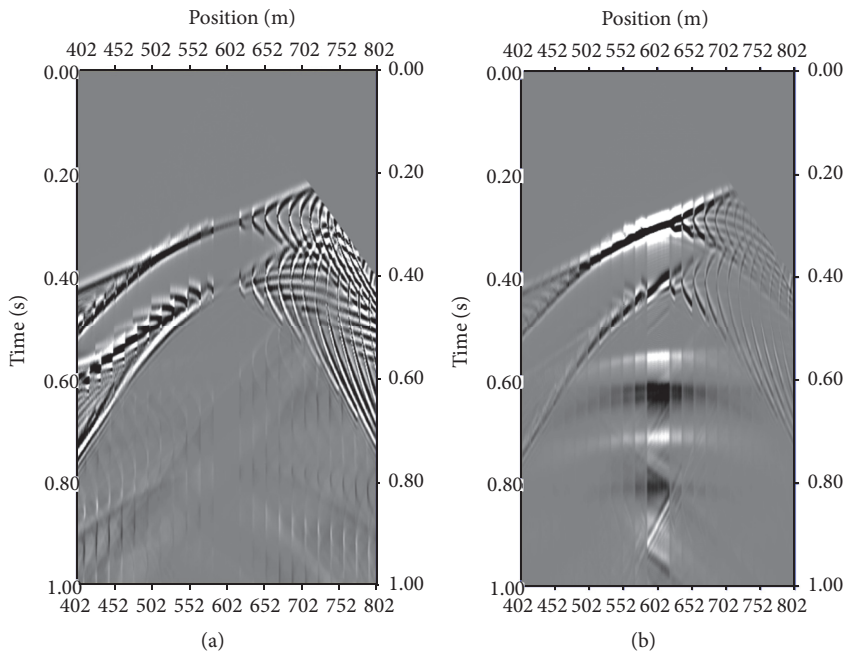

Figure 11: The CSP gather at 600 m using the algorithm for horizontal surface assumption; (b) the CSP gather at the same point using the algorithm for the rugged surface.

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