

The effect of different CMP stacking techniques on signal-to-noise ratio of seismic data: two examples from Osaka and Nara, Japan

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Abstract

Seven different common midpoint (CMP) stacking methods are applied to two seismic data sets that are acquired in Osaka City and Nara City, Japan, in order to examine the most effective stacking technique for seismic data acquired in urban areas. The comparison between the qualities of the resultant seismic sections is based on calculating the correlation coefficients between adjacent traces, the maximum/average amplitude ratios of individual traces and the standard deviations as well as on the visual inspection of the seismic sections. Two stacking techniques, namely "alpha-trimmed stacking" and "optimum-offset weighted stacking", resulted in significantly good seismic sections compared to the commonly used straight mean stacking. Several geological features that appear fuzzy on the straight mean stack are clearly detectable on the optimum-offset weighted stack and the alpha-trimmed stack. Precise selection of the appropriate stacking technique when processing seismic data acquired in urban areas can significantly enhance the signal-to-noise ratio of the stacked seismic section and can also make the final interpretation easier and more precise.

Key-words : S/N ratio, CMP stacking, urban areas, seismic data, optimum-offset

Introduction

In the field of exploration geophysics, the term "stacking" is used to denote some way of combining several geophysical measurements to produce one output measurement (Naess and Bruland, 1985). Assuming that signal is coherent while noise is incoherent or random, taking several geophysical measurements instead of a single measurement reduces the noise level within the final output. Among stacking techniques commonly applied to geophysical measurements, the most widespread application of stacking is the averaging of common midpoint (CMP) gathered traces of seismic reflection data. The reason for the outstanding success of CMP stacking is its ability to separate noise from signal of the same frequency. Almost all other seismic processes either

eliminate both signal and noise or merely modify the amplitude of both signal and noise without changing the proportion (Lindseth, 1982).

Shortly after the invention of the CMP straight mean stacking technique (Mayne, 1962), many studies started arguing that straight mean stacking is not the most appropriate procedure for every seismic data and several alternative stacking techniques were proposed for seismic data acquired in various environments and for seismic data with some special characteristics. These alternative stacking techniques include diversity stack (Embree, 1968), Nth-root stack (Muirhead, 1968; Kanasewich *et al.*, 1973), random stack (Currie, 1982), single-trace iterative stack (Naess, 1982) iterative weighted stack (Pruett, 1982), and alpha-trimmed stack (Watt and Bednar, 1983). However, these proposed techniques did not attract much attention at the time because the field of seismic

exploration was having great advances in the fields of recording equipment and the data acquisition techniques such as high-fold coverage, sub-weathering shooting, source and receiver arrays, and vertical stacking. The huge advances in these fields obscured the importance of alternative stacking techniques.

Since the mid of 1990s, the use of shallow seismic method in academic, geotechnical and environmental geophysical studies flourished, mainly because of the drastic drop of the cost of hardware and software of seismic exploration. Due to the limited budgets available for these studies, relying on the relatively less expensive processing strategies to enhance signal-to-noise (S/N) ratio of the acquired seismic data is more practical than using the extremely expensive acquisition techniques applied to oil exploration. Another difference between oil exploration and geotechnical studies is that the latter are frequently conducted near and sometimes inside urban areas. Conducting a seismic survey in an urban area is usually faced with numerous difficulties and challenges caused by accessibility, space handling and safety and environmental precautions. Sometimes, even when the financial resources are available, it is impossible to use the desired seismic source, such as dynamite, or to apply certain field techniques, such as sub-weathering shooting and recording. Thus, under the aforementioned conditions, non-conventional processing routines should be adopted to get better seismic sections in these environments. It seems, therefore, valuable to reexamine the processing approaches that were abandoned in the past, particularly alternative stacking techniques.

This study presents the results of comparing the S/N ratio of 7 different CMP stacking methods applied to 2 seismic lines acquired in Osaka City and Nara City, Japan in order to achieve a better understanding of the effect of various stacking methods on S/N ratio and to find out the most effective stacking method for seismic data acquired in urban areas.

Review of Stacking Techniques

Stacking is one of the most important steps in the processing of seismic data and one should consider carefully how to perform this process. The choice of stacking method is dependent on what kind of unwanted energy or noise is present in the seismic data. If some coherent noise is still present in the CMP gathers, it may be worthwhile to consider other stacking techniques instead of the commonly used straight mean stacking (Naess and Bruland, 1985). The following is a brief description of the principles, the prominent features, the advantages and the

disadvantages of the stacking techniques examined in this study.

Straight mean stack:

The conventional straight mean stacking technique is the simplest and the most commonly used procedure in seismic data processing. In this technique, the sample values of all traces in a CMP gather are summed and divided by the number of samples, then raised to a supplied power. This process can be expressed in the following equation:

$$A(t) = \frac{1}{N} \sum_{i=1}^N a_i(t) \quad (1)$$

Where $A(t)$ is the sample value of the stacked trace at two-way time t , N is the number of stacked traces and $a_i(t)$ is the sample value on trace i at two-way time t (Hatton *et al.*, 1996).

This stacking technique assumes that all traces in the CMP gather being stacked have equal validity and thus should be given equal weight (Sheriff and Geldart, 1995).

Maximum/minimum exclusion stack:

This stacking technique is similar to the straight mean stacking but the samples with the highest and lowest amplitudes are dropped before stacking. This simple procedure aims to exclude anomalously high positive and negative samples from the stack, because they are most probably noise rather than signal (ProMAX, 1999). Excluding noise bursts from the stack is thought to considerably enhance the S/N ratio of the stacked data.

Sign bit stack:

Sign bit stack sets +1.0 to the sum when the sample is positive or zero, and -1.0 when the sample is negative. The actual sample values are ignored (ProMAX, 1999). This stacking technique is suitable where the target is to discriminate between positive and negative reflections in the final stack but it destroys the real amplitude and distorts the frequency content of the original seismic data.

Median stack:

Median stack is a simple procedure where the median value of the amplitudes is given to the stacked trace across the CMP gather at each time level. The median value of a set of amplitudes is found by sorting the amplitudes in order of increasing value and then picking the one in the center (ProMAX, 1999). The advantage of the median stack procedure is that it can exclude abnormal amplitudes caused by noise occurring in a small number of the input traces. Moreover, the median stack is little influenced by a partly coherent noise occurring in the same time level of a

primary signal on less than half of the traces (Naess and Bruland, 1985). A major disadvantage of the median stack is that abrupt changes in amplitude between consecutive samples in the output trace may result in waveform distortion in the final stack.

Alpha-trimmed stack:

The high frequency noise appearance in median stack can be avoided by using a summation of several amplitudes situated around the middle position after reorganizing the input values in increasing order or what is so called the alpha-trimmed stack (Watt and Bednar, 1983). The alpha-trimmed mean A_α of a number of samples N is given by:

$$A_\alpha = \frac{1}{N-2L} \sum_{i=L+1}^{N-L} a_{(i)} \quad (2)$$

Where N is the number of samples or the CMP fold, $a(i)$ is the amplitude of the i th sample, α is the trimming parameter ($0 < \alpha < 0.5$) and $L = [\alpha N]$.

When α is equal to zero, A_α becomes the conventional straight mean stack and when α is equal to 0.5, A_α is the same as the median stack. By verifying the parameter α , a result that would partly have the properties of the median stack and partly those of the straight mean stack, can be achieved.

Diversity stack:

The diversity stack is a procedure that has been widely applied to noise suppression of land seismic data. The real advantage of the diversity stack is mainly due to its ability to preserve amplitude variations in the input records. The following is a description of the steps of the diversity stacking method:

(1) Each trace is divided into time windows and the total energy, E , within each window is calculated as follows:

$$E = \sum_{\Delta T} a_i^2 \quad (3)$$

Where a_i is the amplitude or power of the time gate and ΔT is the length of the time window.

(2) A scaling factor, D , is calculated for each window: $D = C/E$ where C is a constant.

(3) The “gain trace” is defined by assuming that the scaling factor D is the center value for the same window in the “gain trace”. The remaining sample values on the “gain trace” are then calculated by linear interpolation between the center values of consecutive windows.

(4) The “scaled trace” is calculated by cross multiplication of the “gain trace” by the “original trace”.

(5) The scaled traces and the gain traces are summed, then

the sum of scaled traces is divided by the sum of the gain traces.

Optimum-offset weighted stack:

The optimum-offset weighted stacking technique is proposed to enhance S/N ratio in seismic data acquired in urban areas (Rashed *et al.*, 2002). The technique enhances the S/N ratio of the stacked data by giving more weight for traces with good reflections and less weight for those traces contaminated by noise. The procedures of this technique are as follows:

First, each CMP gather is inspected to select the trace or group of traces that contain the strong reflections and the less noise. The offset of this trace is then assigned as the optimum-offset (X_{opt}). The weight of each trace within this CMP gather is calculated using the following equation:

$$W_i = a - \left(b \sqrt{\frac{(X_{opt} - X_i)^2}{(\Delta X)^2}} \right) \left(\frac{N}{\sum_{i=1}^N W_i} \right) \quad (4)$$

Where, W_i is the weight for the i th trace; X_i is the offset of the i th trace and ΔX is the distance between each two successive traces while a and b are user-defined constants that control the slope of the weighting curve and N is the CMP fold. This equation is based on the general inverse distance weighting equation (Shepard, 1968).

The optimum-offset weighted stacking technique was applied to seismic data acquired in urban area and provided a seismic section with higher S/N ratio and stronger, more coherent reflections than straight mean stack (Rashed, 2003).

Field Examples

The two seismic lines presented in this study are Osaka line, acquired in the Osaka Basin and Nara Line, acquired in the Nara Basin in the central part of Honshu Island, Japan (Fig. 1). Both lines were acquired in the middle of highly urbanized areas and across two buried reverse faults where faulted basement is covered by alternating sedimentary layers of marine and non-marine clay, sand and gravel (Huzita and Kasama, 1983). Osaka line was acquired by the Laboratory of Urban Geosciences, Osaka City University while the Nara Line was acquired by the Geological Survey of Japan (Geol. Surv. Japan, 1997).

Data acquisition:

The Osaka line is a 1200 meters seismic line that was acquired using a 3.5-ton, T15000 MiniVib with an up-sweep from 10 to 100 Hz and a sweep time of 10s. For

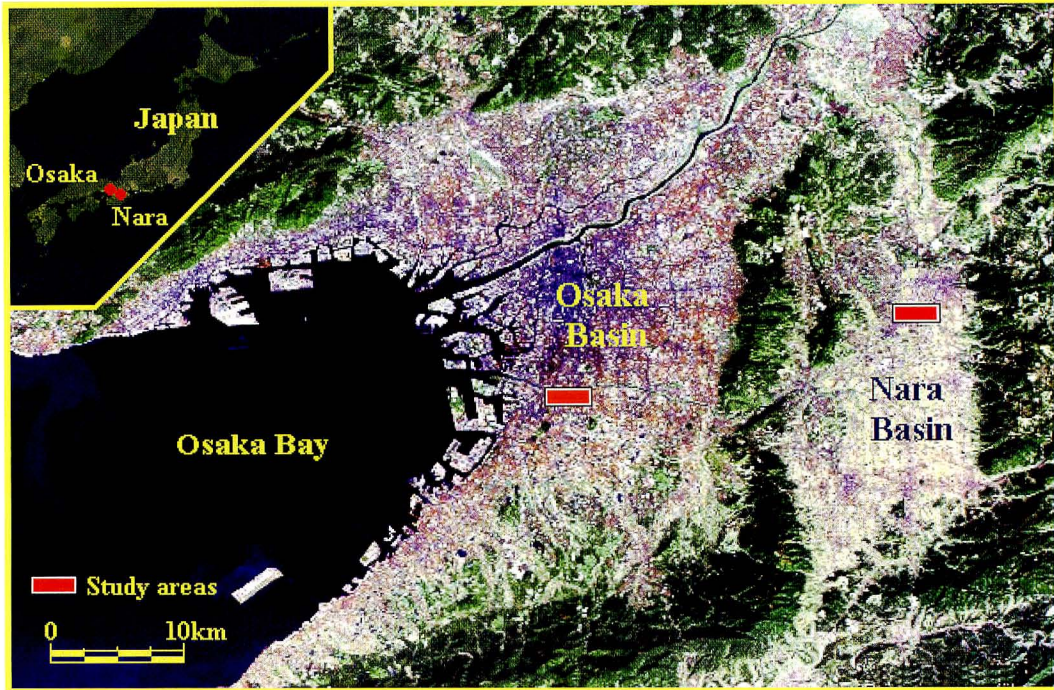


Fig. 1 Location map of the study areas.

Table 1 Recording data

	Osaka Line	Nara Line
Recording system	StrataView RX60	Bison 9060A
Seismic source	T15000 MiniVib	JIM-200 P-wave Impactor
Sweep band	10-100 Hz	—
Sweep length	10 sec	—
Vertical stacking	3 fold	10 fold
Geophones	30-300 Hz	30-300 Hz
Geophones/Station	6 in-line array	6 in-line array
Geophone interval	1.4 m	1.4 m
Shot interval	10 m	5 m
Receiver interval	10 m	10 m
Offset	20 m	10 m
Channels	60	60
Sampling interval	1.0 ms	1.0 ms
Pre-filter	35-300 Hz	16-250 Hz

each shot, the MiniVib was fired 3 times, or more when it was necessary, and the collected traces were vertically stacked. The data were collected using an array of 6 in-line geophones to attenuate the airwave. The distance between each two successive geophones is 1.4 m producing 10-m array interval. The seismic data were recorded using a 60-channel StrataView RX60 recording system with a 1.0 ms sampling interval. A 35 Hz pre-A/D low-cut filter, a 300 Hz high-cut filter and a 60 Hz notch filter were applied to attenuate the interference of low frequency noise, high frequency jitter and the electrical

appliance with the recorded data. A shot interval of 10 m and source-receiver offset of 20 m were used.

The Nara line is also 1200 meters long that was acquired using a JIM-200 P-wave Impactor. The data were also collected using 6 in-line geophones with an array spacing of 10 m and shot interval of 5 m. The data was recorded using a 60-channel Bison-9060A system with a sampling interval of 1.0 ms. A 16 Hz pre-A/D low-cut filter and 250 Hz high-cut filters were applied to the filed records. Recording parameters of the two seismic lines are summarized in table 1.

Data processing:

A standard processing routine was applied to the 2 seismic lines including some intensive noise attenuation techniques such as frequency-wave number ($f-k$) filtering and iterated velocity analysis. The data processing was carried out using ProMAX seismic data processing package (ProMAX, 1999). Pre-processing involved converting raw data from the SEG Y format into the processing software internal format. The field geometrical parameters were then edited into the file's header and followed by routine editing of the 2 data sets. The elevation statics corrections were followed by refraction statics corrections to compensate for minor surface irregularities and to remove the effect of the near surface low-velocity layer (LVL). The data were scaled analytically using parametric gain function derived from the average amplitude-decay curve estimated from the inspection of the raw data. The inspection of frequency panels and frequency spectral analysis show that band-pass filter of 15-25-50-60 Hz was adequate for the Osaka line while a filter of 35-45-175-200 Hz is best for the Nara line. The slope of the high cut part of the filter was kept gentle to avoid frequency aliasing (Yilmaz, 2000). Frequency filtering was not successful in completely removing coherent noise such as ground roll and guided waves. Accordingly, $f-k$ filtering was applied to shot gathers to remove these noises. Stacking velocities were estimated from an integrated analysis of constant velocity gathers, hyperbolic fitting, dynamic stack and semblance plots. The velocity analysis was performed twice to improve the results of the velocity analysis and to get more precise image of the subsurface velocities by removing any remained statics from the CMP gathers before final velocity analysis. Predictive deconvolution was performed to improve the temporal resolution by suppressing multiples and collapsing the wavelet to as much spike as possible. The 2 seismic lines were then stacked using the previously mentioned 7 stacking techniques. In alpha-trimmed stacking excluding 30% of samples gave the best results for both seismic sections while in optimum-offset weighted stacking, $a = 1$ and $b = 1.2$ were found adequate. The stacked data were then converted into ASCII format to perform the statistical evaluation and comparison between them.

Results and Discussion

Signal-to-noise ratio is difficult to determine in practice because of the difficulty in separating out the signal (Sheriff, 1973). However, the quality of seismic data can be measured by how well the final stack can be

interpreted or how good it looks (Shon and Yamamoto, 1992). Thus, visual inspection of the final stack is the cornerstone of judging the quality or S/N ratio of seismic data. Among other things, the relative amplitude and lateral coherency of seismic events are the basis of judging the S/N ratio of the final stack (Mitchum *et al.*, 1977; Shon, 1990). In seismic sections with mainly horizontal reflections, correlation coefficient between adjacent traces can be used as an indication of the lateral continuity of seismic events, while the maximum amplitude-to-average amplitude ratio of individual traces is a measure of the relative amplitude of seismic events (Rashed *et al.*, 2002). The width of the distribution of noise in stacked traces can be represented by the standard deviation of the stack values (Haldorsen and Farmer, 1989). In this study, the comparison between the S/N ratio or the quality of the final stacks resulted from different stacking methods is based on the following 4 parameters:

- (1) Correlation coefficients between adjacent traces of the final stacks as a function of coherency.
- (2) Maximum/average amplitude ratio of each stacked trace as an indication of the strength of reflection amplitudes.
- (3) Standard deviation of each stacked trace as a function in S/N ratio.
- (4) Visual inspection of the stacked sections to judge how interpretable they are.

Osaka Line:

Figure (2A) is a bar diagram of the average correlation coefficient of adjacent traces from various stacks of Osaka line. The correlation coefficients between the adjacent traces of the maximum/minimum exclusion stack, the alpha-trimmed stack and the optimum-offset weighted stack are 14%, 15% and 19%, respectively, higher than the straight mean stack. On the other hand, the correlation coefficient of the sign bit stack, median stack and diversity stack are 5%, 10% and 10%, respectively, lower than the straight mean stack. The noticeable phenomena is that the correlation coefficients increased in the three stacks that are based on rejecting and/or down-weighting the marginal part and concentrate on the central part of the seismic data. The decrease of the correlation coefficient of the median stack can be attributed to the reliance of this stack on a single value. This value can vary significantly from one CMP gather to the next, which may be the reason of the low correlation coefficients between adjacent traces in the final stack. Optimum-offset weighted stack, alpha-trimmed stack and max/min exclusion stack show the best lateral continuity among all other stacks. Both max/min exclusion stack and alpha-

trimmed stack are based on rejecting a part of the highest and lowest amplitudes from the stack. Anomalous high amplitudes are mostly noise, unavoidable in urban areas. Low amplitudes can also degrade the final trace by reducing the final sum of the stacked trace. Optimum-offset weighted stacking method down-weights the parts of the CMP that are dominated by noise. Those parts are located mainly in the far and near offset traces in the CMP. Optimum-offset weighted stacking, on the contrary, up-

weights the medium offset traces with good seismic reflections and no interference of noise.

The maximum/average amplitude ratio of individual traces represents the ratio between the amplitude of the strongest reflection in a trace to the background of that trace. Increasing this ratio means generally stronger reflections within the final stack and hence enhancement in the S/N ratio. Average of maximum/average amplitude ratios of the 7 stacks of Osaka line are plotted in figure (2B). Maximum/average amplitude ratio decreased only in the sign bit stack with about 5%, it has increased in the diversity stack, max/min exclusion stack, median stack, alpha-trimmed stack and optimum-offset weighted stack by 1%, 22%, 46%, 52% and 56%, respectively. It can be seen that S/N ratio has drastically increased in the same stacks in which the lateral continuity of reflections has enhanced which are, max/min exclusion stack, alpha-trimmed stack and optimum-offset weighted stack.

Standard deviation of single traces can be used as an indication of the S/N ratio in seismic data (Haldorsen and Farmer, 1989). Figure (2C) shows average standard deviations of traces from various stacking methods applied to Osaka line. Optimum-offset weighted stack, max/min exclusion stack and alpha-trimmed stack give the smallest standard deviations. Sign bit stack also gives small standard deviation values. However, this result may be influenced by the alteration of the original data by adding ones or minus ones to the sum.

From the evaluation of the 7 stacking methods, examined in this study, using the 3 statistical parameters mentioned above, the optimum-offset weighted stacking method and the alpha-trimmed stacking method show the best results.

The quality of a seismic section can be best judged by how well the eye of interpreter can recognize different features on that section. In order to demonstrate the difference in quality between mean stack and other stacks, both mean stack and optimum-offset weighted stack are illustrated in figure (3). The optimum-offset weighted stack was selected as an example for alternative stacking techniques because it showed the best enhancement in all statistical evaluation parameters. Figure (3A) shows a conventional straight mean stack of the acquired seismic section while figure (3B) shows the optimum-offset weighted stack of the same section. The difference in the strength of reflections on both sections can be clearly seen. Reflection events on the optimum-offset weighted stack are much stronger, more coherent and have less waveform distortion. Moreover, some features that cannot be seen in the straight mean stack are quite clear on the optimum-offset weighted stack. Five specific features on the section

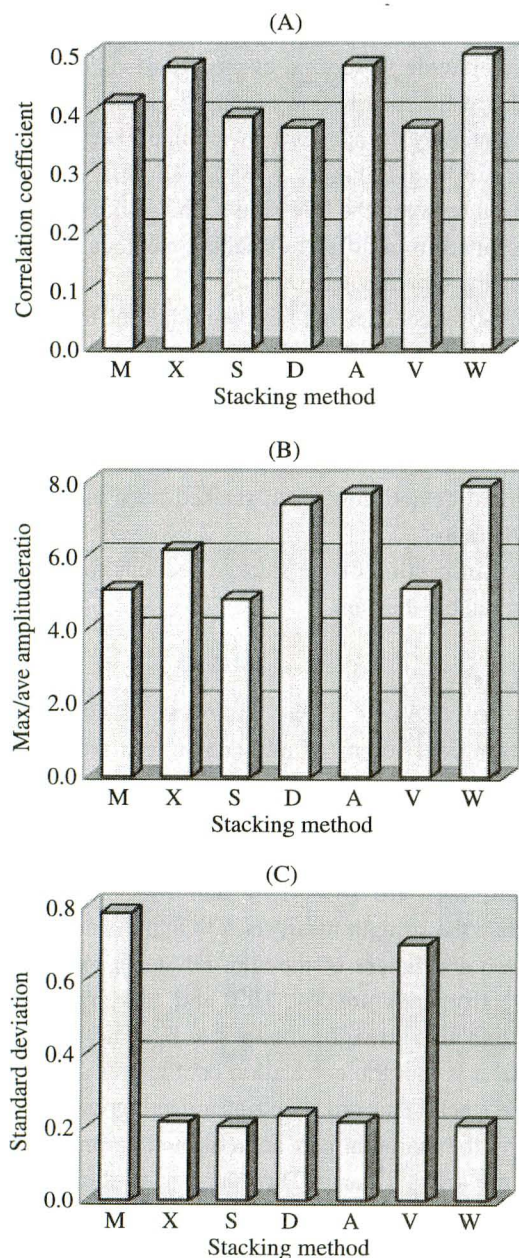


Fig. 2 Statistical evaluation of signal-to-noise ratio of different stacks of Osaka seismic line using (A) correlation coefficient, (B) maximum/average amplitude ratio, and (C) standard deviation. M=straight mean, X=maximum/minimum exclusion, S=sign bit, D=median, A=alpha-trimmed, V=diversity and W=optimum-offset weighted stack.

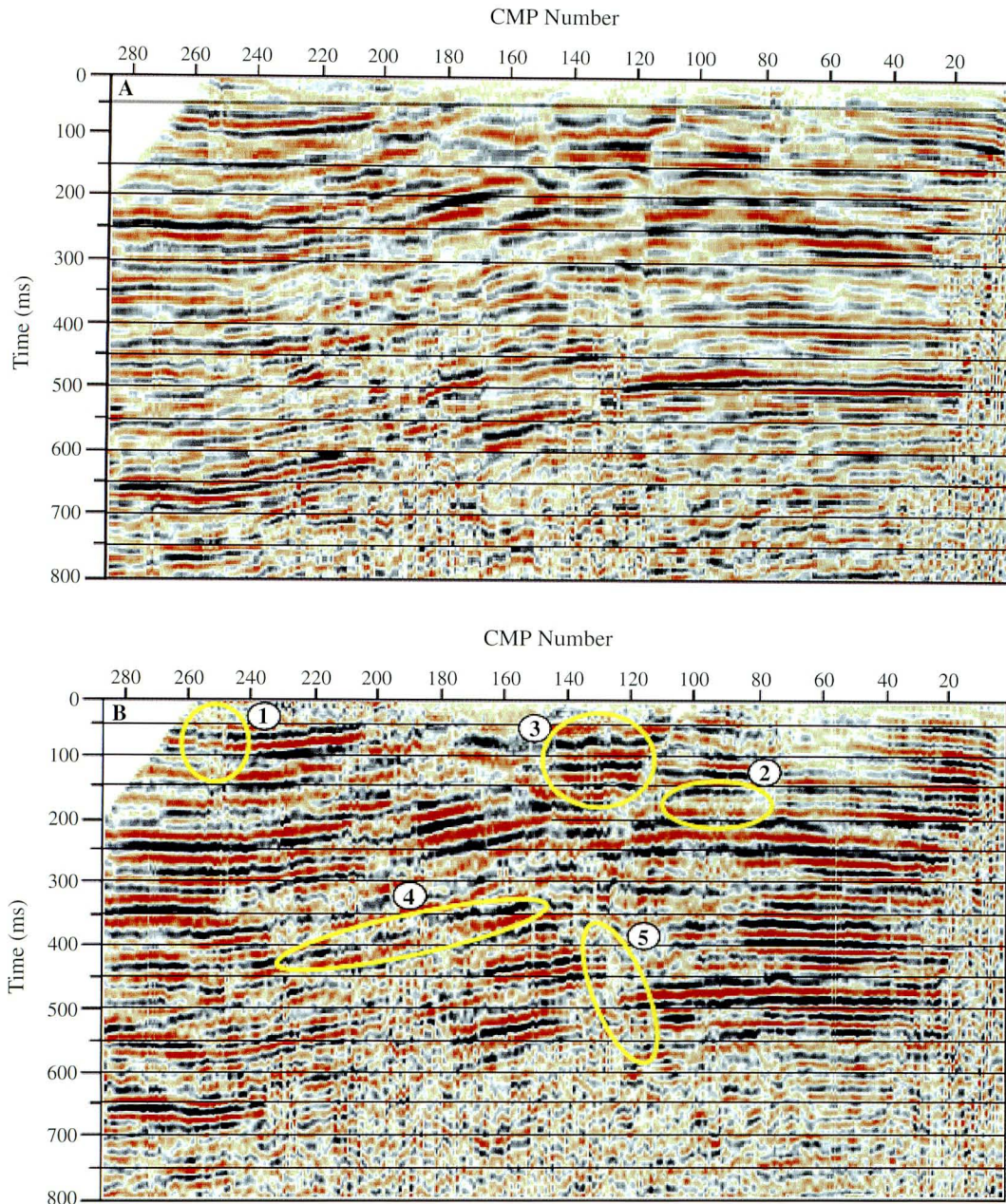


Fig. 3 Time section of Osaka seismic line (A) straight mean stack (B) optimum-offset weighted stack.

are selected to compare the difference between the 2 seismic sections. Some of these features can significantly affect the interpretation of the seismic section. The two shallow small normal faults (mark 1 on figure 3B) between CMP's number 240 and 260 between 0 and 200 ms are good example. These two subtle faults can be easily missed on the mean stack while they are quite clear on the optimum-offset weighted stack. Another example is the two reflectors between 150 and 200 ms between CMP's number 70 and 110 (mark 2). On the mean stack, these two reflectors are merged to one smeared reflector. However, on the optimum they are completely distinguishable from each other. Another phenomenon is

the waveform distortion in the mean stack, which is much less in the weighted stack (mark 3). This distortion is reduced in the weighted stack because of the down-weighting of the near-offset traces, which contain low-frequency noise, and the far-offset traces where the frequency stretching occurs during the normal-move-out correction. Mark 4 on figure (3B) indicates a reflection event that can be easily tracked on the optimum-offset stack whereas it appears scattered and discontinuous on the straight mean stack. Some strong reflection events (mark 5) near the fault zone on the weighted stack show clear-cut termination while, on the straight mean stack, these reflection events gradually vanish making it more difficult

to estimate the exact location of the fault plane.

Nara Line:

The same statistical parameters, mentioned above, are used to evaluate S/N ratio of stacked data obtained from the Nara seismic line. Figure (4A) is a bar diagram of average correlation coefficients between adjacent traces of various stacks. Unlike Osaka line, in Nara line, alpha-trimmed stacking shows the highest correlation

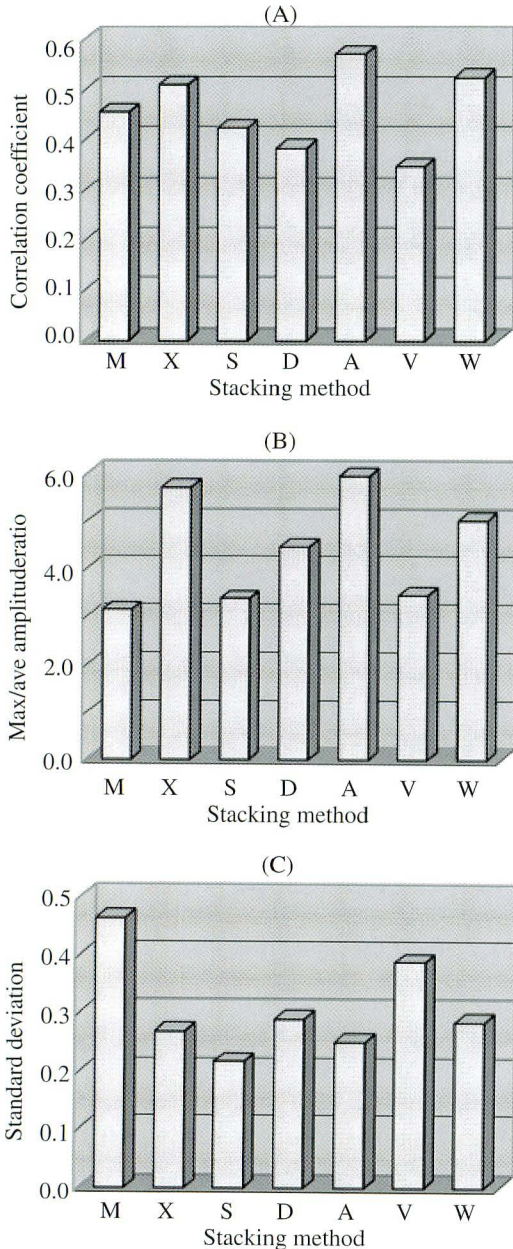


Fig. 4 Statistical evaluation of signal-to-noise ratio of different stacks of Osaka seismic line using (A) correlation coefficient, (B) maximum/average amplitude ratio, and (C) standard deviation. M=straight mean, X=maximum/minimum exclusion, S=sign bit, D=median, A=alpha-trimmed, V=diversity and W=optimum-offset weighted stack.

coefficient, followed by optimum-offset weighted and maximum/minimum exclusion stack.

On the maximum/average amplitude ratio diagram (Fig. 4B), both alpha-trimmed and maximum/minimum exclusion stacking show significantly high ratios, nearly twice that of straight mean stack. Optimum offset weighted stacking comes third.

Figure (4C) shows a plot of average standard deviation of traces resulted from various stacking methods. Sign-bit stack gives the highest S/N ratio but, as mentioned earlier, this false indication may be resulted from manipulating the original sample amplitudes by adding ones or minus ones to the sum. Alpha-trimmed stack comes second followed by maximum/minimum exclusion and optimum-offset weighted stack.

Figure (5) shows the final stack of Nara seismic line resulted from straight mean stacking (A) and alpha-trimmed stacking (B). Although in this case, there is no much difference in the amount of geological information that can be extracted from both lines, it is quite obvious that alpha-trimmed stack has less noise than straight mean stack (mark 4 on figure 5B). Moreover, reflections on the alpha-trimmed are more coherent and show much better lateral continuity (marks 3), especially on the shallow part of the section (marks 1 and 2).

Conclusions

In this study, the suitability of the conventional straight mean stacking method is argued and several other stacking techniques are presented. These stacking techniques are tested using 2 seismic data sets acquired in Osaka City and Nara City, Japan as examples for seismic data acquired in urban areas. Statistical evaluation of Osaka line shows that optimum-offset weighted stacking technique produced a seismic section with better lateral continuity of reflections and higher S/N ratio than the straight mean stack. Visual inspection also shows that several features that can hardly be seen on the straight mean stack are easily detectable on the optimum-offset weighted stack. Alpha-trimmed stack and max/min exclusion stack come second and third, respectively, in both statistical analysis and visual inspection.

On the other hand, both statistical evaluation and visual inspection of final stacks resulted from different stacking techniques of Nara line show that alpha-trimmed stacking gives the best output. Max/min exclusion stack and optimum-offset weighted stack come second and third, respectively.

For seismic data acquired in urban area, it is therefore concluded that, straight mean stack may not be the best

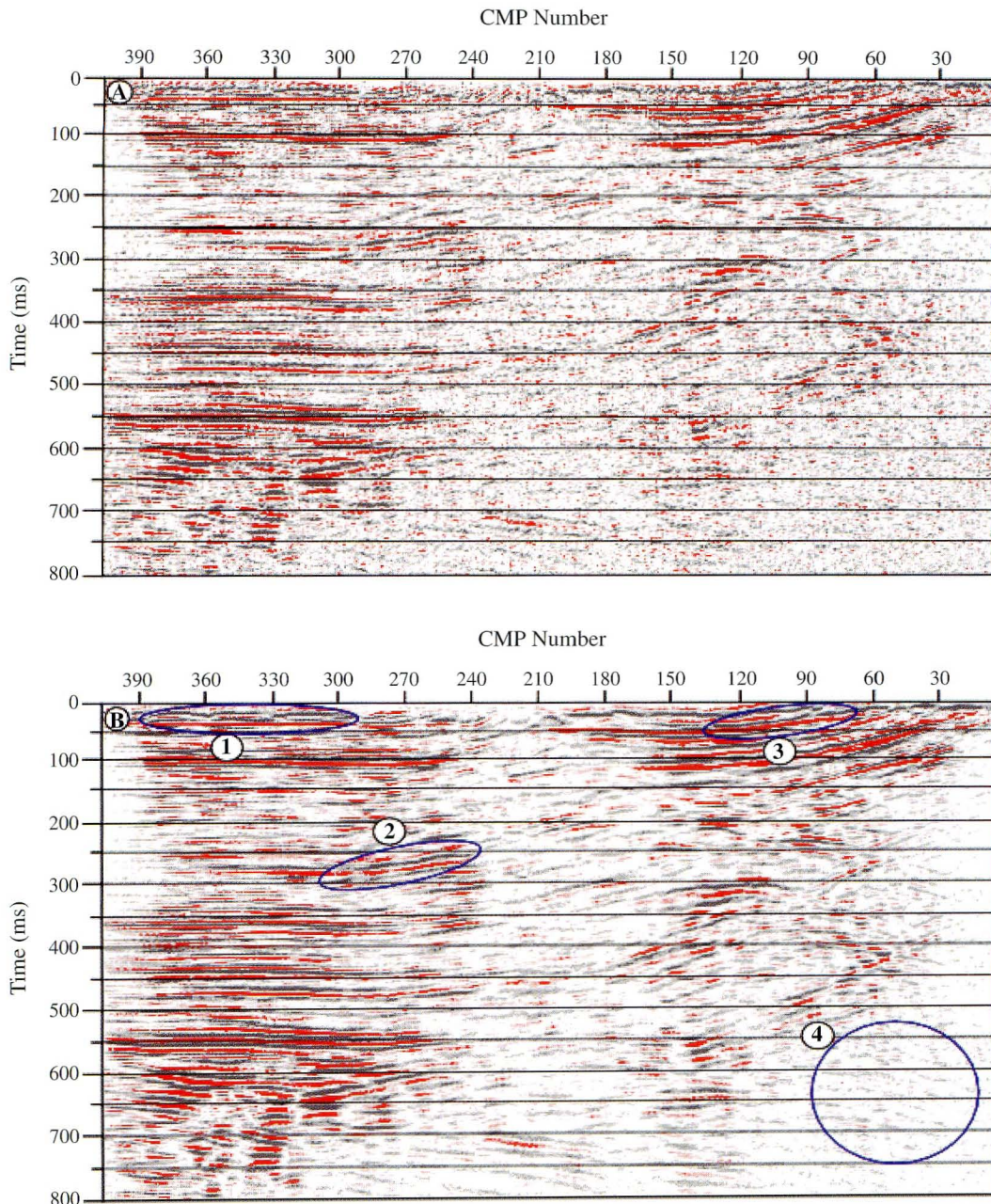


Fig. 5 Time section of Nara seismic line (A) straight mean stack (B) alpha-trimmed stack.

choice. Alternative stacking techniques not only enhance the S/N ratio of the final stack but also can affect the interpretation of the seismic data. It is worth spending a little more time and effort to explore the most appropriate stacking method as a final stage of seismic data processing because it affects the quality of the final seismic section and hence the amount of geological information that can be extracted from this section.

Acknowledgement

The field survey and data processing of Osaka line

were done using the equipment and with the assistance of Kokusai Kogyo Co. Ltd., Amagasaki, Japan. The authors would like to express their deep gratitude to the staff of the company, especially to Mr. Tonoko, Late Mr. Fujii, T., and Mr. Ono, N. who were fully involved in data acquisition and processing. The raw data of Nara seismic line was provided by Mr. Yamada of Hanshin Consultant Co. The authors would also like to thank Dr. Nemoto, H., and the students of the Graduate School of Science, Osaka City University for their help in the field data acquisition of Osaka seismic line.

References

- Currie, W.S. (1982): Seismic velocity determination using random and nonlinear processes, Technical Program Abstracts and Biographies, SEG.
- Embree, P. (1968): Diversity seismic record stacking method and systems, US Patent 3398396, 1968.
- Geological Survey of Japan (1997): Nara basin-toen fault system, Geological and geomorphic survey, Open-file Report No. 286.
- Haldorsen, B.U.J., and Farmer, P.A. (1989): Suppression of high-energy noise using alternative stacking procedure. *Geophysics*, 54, 181-190.
- Hatton, L., Worthington, H., and Makin, J. (1996): Seismic data processing, theory and practice. Blackwell Science Ltd, 177p.
- Huzita, K. and Kasama, T. (1983): Geology of the Osaka-Seihokobo district. Quadrangle Series, (1:50,000 scale) Geological Survey of Japan, 8 pp. (In Japanese with English abstract).
- Kanasewich, E.R., Hemmings, C.D. and Alpaslan, T. (1973): *N*th-root stack nonlinear multi-channel filter. *Geophysics*, 38, 327-338.
- Lindseth, R.O. (1982): Digital processing of geophysical data, a review. 2nd edition, Continuing Education Program, Teknica Resource Development Ltd., SEG, Calgary, 282p.
- Mayne, A.H. (1962) Common reflection point horizontal stacking techniques. *Geophysics*, 27, 927-938.
- Mitchum, R.M., Vial, P.R. and Sangree, J.B. (1977): Seismic stratigraphy and global changes of sea level, Part 6. AAPG Memoir, 26, 117-133.
- Muirhead, K.J. (1968): Eliminating false alarms when detecting seismic events automatically. *Nature* 27, 10 Feb.
- Naess, O.E. (1982): Single trace processing using iterative CDP-stacking. *Geophysical Prospecting*, 30, 641-652.
- Naess, O.E. and Bruland, L. (1985): Stacking methods other than simple summation. *Developments in geophysical exploration methods* 6, pp. 198-223. Edited by A. A. Fitch, Elsevier Applied Science Publishers, London.
- ProMAX, (1999): A commercial seismic data processing software and reference manual. Landmark Graphics Corporation.
- Rashed, M., Yamamoto, E., Mitamura, M., Toda, S., Nishida, T., Terada, Y. Uda, H., Yokota, H., Nemoto, H., and Nakagawa, K. (2002): Weighted stack of shallow seismic reflection line acquired in down town Osaka City, Japan. *Journal of Applied Geophysics*, 50, 231-246.
- Rashed, M. (2003): Optimum-offset weighted stacking: a novel processing technique to enhance signal-to-noise ratio in seismic data acquired in urban areas and its application on Uemachi fault, Osaka, Japan. Ph.D. thesis, Osaka City University, Osaka, Japan, 147p.
- Shepard, D. (1968): A two-dimensional interpolation function for irregularly-spaced data. *Proceedings 23rd National Conference ACM*, 517-524.
- Sheriff, R.E. (1973): *Encyclopedia dictionary of exploration geophysics*. SEG, Tulsa, 339p.
- Sheriff, R.E. and Geldart, L.P. (1995): *Exploration seismology*. 2nd Edition, Cambridge University Press, 300p.
- Shon, H. (1990): Seismic multiple deconvolution using the multipulse model: Thesis, Duke University.
- Shon, H. and Yamamoto, T. (1992): Simple data processing procedures for seismic section noise reduction. *Geophysics*, 57, 1064-1067.
- Watt, T. and Bendar, J.B. (1983): Role of the alpha-trimmed mean in combining and analyzing seismic common-depth-point gathers, Technical Program Abstracts and Biographies, SEG, Las Vegas.
- Yilmaz, Oz., 2000, *Seismic data analysis*. SEG, 2027p.

Manuscript received September 13, 2005.

Revised manuscript accepted January 16, 2006.