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First Arrival Picking of Seismic Data Based on Trace Envelope

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ABSTRACT We introduce a new method for first arrival traveltimes picking based on the maximum difference between adjacent points of the envelope (MDPE) of a seismic trace. The method starts by calculating the Hilbert transform of the seismic trace to generate the complex seismic trace, which consists of the real and imaginary parts of a seismic trace. After generating the complex seismic trace, the instantaneous amplitude or envelope is extracted and used to pick the first arrival traveltimes. We test the proposed method on synthetic shot records. When we compared the automatically picked first arrival traveltimes using our proposed method versus those picked manually by an experienced processor, we found that our proposed method estimated the first arrival traveltimes with more than 88% picking accuracy (within 0.1 s of manual picks). Furthermore, we perform the same test on real shot records and the proposed method estimated the first arrival traveltimes with a picking accuracy of 85% (within 0.1 s of manual picks). Finally, we apply the proposed method on 58 traces extracted from a real 2D land seismic data set from southeast Texas on which first arrival traveltimes was difficult to pick automatically. We compare our proposed method and the P-phase picker method against manual picks. Results show that the proposed method has a picking accuracy of 99%, while the P-phase picker method gives 83% picking accuracy (within 0.1 s of manual picks).

INDEX TERMS Complex seismic trace, envelope, first arrival traveltimes picking, Hilbert transform, instantaneous amplitude.

I. INTRODUCTION

Static correction is an important step of seismic data processing. However, there are challenges that could face the static correction calculation such as in areas with complex near-surface geology, weak source wavelet penetration, or data with a low signal-to-noise ratio (SNR). The accuracy of the first arrival traveltimes picking is important for increasing the efficiency of the static correction methods for both seismic reflection and refraction data processing.

First arrival traveltimes picking is divided into two main techniques: manual and automatic [1]. Manual determination of the first arrival traveltimes is done by visual inspection of the amplitudes by an experienced processor. In general, manual picking of first arrival traveltimes gives good results, but it is time-consuming because of the large volumes of seismic data and the need for real-time seismic

data processing [2]. Furthermore, if the data is noisy, first arrival traveltimes may be difficult to pick. As a result, the picking procedure takes more than 20% of the total processing time, especially when the data set is large [3]. On the other hand, using advanced algorithms and techniques, machines can perform automatic first arrival traveltimes picking. There are many automatic first arrival traveltimes picking techniques that give good results under certain conditions but may fail or give inaccurate results under other conditions.

One of the early picking methods were done by correlation of adjacent traces to find delay times between adjacent arrival times [4]. Another method employs energy ratios such as the Short-Term Average over Long-Term Average (STA/LTA) method of [5]. Another picking algorithm uses the Akaike information criterion ([6] and [7]). Other methods depend on polarization analysis [8]. Additional automatic picking methods include those based on fractals [9], neural networks ([10], [11], and [12]), and deep-learning algorithms [13].

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The STA/LTA algorithm uses ratios of the signal's envelope to detect first arrivals. Alternatively, ratios of the signal's absolute values or energies are also used for picking ([14], [15], and [16]).

In all ratio-based picking methods, the assumption is that short-term windows are sensitive to rapid signal variations while long-term windows represent background variations. This ratio minimizes effects of local signal variations and acts as a measure of local SNR. Despite its additional computational cost, the envelope function has the advantage of remaining positive at zero crossings during phase arrivals [5]. Reference [17] refined Coppens' method by adding thresholds. Reference [3] modified Coppens' method using the energy ratio along with the entropy method and fractal dimensional analysis. Reference [18] suggested a new method based on the digital image segmentation for picking first arrival traveltime of refracted data. Furthermore, [19] proposed a method that enhanced the first arrival traveltime picking by using the τ - p transform on energy ratios.

In this paper, we present a new method for automatically picking the first arrival traveltime based on the magnitude of the complex seismic trace. References [20] and [21] proposed the 1-D complex seismic trace analysis, which later boosted the use of seismic attributes in geophysical exploration. Furthermore, the Hilbert transform has been used in seismic data processing and interpretation for many years. There are many applications for the Hilbert transform that use the attributes of the complex seismic trace, such as the instantaneous amplitude (i.e., envelope), instantaneous phase and frequency ([21] and [22]).

The concept of our proposed method starts with calculating the Hilbert transform from the original trace to obtain the complex seismic trace that contains the real and imaginary parts of the trace. The magnitude of the complex seismic trace is called the envelope, which gives amplitude information about the trace, and is usually expressed in decibel units, which are highly fluctuating and difficult to represent. Because of this feature, the envelope is usually smoothed by calculating its moving average within a sliding window.

This paper begins by introducing the main concepts of the Hilbert transform and the envelope, followed by the steps of the proposed method based on the maximum difference between adjacent points of the envelope (MDPE). Application of the proposed method to synthetic and real data sets is subsequently presented. After that, the advantages and limitations based of the MDPE method are discussed. Finally, we summarize our method in the last section.

II. METHODOLOGY

The proposed MDPE method consists of the following five steps:

- 1) Calculate the Hilbert transform to generate the envelope from the complex seismic trace.
- 2) Convert the envelope readings into decibels.
- 3) Calculate the moving median of the envelope within a sliding window.

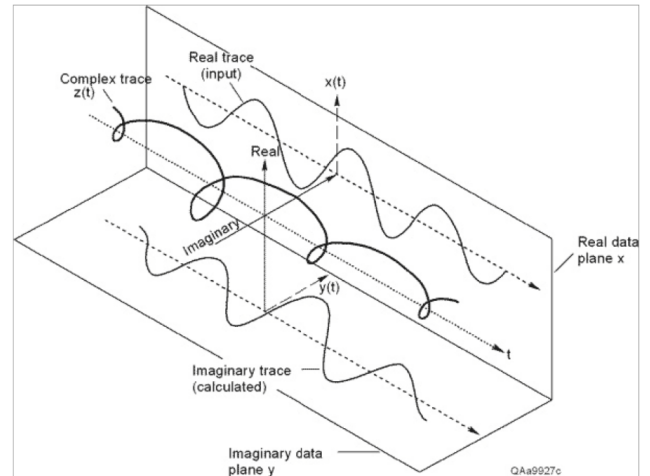


FIGURE 1. A complex seismic trace that contains both a real part, which is the real seismic trace, and an imaginary part, which is calculated by Hilbert transform of the real seismic trace (Taner et al., 1979).

- 4) Calculate the differences between adjacent points of the median along the trace envelope.
- 5) Pick the first arrival traveltime at the point with the maximum difference between adjacent points.

A. HILBERT TRANSFORM AND ENVELOPE

The Hilbert transform is an alternative method for extracting the instantaneous amplitude, frequency and phase information from signal data. Figure 1 illustrates the concept of the complex seismic trace $z(t)$, which consists of real $x(t)$ and imaginary $y(t)$ parts as defined by equation 1:

$$z(t) = x(t) + iy(t). \quad (1)$$

The real part $x(t)$ is the real seismic trace while $y(t)$ is called the imaginary seismic trace and is the Hilbert transform of $x(t)$. With the real data, it is not possible to extract information such as instantaneous amplitude, phase and frequency. To do this, it is necessary to estimate the complex seismic trace by applying the following steps:

- 1) Take the Fourier transform of the real signal to convert it from the time domain to frequency domain.
- 2) Apply a 90° phase shift to all frequency components of the phase spectrum.
- 3) Apply the inverse Fourier transform.

By applying the previous steps, the complex seismic trace in equation 1 will be generated with the real and imaginary parts of the data. In addition, equation 1 will allow us to extract and define such important attributes as the instantaneous amplitude, frequency and phase. Instantaneous amplitude, or envelope $a(t)$, can be calculated as:

$$a(t) = \sqrt{x^2(t) + y^2(t)}. \quad (2)$$

After that, the envelope of the complex seismic trace is converted to the decibel scale using the following equation:

$$Envelope (dB) = 20 \times \log_{10}[a(t)]. \quad (3)$$

By applying equation (3) to the envelope, a spike on the envelope of the complex seismic trace occurs when we approach the first arrival traveltime. However, to obtain an accurate value of the first arrival traveltime, the envelope needs to be smoothed by calculating the moving median in a sliding window of a user-defined length as explained in the next section.

B. SLIDING WINDOW MEDIAN

In general, the median is the middle integer value of an ordered odd-numbered list in an array. If the count of the list is even, the median will be the mean of the two middle values in the list. It is also possible to take a median within a sliding window of a user-defined length (k). The window moves from the beginning to the end of the array one sample at a time. The user selects the sliding window length carefully depending on the signal's dominant frequency, time sampling interval and the number of time samples per trace. After calculating the sliding-window-median of a certain trace, a spike should appear at the first-arrival traveltime position.

C. MAXIMUM DIFFERENCE BETWEEN ADJACENT ELEMENTS (MDPE)

The slope between any two adjacent points along the trace envelope can be found by calculating the ratio of the vertical change to the horizontal change between the two points:

$$\text{Slope} = (y_2 - y_1)/(x_2 - x_1). \quad (4)$$

The difference between adjacent elements uses almost the same concept as the slope with a small change. It assumes that the distance between each two adjacent points (x_1, x_2) equals one, calculates the difference in envelope values between each two adjacent points, and applies this technique to the whole trace envelope. Finally, the position of the maximum envelope difference is selected as position of the first arrival traveltime for that specific trace. The overall workflow of the proposed MDPE method is shown in Figure 2.

III. RESULTS

This section is divided into three subsections. The first section shows the application of the MDPE method on a synthetic data set. The second section shows the results of applying the proposed method on a 2-D real surface seismic data from southeast Texas and compares the performance of the proposed method to the P-phase arrival-time picker method [23]. The last section shows the results of applying our method on two of Yilmaz's worldwide assortment of shot records [2].

A. SYNTHETIC DATA

A 3-layer 2D velocity model (Figure 3) is used to generate a synthetic data set using acoustic finite difference forward modeling. The velocity model is $2400 \times 200 \text{ m}^2$. The first layer has a constant velocity of 400 m/s, while the 2nd and 3rd layers have velocities increasing with depth. The velocities range from 1200 to 1370 m/s in the second layer and from 2600 to 2800 m/s in the third layer. The data is generated

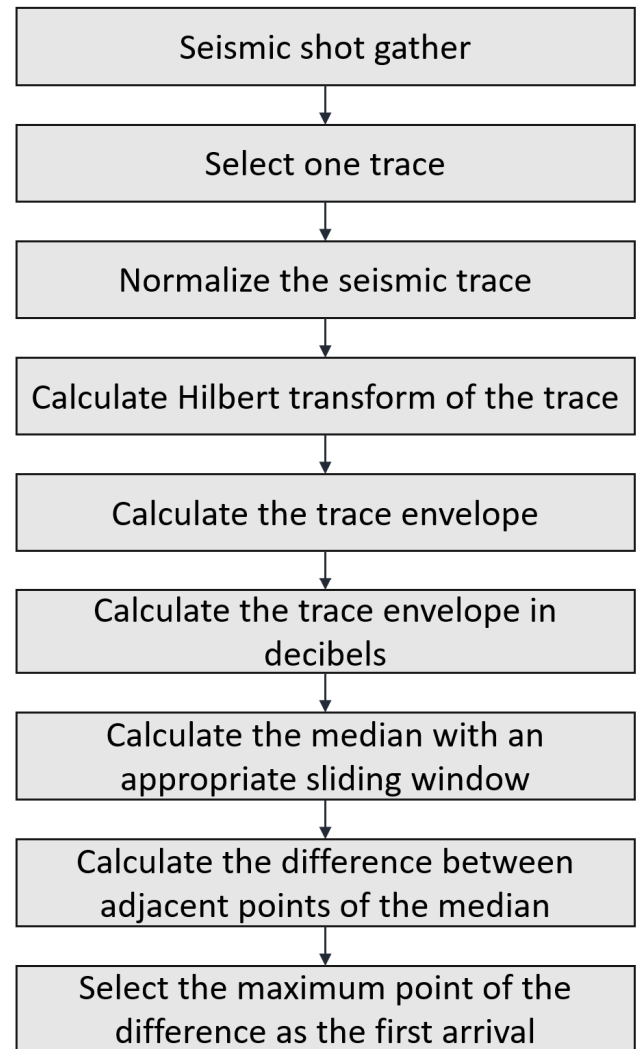


FIGURE 2. Workflow of the MDPE method for picking the first arrival.

using 110 receivers with 10 m receiver interval, 0.001 s time interval and 1 s total recording time.

Figure 4 shows synthetic shot gathers 1 and 56, which contain several seismic events (e.g., head waves and primary reflections). Figures 5 shows results of applying the proposed picking method (blue) compared with manual picking (red) for each shot record. Both shot records give good results with picking accuracy (within 0.1 s of manual picks) of 99% for shot gather 1 and 88% for shot gather 56.

To test the effects of noise, we added random Gaussian noise with zero mean and 0.01 standard deviation to the raw amplitudes of synthetic shot gather 1. Results show that picking accuracy (within 0.1 s of manual picks) decreased from 99% to 87%. We also test the proposed method with different lengths of the sliding window on synthetic shot gather 1. Accuracy of picks (within 0.1 s of manual picks) decreased from 99% (when an optimum window of 50 samples was used) to 69% (with a 25-sample window) and 75% (with a 75-sample window). Finally, we compare the STA/LTA and MDPE methods on synthetic shot gather 1. Results show that

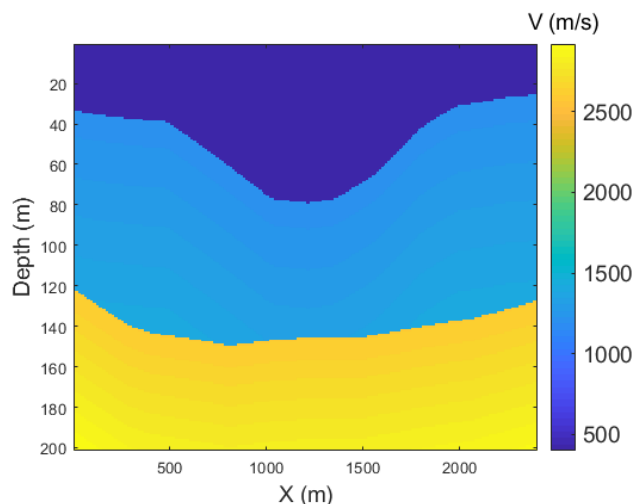


FIGURE 3. Velocity model used to generate our synthetic data set. Color bar shows the variation of velocities for the three different layers (400-2800 m/s).

both methods give almost the same result when compared to manual picking. Figure 5 (c) shows results of this analysis on trace 110 of this shot. STA/LTA estimates the first arrival at 0.533 s and MDPE estimates it at 0.530 s, which are both very close to the manual pick at 0.532 s.

B. REAL DATA

1) REAL DATA SET FROM SOUTHEAST TEXAS

The proposed method was applied to a data set published by [25]. The data set is a 2-D set from southeast Texas and consists of the following parameters:

- 18 shot gathers
- 33 traces in each shot
- Dynamite source
- Receiver interval = 67 m
- Time sampling interval = 0.002 s
- Number of time samples per trace = 1501

Figure 6 shows sample shot gathers (7 and 17) from this data set. To illustrate how the proposed MDPE method works, we apply the workflow on two selected traces of this data set: trace 31 from shot 7 (with high SNR before the first arrival) and trace 29 from shot 2 (with low SNR before the first arrival) and compare the results with those from the P-phase method and the manual picking. Figure 7 shows the details of the raw selected traces. The envelope of these two traces is calculated (Figure 8) and expressed in decibel units (Figure 9). A smoothed version of the traces in Figure 9 is calculated using a 50-sample moving median (Figure 10). Finally, the difference between successive points of the smoothed envelopes is calculated (Figure 11). The first arrival traveltimes is picked at the position of the maximum difference. The first arrival traveltimes estimated from the proposed MDPE method and P-phase picker method are compared with of manual picks. Figure 12 shows that application of these two methods on trace 31 from shot 7 estimates

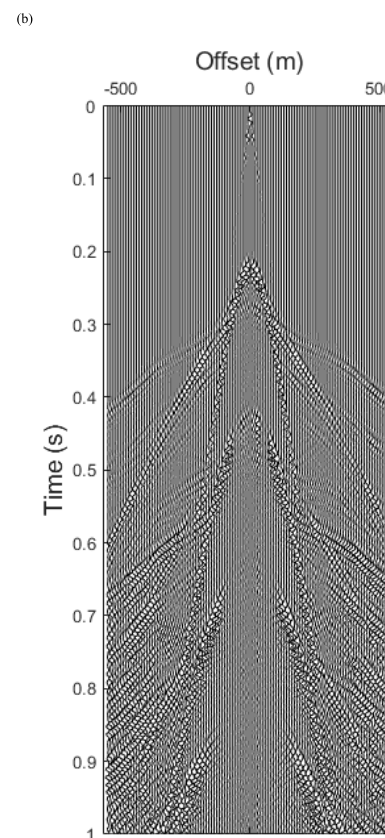
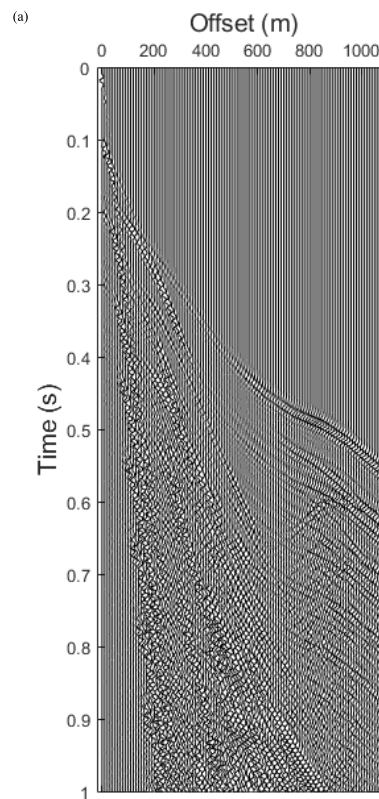


FIGURE 4. Sample shot gathers from the synthetic seismic data: (a) Shot gather 1; (b) Shot gather 56.

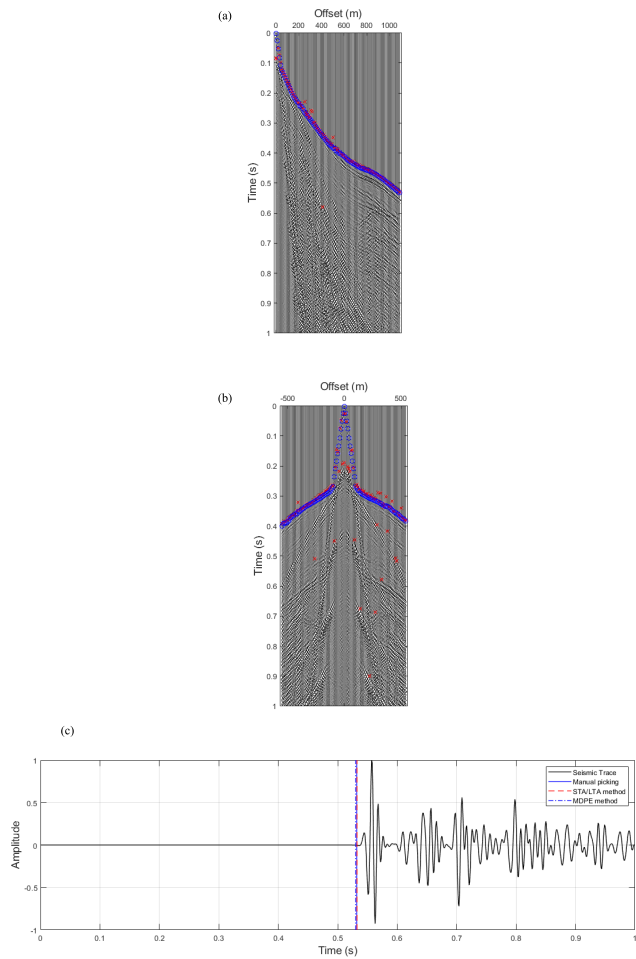


FIGURE 5. The same synthetic shot records shown in Figure 4 showing first arrival picks from the proposed method (red crosses) and manual picks (blue circles): (a) Shot gather 1; (b) Shot gather 56. (c) Comparison of the MDPE method (dash-dot line) and STA/LTA method (dashed line) versus manual picking (solid line) for trace 110 of shot gather 1.

the manual pick accurately by both methods (Figure 12(a)). On the other hand, application on the more noisy trace 29 from shot 2 shows that the proposed MDPE method estimates the manual pick more accurately than the P-phase method.

Furthermore, Figure 13 shows the result of applying the proposed MDPE method on 54 traces selected from this data set. The proposed method gives almost the same first arrival traveltime picks as the manual picks. On the other hand, Figure 14 shows the result of applying the P-phase picker method on the same 54 traces which results in 83% picking accuracy within 0.1 s of manual picks.

2) YILMAZ'S REAL SHOT GATHERS

We have chosen two real shot gathers (6 and 25) from Yilmaz's published assortment of worldwide real seismic data [24] to test our proposed method and compare it with manual picking. Figure 15 (a) shows shot gather 6 that contains 48 traces with a time sample interval of 0.004 s and a receiver interval of 100 m using a dynamite source.

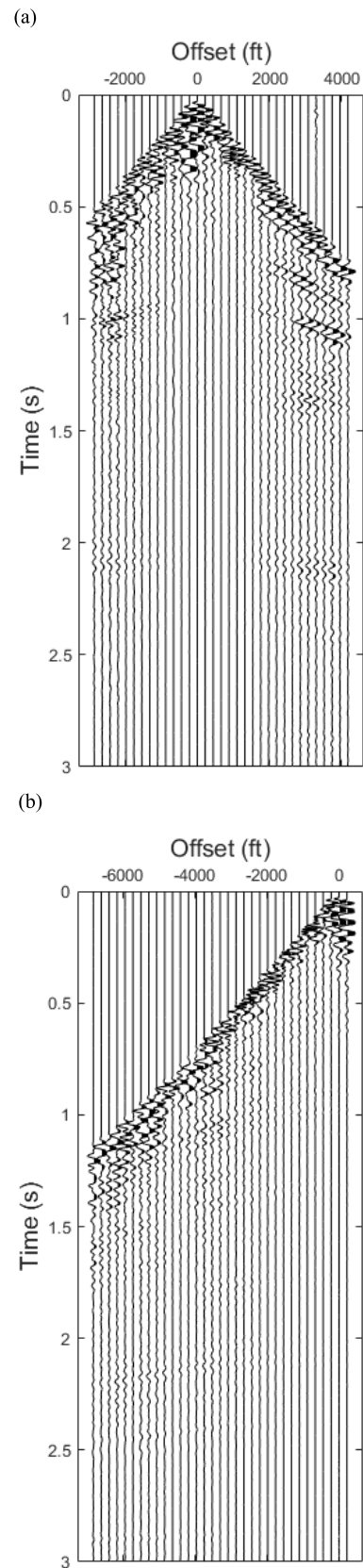


FIGURE 6. Sample shot gathers from the real data set from southeast Texas: (a) shot gather 7; (b) shot gather 17.

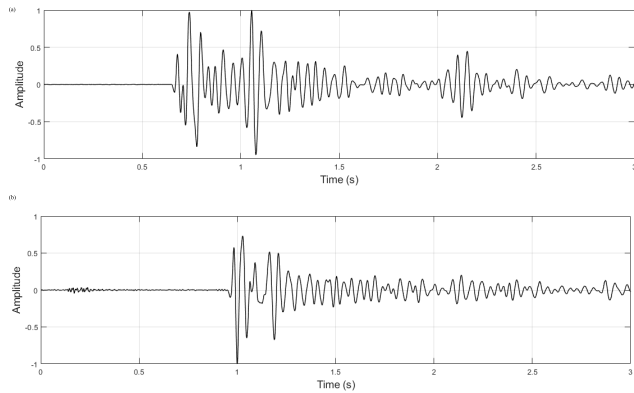


FIGURE 7. Sample traces from the real data set from southeast Texas: (a) trace 31 from shot 7; (b) trace 29 from shot 2.

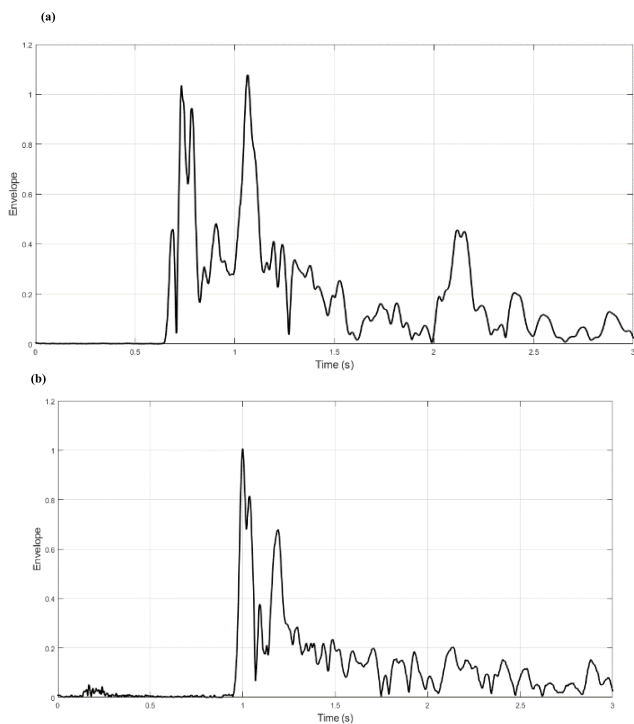


FIGURE 8. The envelope of the traces in Figure 7.

The first arrival traveltimes determined by MDPE method (crosses) is shown in Figure 16 (a) compared with manual picks (circles). The picks from the MDPE method have 85% accuracy from manual picking (within 0.1 s of manual picks).

Shot gather 25 is shown in Figure 15 (b) where data contains 96 traces with 0.002-s time sampling interval and 50-m receiver interval using a dynamite source. The first arrival traveltimes picks determined by the MDPE method (crosses) are shown in Figure 16 (b) compared with manual picks (circles).

The picks from the MDPE method are very close to the manual picks except for few traces at very near offsets requiring a sliding window length less than 50 samples and also at very far offsets due to the very weak first arrivals.

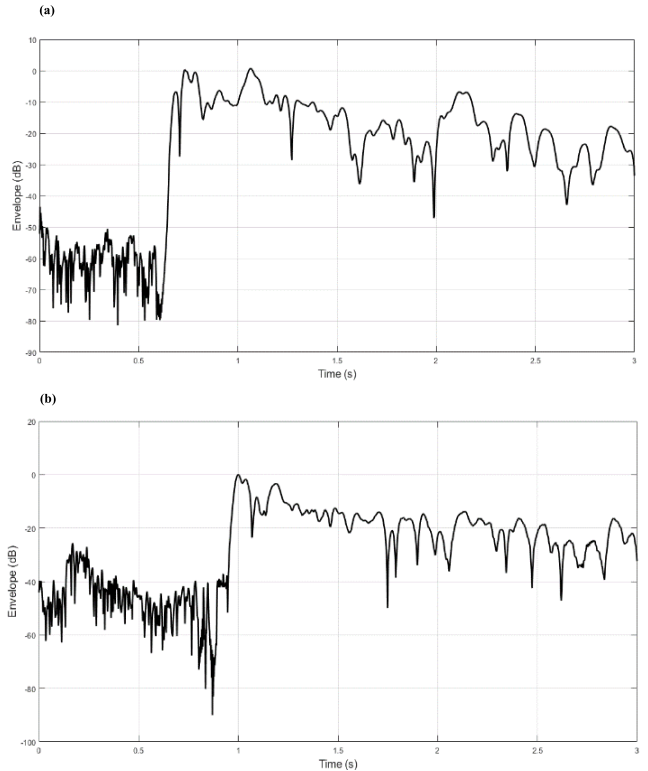


FIGURE 9. The envelope in decibel units for the traces in Figure 7. Note the spike near the first arrival time position.

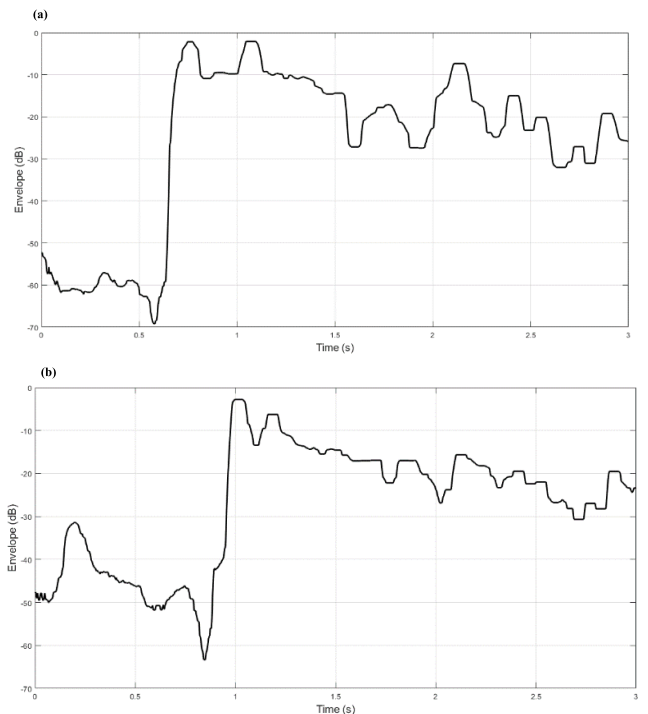


FIGURE 10. Median smoothing with a 50-sample sliding window of the envelope for the traces in Figure 7. Note the smoothness near first arrival.

IV. DISCUSSION

The proposed method works with raw data requiring no type of gain to the data. It can be used for picking weak traces

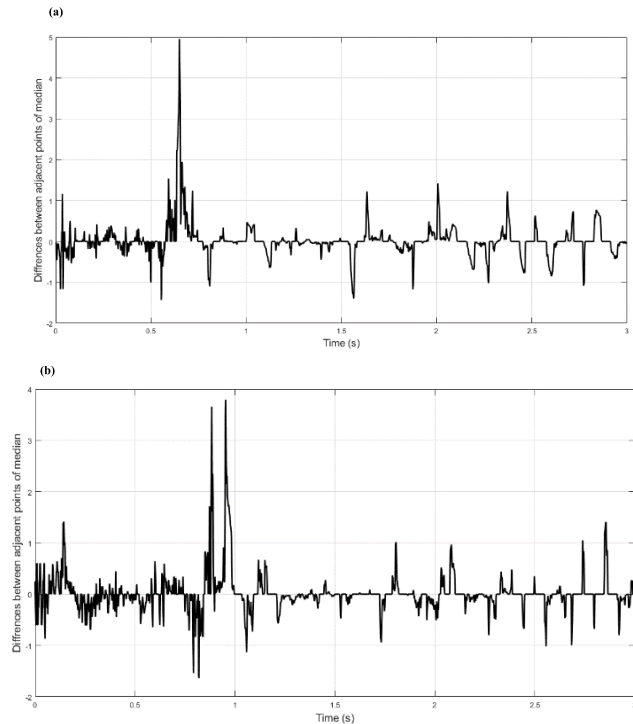


FIGURE 11. Difference between adjacent points of the envelope after applying moving median smoothing. The first arrival is always picked at the point with maximum difference.

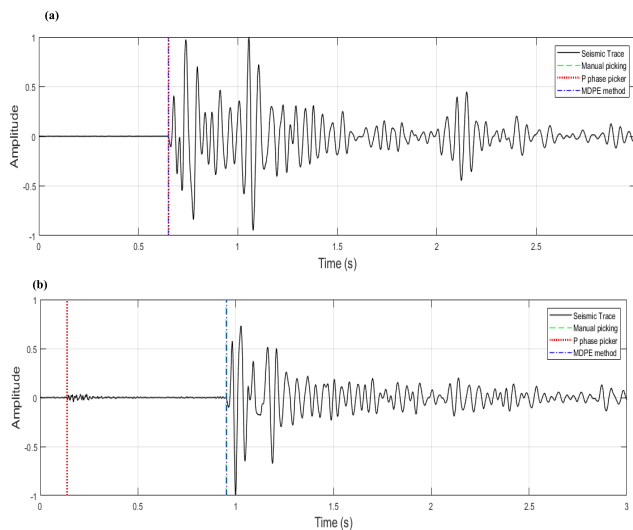


FIGURE 12. Comparison of the MDPE method (dash-dot line) and P-phase picker method (dotted line) for the traces in Figure 7. The manual picking is shown by the dashed line. (a) Application on this trace gives almost the same accuracy for the two compared methods; (b) Application on this trace shows more agreement between the proposed MDPE method and manual picking than the P-phase picking method.

that pose difficulties for other methods. Another benefit of the method is that it needs only the sliding window length from the user, while the rest is calculated automatically. To compute the differences between the adjacent points along the time samples, it is important to convert the envelope of the complex seismic trace into decibel units.

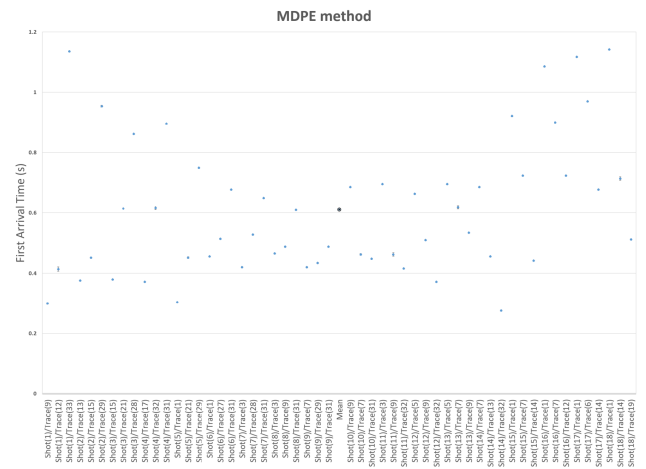


FIGURE 13. Results of applying the proposed MDPE method on 54 selected traces from the southeast Texas data set. Trace and shot numbers are indicated on the x-axis while the first arrival traveltimes of each trace is indicated on the y-axis. Filled circles indicate first arrival estimated by the proposed MDPE method on each of the traces indicated on the x-axis while the error bar indicates its deviation from manual picking. The concentric circle in the middle of figure represents the mean first arrival traveltimes of all 54 traces together with the mean error from manual picks.

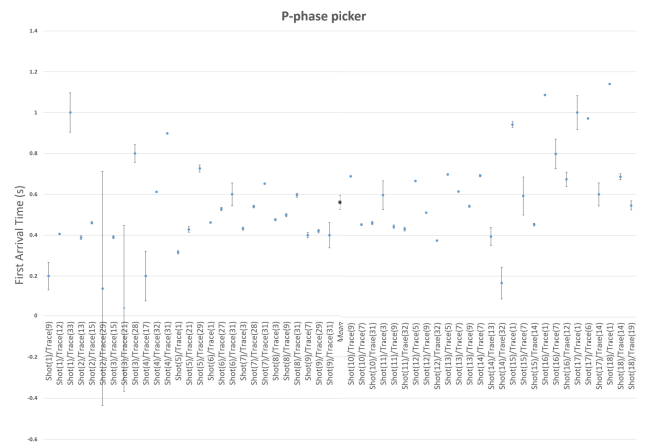


FIGURE 14. Results of applying the P-phase picking method on the same 54 traces shown in the previous figure. Filled circles indicate first arrival estimated by the P-phase picking method on each of the traces indicated on the x-axis while the error bar indicates its deviation from manual picking. The concentric circle in the middle of figure represents the mean first arrival traveltimes of all 54 traces together with the mean error from manual picks. Note the high errors compared to the proposed method.

An initial choice for the length of the median's sliding window is the period of the dominant signal; although this value depends on the data itself. In general, an optimum window length should produce a spike in the data near the first arrival traveltimes in the envelope (in dB scale) after calculating the median. This is important in order to obtain the maximum difference at the correct first arrival position.

Moreover, there is a possible problem with the proposed method in the near offset traces. Near offset traces need smaller sliding windows to produce a median with the correct trace spike although more fluctuations in the

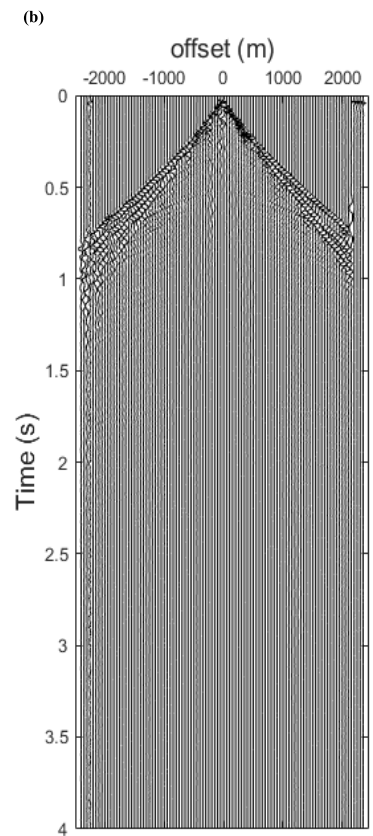
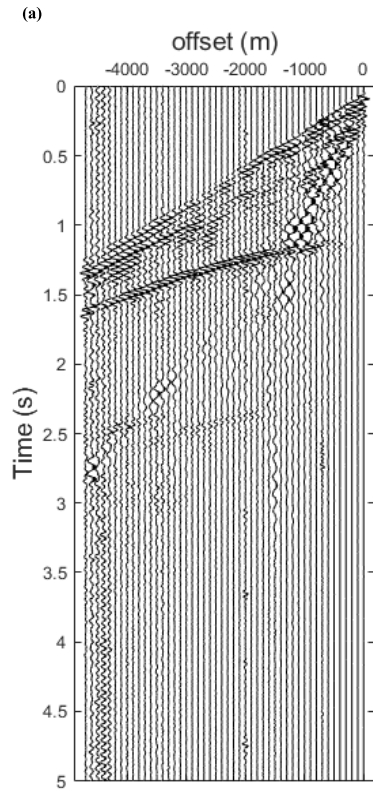


FIGURE 15. Raw shot records selected from Yilmaz (2001). (a) Shot record 6; (b) Shot record 25.

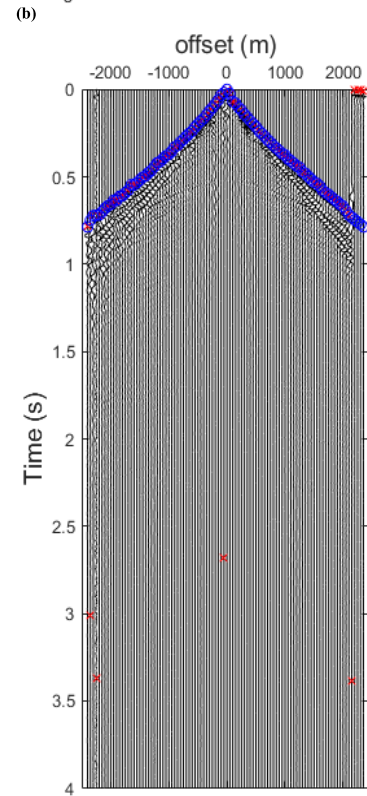
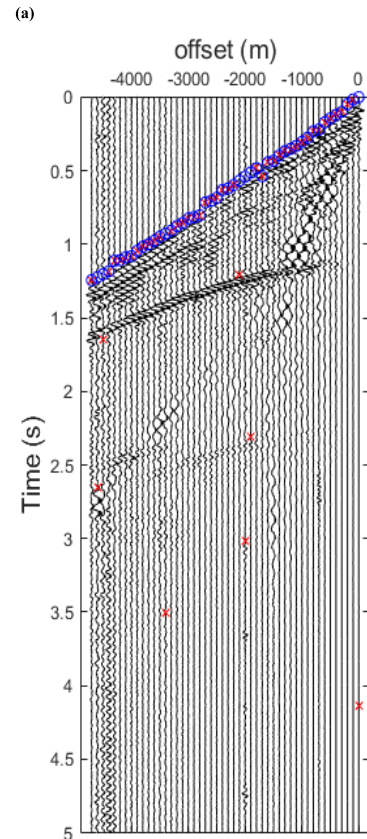


FIGURE 16. The same two Yilmaz's shot records shown in Figure 15 with a comparison of first arrival picks between the proposed MDPE method (crosses) and the manual picks (circles). (a) Shot gather 6; (b) Shot gather 25.

data will be generated. Therefore, one must assure that the envelope after computing the median looks smooth and the spike is still at the same position as in the original envelope.

All real data used in this work have a dynamite source with minimum phase. In case we need to apply the proposed method on a data set with non-minimum phase wavelet (e.g., Vibroseis source), it is important to convert the wavelet to its minimum-phase equivalent using an appropriate spectral decomposition method [24]. Finally, the proposed method needs more testing with different data sets to understand its limitations.

V. SUMMARY

A new automatic first arrival traveltime picking method is proposed. The proposed MDPE method picks the first arrival traveltime automatically based on the maximum difference between adjacent elements of the envelope of a complex seismic trace. At the beginning, we introduced the Hilbert transform and how can we apply it on the original signal of any seismic trace to produce the imaginary part of the complex seismic trace.

After that, the complex seismic trace envelope has been calculated as the magnitude of the real and the imaginary parts. Moreover, the envelope has been converted to decibel scale to obtain a spike near the position of the first arrival traveltime.

Next, we calculate the median of the envelope to reduce its fluctuations and make it smoother. Finally, we picked the first arrival traveltime as the maximum difference between adjacent samples of the smoothed envelope.

The proposed method was tested on two synthetic shot records, and then we compared it with the manual picking and found that our method estimated the manual picks with more than 88% picking accuracy. Moreover, we used the same test on two of Yilmaz's published real seismic shot gathers and found that our method estimated the manual picks with a picking accuracy of more than 85%. The proposed method was tested on real data from southeast Texas and compared with the P-phase picker method. The results from that data show that the proposed method performs better than the P-phase picker method in most cases.

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