TAO, Vol. 9, No. 2, 183-196, June 1998

Removing Bad Traces in Shallow Seismic Exploration

Robert Sun[1] and Amy Wang[1]

(Manuscript received 24 April 1997, in final form 11 March 1998)

ABSTRACT

In reflection shallow seismic exploration, bad traces in common shot gather can be identified and removed by quantifying their properties. The relevant properties include: (1) the amplitude of a trace in some window; (2) the decrease in amplitude as time increases; and (3) the average period of a trace over some window. In general, using each individual property alone only identifies some of the bad traces. However, using all three properties combined identifies almost all them. Therefore, a computer program can be coded to remove most of the bad traces, thereby largely reducing the need for human intervention.

(Key words: Shallow seismic, Noise reduction, Least squares, Bad traces)

1. INTRODUCTION

In reflection shallow seismic exploration, it is desired that all traces in a common shot gather (CSG) represent the true records of the propagating seismic waves. However, due to complexities in the field, it is quite difficult for seismic equipment to operate perfectly. For instance, human construction in some places may forbid laying out geophones; or some electronic circuits may malfunction, etc. Such factors may give rise to bad traces in a common shot gather, or alternatively the energy in a bad trace may have nothing at all to do with the propagating seismic waves.

Figure 1 presents an example illustrating bad traces in a CSG. It is easy to observe that traces 26, 41 and 45 are in no way related to the propagating seismic waves. These are obviously bad traces. It is desired that these bad traces be removed because they are destructive rather than constructive to the signal-to-noise (S/N) ratio.

In the past, such bad traces could only be removed by human eye-picking which, obviously, involved huge manual labor costs. For this reason, some geophysical data processors just ignore the existence of bad traces. Though this practice does not prevent one from obtaining seismic profiles, the removal of the bad traces certainly enhances the S/N ratio, thus improving the quality of the resulting profiles.

In this research, an attempt is made to have bad traces removed with a computer instead of by eye-picking. It is hoped that a program can be designed to substitute the human element in

[1]Department of Earth Sciences, National Chengkung University, Tainan, Taiwan 70101, ROC

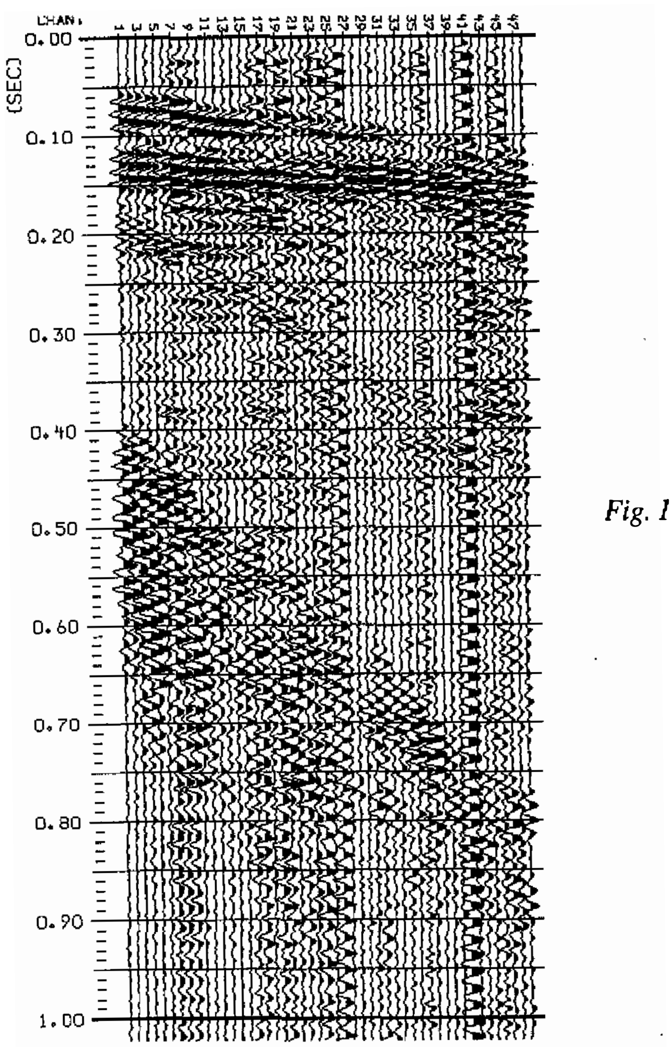


Fig. 1. 48-channel shallow seismic common shot gather. It is easy to identify traces 26, 41 and 45 as bad ones.

this task. In the design, it is necessary to determine the property differences between good and bad traces. Subsequently, the program must be able to quantify the differences, thereby distinguishing bad traces from good ones.

At least 3 such property differences exist. First is the difference in amplitude. Since the amplitude of bad traces is from some unwanted origins and not from seismic waves, their amplitude is usually very different from that of good traces. This translates into bad traces, due to bad circuits, usually having amplitudes much larger or smaller than those of good traces. Bad traces due to bad, or even no, geophones have an amplitude much smaller than that of good traces. In Figure 1, the amplitude differences between bad traces (channels 26, 41 and 45) and good traces are clearly seen. In general, those traces with extreme amplitudes (high or low) are bad traces, whereas those with intermediate amplitudes are usually good ones.

The second property is the tendency for the amplitude to decrease with time. Good traces are records of true seismic waves. In seismic wave propagation, geometrical spreading (Aki & Richards 1980, p. 97-100) and attenuation (Aki and Richards 1980, p. 167-185) are intrinsic phenomena. The amplitude of propagating waves therefore decreases as the travel distance increases. An increase in travel distance means an increase in travel time. Thus, the amplitude on a good trace decreases with increasing time. Conversely, as the energy on a bad trace has nothing to do with the propagating seismic waves, its amplitude usually does not decrease with time. It is evident that the rate of amplitude change with time also represents another factor which can distinguish bad traces from good ones.

The third property difference is the period of the wave on a trace. Good traces are true records of seismic wave. Their period (or frequency) is determined by the spectrum of the wave from the seismic source. However, as previously stated, the waves on bad traces have some other origin not related to the seismic source. Their period may be very different from that of good traces. If such a difference does exist, then it can be used as a third criterion to distinguish bad traces from good ones.

These three properties have all been observed thus far. In this paper, the numerical method is used to quantify these properties and to design a computer program to identify bad traces in a CSG. As long as bad traces can be separated from good ones on the basis of their property differences, they can, indeed, be removed. The test results here show that although not all bad traces can be identified, for many survey lines most of them can be. Accordingly, human intervention can be largely reduced.

In this text, each bad-trace-identifying property is discussed individually and tested with field data. The field data used in the testing is acquired during field shallow seismic work in southwestern Taiwan. The parameters of the seismic data are: vertical component 48-channel; near offset 60 m; geophone and shot intervals 2 m; sampling rate 1 ms; low cut 35 hz; and peak frequency 95 hz. The Elastic Wave Generator (EWG) manufactured by Bison Instruments, Inc. is employed as the seismic source.

2. IDENTIFYING BAD TRACES

Bad trace removal is implemented in common shot gather. Since the amplitudes of the propagating seismic waves decrease as time increases, the signal-to-noise (S/N) ratio also decreases. To best describe the amplitude of the seismic wave in a CSG, it is best to use that portion of the CSG with the highest S/N ratio. The portion that fits this goal is the first reflection.

In order to determine the arrival time of the first reflection, a priori velocity analysis is required. Such velocity analysis, however, only needs to cover the first reflection rather than the entire record length. In this paper, the normal moveout (NMO) velocity analysis method (Yilmaz 1987, p. 162-200) is applied. Based on the results of velocity analysis, a window is determined to enclose the first reflection. Figure 2 presents the first reflection windowed from the CSG in Figure 1. It should be noted that for each trace, the starting time of the window depends on the arrival time of the first reflection on that trace.

In the following, the quantification of each of the three properties is explained individually. The CSG in Figure 1 is used as an example in the explanation.

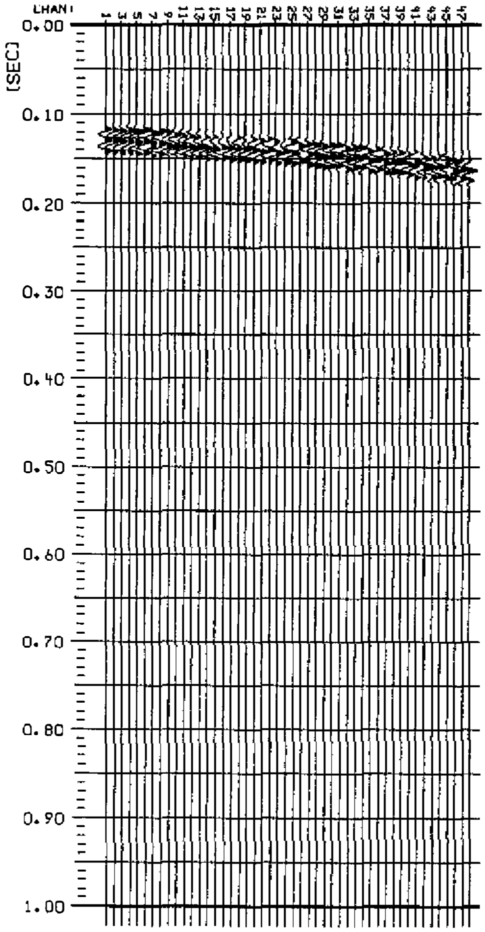


Fig. 2. Signal with the highest S/N ratio, i.e., the first reflection, windowed from the CSG in Figure 1.

2.1 Differences in Amplitude

As stated previously, only the (windowed) first reflection is utilized to model the differences in amplitude. In a CSG, the record in a good trace should be the wave function f of offset x and arrival time t; that is, $f = f(x,\ t)$. To obtain amplitude function, the Hilbert transform (Claerbout 1976, p. 20-23) can be applied to the wave function $f(x,\ t)$ to obtain a 90-degree phase shift function $g(x,\ t)$, and then the relation used is:

$$\phi(x,t) = \left[f^2(x,t) + g^2(x,t)\right]^{1/2} \tag{1}$$

to calculate the amplitude function $\phi(x,t)$. This procedure is explained in Figure 3. Figure 3a represents the displacement function of a trace in a window. Figure 3b shows the Hilbert transformed 90-degree phase shift function, while Figure 3c illustrates the amplitude function.

There are two options in using amplitude difference: (a) the maximum amplitude $\phi_{max}(x)$ of a trace in the window and (b) the average amplitude $\phi_{avg}(x)$ of a trace in the window:

$$\phi_{avg}(x) = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \phi(x,t) dt, \tag{2}$$

where t_1 and t_2 are the beginning and ending times of the window on a trace, respectively. For the windowed data in Figure 2, the maximum amplitudes and the average amplitudes as functions of the traces are plotted in Figures 4a and 4b, respectively. For clarity, the amplitudes in Figures 4a and 4b are in logarithm scales.

Maximum amplitude is discussed first. According to Figure 4a, the maximum amplitude decreases with increasing channel number. This is because the amplitude decreases with an increasing offset. On the other hand, the amplitudes of channels 26 and 45 are found to be anomalously low. Compared with Figure 1, these two channels are regarded as bad traces, due to a bad circuit and to a bad geophone, respectively. Even so, the maximum amplitude does not show any anomaly on channel 41, which is also a bad trace.

Next, on observing the average amplitude in the window (Figure 4b), it is noted that, just like the maximum amplitude, the average amplitude has a tendency to decrease with increasing channel number. Again, the amplitudes of the bad traces, namely channels 26 and 45, are anomalously low, yet the average amplitude does not show any anomaly on bad trace channel 41.

Based on the above findings, in this paper, the least squares method (Dahlquist *et al.* 1974, p. 196-216) is used to find a linear function of offset (or channel number) so as to model the maximum amplitudes or the average amplitude of the windowed portion in a CSG. However, the anomalous amplitudes on the bad traces may distort the determination of the modeling linear function. In light of this, to avoid such distortion, although bad traces should not be included in the least square modeling, they are not identifiable prior to the modeling. As a

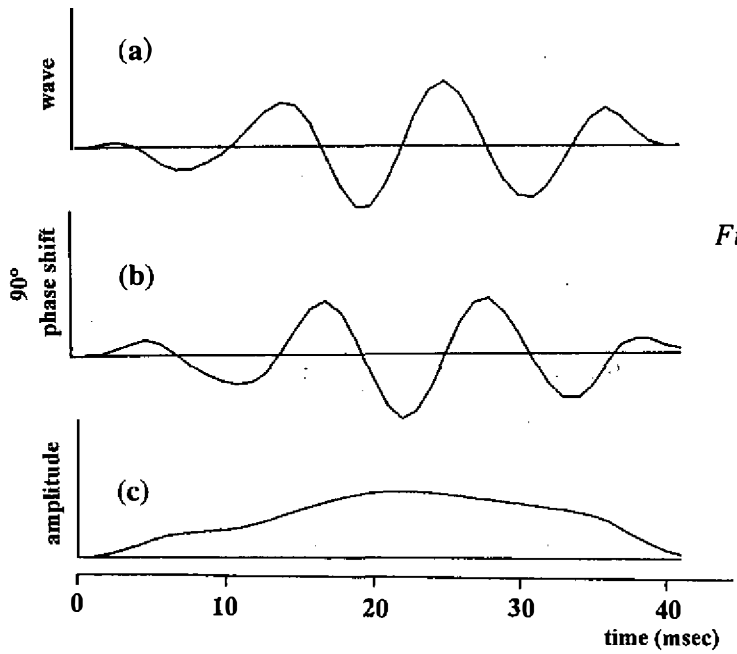


Fig. 3. (a) Portion of the wave function on a trace; (b) 90-degree phase shift of the wave function; and (c) amplitude function from Eq. (1).

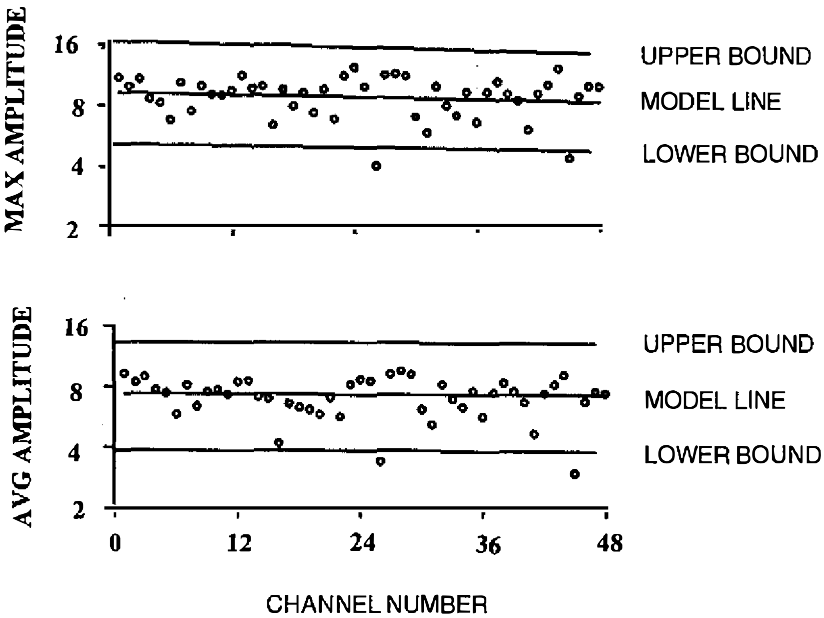


Fig. 4. Amplitudes of the windowed portion of the traces in a common shot gather: (a) the maximum amplitude and (b) the average amplitude. The amplitudes between the lower and upper bounds are identified as good traces.

trade-off, the amplitudes are sorted in increasing order. For a CSG with N channels, two integers n_1 and n_2, where $1 < n_1 < n_2 < N$ are selected such that the sequence numbers between n_1 and n_2 do not include any anomalously high or anomalously low amplitudes. In other words, the least square modeling only uses those amplitudes between sequence numbers n_1 and n_2. However, not each and every good trace is required for the least square modeling. On the contrary, just a portion of the good traces are in fact enough to obtain an acceptable least square modeling function.

Take the 48-channel CSG as an example. It is necessary to determine the maximum possible number of bad traces with both anomalously low amplitudes, and anomalously high amplitudes. If the maximum number of bad traces with anomalously low amplitudes is 9, then n_1=10 can be selected. If the maximum number of bad traces with anomalously high amplitude is 11, then n_2=48-11-1=36 can be selected.

If p_i is the trace amplitude with amplitude sequence number i and x_i is the corresponding offset, then the least square modeling determines coefficients a and b such that the function is minimized.

$$E = \sum_{i=n_1}^{n_2} \left[p_i - \left(a x_i + b \right) \right]^2 \tag{3}$$

For good traces with true amplitude p_i, the difference between true amplitude and the modeled amplitude is expected to be small. That is, the ratio,

$$r_i = \left| \frac{P_i - (ax_i + b)}{(ax_i + b)} \right|, \tag{4}$$

should be small, where x_i is the offset corresponding to that good trace. For a bad trace, the true amplitude p_i can be far away from the modeled value $ax_i + b$, and the ratio in Eq. (4) may be very large compared to that of a good trace. Hence, a threshold can be assigned to distinguish bad traces from good ones. A trace is considered good if r_i in Eq. (4) is less than the threshold, but a trace is bad if r_i is larger.

In Figures 4a and 4b, the least square modeled lines are presented. For both maximum amplitude (Figure 4a) and average amplitude (Figure 4b), 0.20 is chosen as the threshold. Based on this threshold, the lower and upper bounds of the amplitude for good traces can be determined. These bounds are plotted as straight lines in Figures 4a and 4b. Those traces with an amplitude between the lower and the upper bounds have an r_i value [Eq. (4)] of less than the threshold and are taken as good traces. Those traces outside these bounds are considered bad. In this way, Figures 4a and 4b clearly show bad trace channels 26 and 45. However, the identification of the bad trace channel 41 is not successful. Obviously, this criterion identifies some - but not all of the bad traces.

2.2 Amplitude Decreases With Time

In a CSG, the amplitudes of good traces are expected to decrease as time increases. The reasons for this decrease include: (a) geometrical spreading; (b) attenuation; and (c) accumulative product of transmission coefficients. This is because good traces are the records of reflected seismic waves.

If there is no noise, the amplitude of good traces decreases infinitely. However, as time increases, the weighting of noise increases, and the S/N ratio decreases. Thus, the amplitude of a good trace does not decrease infinitely because of noise. Nevertheless, the amplitude in the window enclosing the first reflection appears larger than the amplitude at some later point, say, 200 ms later.

On the other hand, with energy from another origin other than propagating seismic waves, bad traces do not bear this property. The origin of bad traces usually remains throughout the entire record length and maintain the amplitude of a bad trace roughly unchanged.

On these grounds, two windows can be selected, and the rate of amplitude decrease with time can be measured. The first window can be the window enclosing the first reflection, as stated at the beginning of this section. The second window should be later, say 200 ms later, than the first window. On each trace, Eq. (1) is used to compute the amplitude in each window. Then, Eq. (2) is employed to calculate the average amplitude of the traces in each window.

If ϕ_{i1} and ϕ_{i2} are the average amplitudes of the i-th trace in the first and second windows, respectively, then the ratio

$$R_i = {}^{\phi_{i1}}\!\big/_{\phi_{i2}} \tag{5}$$

is a measurement of the amplitude decrease over time. Large R_i ($R_i >> 1$) means the amplitude decreases rapidly as time increases, implying that the i-th trace may be good. Otherwise, an R_i value close to 1.0 means the amplitude does not change significantly as time increases, suggesting that the i-th trace might be bad. Thus, a threshold of, say 2.5 can be assigned. If R_i is smaller than the threshold, then the i-th trace is taken as bad. Otherwise, it is taken as good.

Extra attention must be paid when selecting the second window. In shallow seismic exploration, the amplitude of the air wave can be larger than the overlapping reflection. If the air wave is enclosed in the second window, then the average amplitude in the second window is exaggerated. Hence, the second window must not include any portion of the air wave. If a simple-shaped window (like that in Figure 2) encompasses some portion of the air wave, the beginning and/or the end of the window should be shifted to avoid that portion.

Figure 5 shows the distribution of R_i [Eq.(5)] with respect to channel number i. For clarity, R_i is plotted on a logarithm scale. It is seen that R_i for channels 26 and 41 are very low (0.95 and 0.52 respectively), but all the other channels have R_i larger than 3.0. If a threshold of 2.5 is chosen, then channels 26 and 41 are identified as bad traces, while all the others are good ones. It should be noted that again here, channel 45 is being mistaken as a good trace. Clearly, just like item (1), using this criterion alone identifies some, but not all, of the bad traces.

2.3 Period on a Trace

In seismic exploration, a wave from a seismic source has its own spectrum. The wavelet on a good trace has its peak period (and peak frequency) corresponding to that spectrum. This

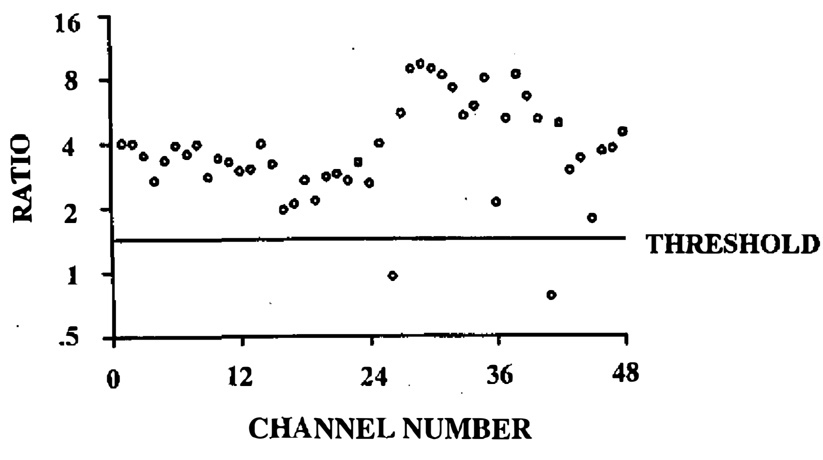


Fig. 5. Amplitude ratio R_i [Eq. (5)] as a function of channel number i. The ordinate is in the logarithm scale. The threshold is also plotted.

means that the peak period on a good trace stays within a reasonable range. In contrast, the wave on a bad trace, being of some other origin, has its own spectrum and period which might be different from those of good traces. If such a difference is significant, it can be used as a criterion to distinguish bad traces from good ones.

Here again a window is chosen which can be exactly the same as that in item (1). For each trace, the average period in the window is calculated. Figure 6 shows the average periods of the windowed traces in Figure 2. It is noted that the average periods of good traces are around 11 ms. However, the period of channel 41, which is a bad trace, is 16.8 ms, very different from the rest. Thus a threshold, say 14.5 ms can be assigned, and those traces with an average period of less than the threshold can be taken as good ones; conversely, those with periods larger than the threshold can be taken as bad traces. In this way, for the CSG in Figure 1, channel 41 can be identified as a bad trace. However, this time, the bad traces channel 26 and 45 are not separated out. This points out that just like items (1) and (2), using average period alone can identify only some, but not all, of the bad traces.

3. TESTING AGAINST A SINGLE CSG

In the last section, it is stated that the use of any property alone (usually) makes it possible to identify only some but not all of the bad traces. This being the case, it is suggested all three of the properties combined be used in order to reduce the number of missed bad traces. In some examples, using all three properties still results in some of the bad traces being missed, but most of them are picked out.

Figure 7 illustrates another 48-channel CSG example that includes 12 bad traces, namely channels 7, 23, 25, 26, 28, 30, 34, 35, 38, 39, 40 and 46. Figures 8a through 8c show the average amplitude in a window [Eq. (2)], the amplitude ratio of two windows [Eq. (5)] and the average period in a window. Exactly the same thresholds as those used for the CSG in Figure

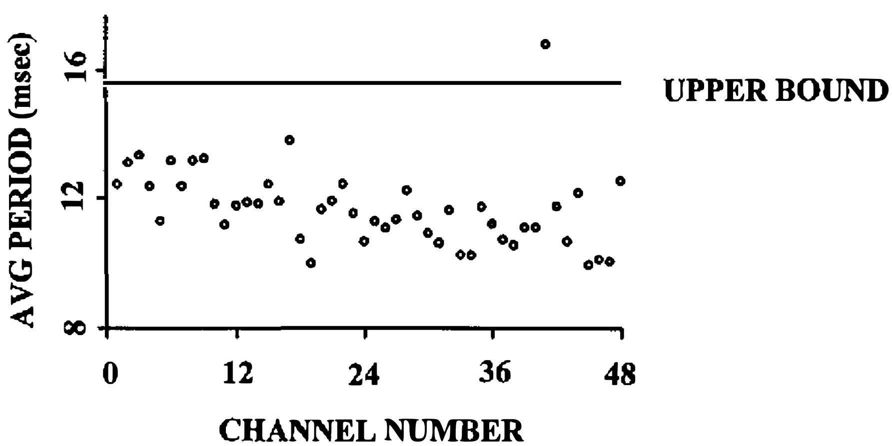


Fig. 6. Average period of the windowed portion of the traces in Figure 1. The threshold is also plotted.

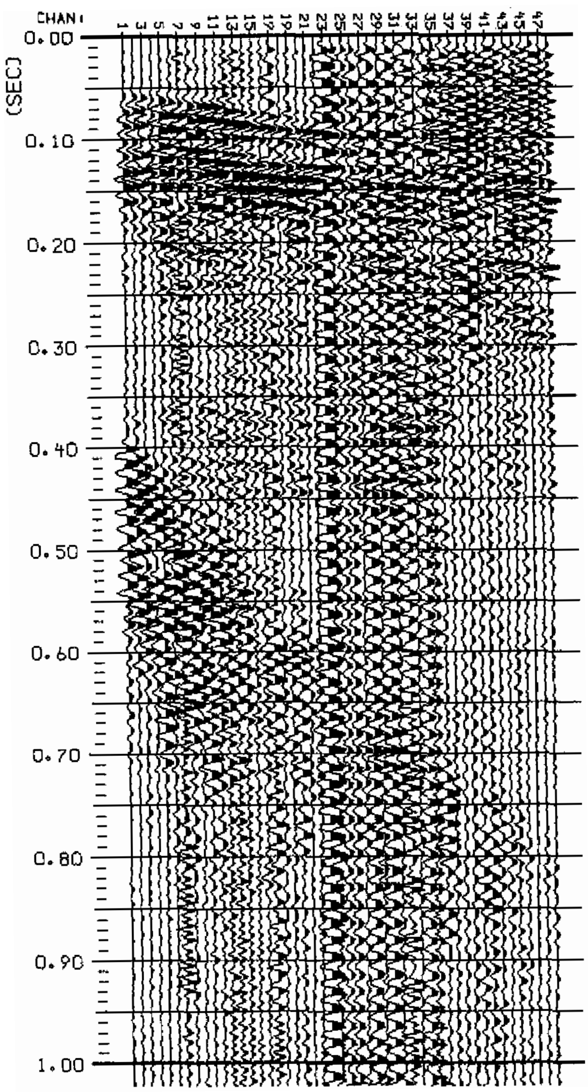


Fig. 7. Common shot gather with numerous bad traces. There are totally 12 bad traces.

1 are used. That is, the threshold for the average amplitude is 0.2, that for the amplitude ratio is 2.5, while that for the average period is 14.5 ms. The bounds for good or bad traces are also plotted in Figures 8a through 8c. It now becomes evident that the three properties combined spot all of the 12 bad traces. The CSG after the bad traces are removed by this algorithm is shown in Figure 9.

4. TEST AGAINST A SURVEY LINE

In order to see the usefulness of the algorithm in this paper, the algorithm is tested against a survey line with 60 shots. Exactly the same thresholds as those used in the previous examples are used. After bad-trace removal, the resulting seismic profile is presented in Figure

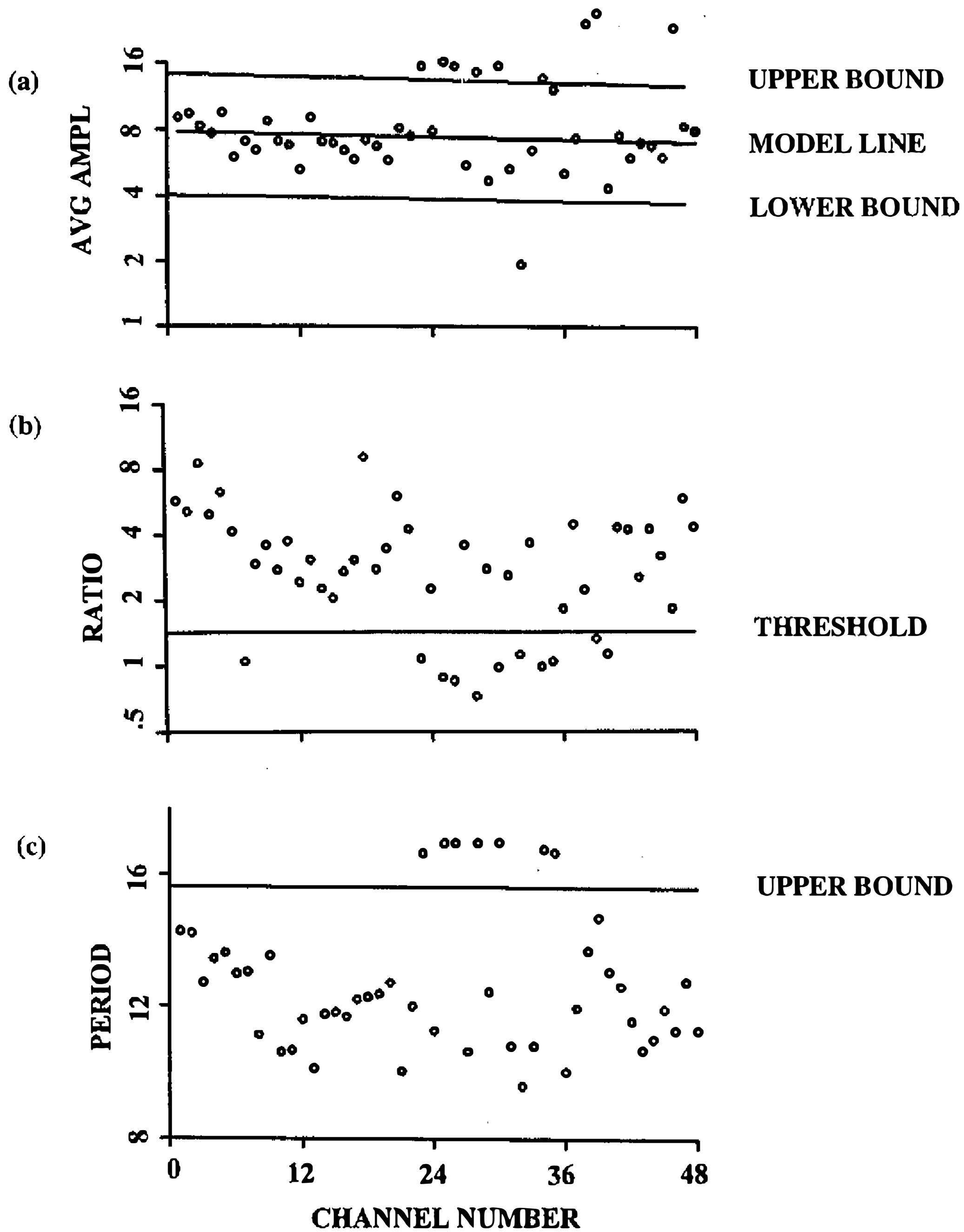


Fig. 8. Quantified properties of the CSG in Figure 7: (a) average amplitude of the windowed portion of the traces; (b) amplitude ratio R_i [Eq. (5)]; and (c) average periods of the windowed portion of the traces. In each figure, proper bounds/thresholds are also plotted.

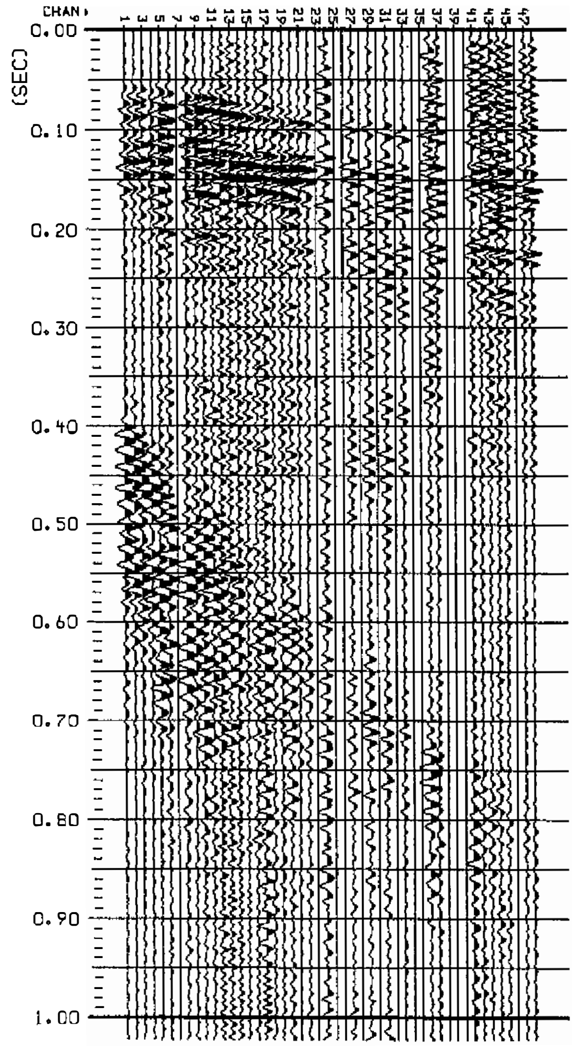


Fig. 9. CSG in Figure 7 after bad traces are removed. What remain are all good traces.

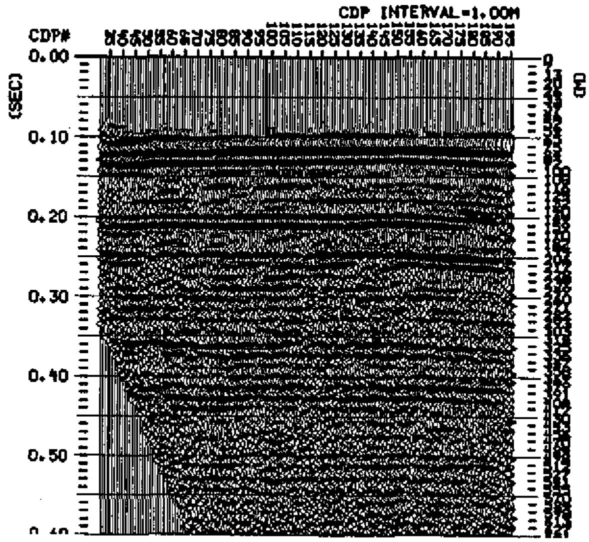
10a. The corresponding seismic profile without bad-trace removal is shown in Figure 10b, which is presented here for comparison. Note that the heavy noise around CDP 168 in Figure 10b, for example, is largely reduced in Figure 10a.

5. CONCLUSIONS AND DISCUSSION

In shallow seismic exploration, the existence of bad traces is harmful to the output seismic profile. If bad traces are removed, the quality of the resulting seismic profiles is greatly improved.

Though human input is certainly able to eliminate bad traces, the manpower costs are high. This has meant that bad-trace removal has often been ignored by data processors. The usefulness of the algorithm in this paper is in the fact that it substitutes human work for a

(a)



(b)

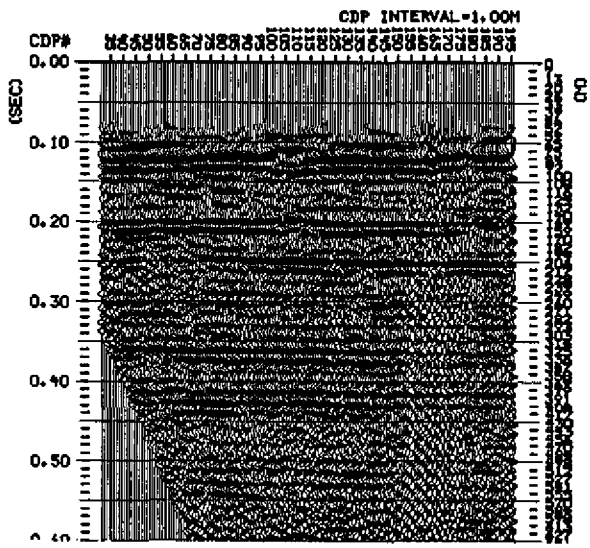


Fig. 10. Resulting profiles from a 60-shot shallow seismic survey line: (a) profile obtained with bad-trace removal and (b) profile obtained without bad-trace removal.

computer. The output bad trace removal by computer is not any better than that of human ability but its benefit is in its capability of reducing human intervention and thus cutting costs.

Three properties are proposed to identify bad traces. From the test example, neither criterion alone can successfully pin point all of the bad traces. Fortunately, as those traces which are missed do not usually overlap all 3 properties, using all 3 of these properties together largely reduces the number of missed bad traces.

It is true that some of the bad traces do have all of the 3 properties and share some similarities with good traces. In such cases, the bad traces cannot be identified with the above criteria. But on the basis of this research, such cases are very rare, indeed.

Because the existence of bad traces in the CSG cannot be avoided, the only thing that can be done is to fix it in data processing. This paper shows that with the computer rather than with manual work alone, the fixing can proceed.

The authors handle bad trace removal simply as an additional procedure in their data processing sequence. The procedure can also be handled as a subroutine in some existing procedures, such as bandpass filtering. In either way, the required CPU time and the need for the operatorís intervention is very limited.

The issue addressed in this paper is the detection and elimination of bad traces. This paper does not intend to attenuate noise if the noise is mixed in good traces. Noise attenuation algorithms can be found in other papers [e.g., Alsdorf (1997)].

Trace equalization and automatic gain control (AGC) are the required procedures in data processing. Both of these procedures change the amplitude of a CSG. As the bad-trace removal algorithm in this paper uses the original amplitude of the traces, bad-trace removal must proceed before trace equalization and AGC. However, if the seismograph does AGC at data acquisition, then criterion (2) cannot be applied in data processing unless a pre-AGC copy of the CSG is saved.

The choice of thresholds is subject to some constraints even though it is somewhat flexible. Improper thresholds may cause the computer to mistake good traces for bad ones or vice versa. Yet, a single test is sufficient for a data processor to determine the optimized thresholds. There might be traces that are partly bad and partly good. In these cases, the operator needs to determine whether to keep these ambiguous traces by adjusting the thresholds.

In general, on a survey line, tens of consecutive CSG's can use the same thresholds. If the survey line is very long, say 200 CSG's or more, it may be necessary to split the survey line into several sections and use different thresholds on different sections.

Acknowledgments The research leading to the publication of this paper was supported by the National Science Council of the Republic of China on Taiwan under grant no. NSC86-2815-C-006-049-M. The manuscript was expertly typed by Ms. Nancy Lu.

REFERENCES

Aki, K., and P. G. Richards, 1980: Quantitative Seismology. Freeman and Co., San Francisco, California.

Alsdorf, D., 1997: Noise reduction in seismic data using Fourier correlation coefficient filtering. *Geophysics*, **62**, 1617-1627.

Claerbout, J., 1976: Fundamentals of Geophysical Data Processing. McGraw-Hill, New York.

Dahlquist, G., A. Bjorck, and N. Anderson, 1976: Numerical Methods. Prentice-Hall, Englewood Cliff, New Jersey.

Yilmaz, O., 1987: Seismic Data Processing. Society of Exploration Geophysicists, Tulsa, Oklahoma.