MASW — Horizontal Resolution in 2D Shear-Velocity (Vs) Mapping

by

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ABSTRACT

An MASW survey to produce a 2-D (surface and depth) shear-wave velocity (Vs) map involves the acquisition of multiple records (of twelve or more channels) with the same source-receiver configuration moved successively by a fixed distance interval (a few to several stations) along a linear survey line. Acquired records then go through the dispersion-inversion processing to produce a 1-D (depth) Vs profile for each record by treating the subsurface distance spanned by one receiver spread as the horizontally-layered earth model. All these 1-D profiles are then assembled according to the surface coordinate at the midpoint of the spread used to acquire the corresponding record and then the final 2-D map is constructed by using a spatial interpolation scheme. The horizontal resolution of the map is therefore most influenced by two field parameters: the receiver spread length and the acquisition interval. The receiver spread length sets the theoretical lower limit and any Vs structure with its lateral dimension smaller than this will not be properly resolved in the final Vs map. An acquisition interval smaller than the spread length will not improve this limitation as spatial smearing has already been introduced by the receiver spread. However, since all 1-D Vs profiles will always contain some error resulting from the imperfect analysis in dispersion-inversion processing, processing accuracy can also influence the resolution. In this sense, a smaller acquisition interval will improve the resolution through the statistical principle as it provides a greater redundancy in measurement at the expense of survey cost. The role of these controls is described based on the numerical simulations.

INTRODUCTION

The procedure with the MASW method (Park et al., 1999a) to produce a 2-D (surface and depth) shear-wave velocity (Vs) map consists of 1) acquisition of a multiple number of multichannel records along a linear survey line by use of the roll-along mode, 2) processing all acquired records independently to produce a 1-D (depth) Vs profile for each record, and then 3) creating the 2-D Vs map through spatial interpolation by assigning each 1-D Vs profile at the surface coordinate in the middle of the receiver spread used to acquire the corresponding record (Figure 1). During data acquisition, a certain number of receivers (*N*) are linearly deployed with an even spacing (*dx*) over a distance (X_T) and a seismic source is located at a certain distance (X_1) away from the first receiver (Figure 2). Then, the same source-receiver configuration (SR) is moved by a certain interval (*dSR*) to successively different locations to acquire more records. The processing step for the 1-D Vs profiles consists of the extraction of the fundamental-mode dispersion curve, followed by inversion to generate the Vs model matching the curve most closely (Figure 3). During this step, the subsurface spanned by one receiver spread is treated as a horizontally-layered earth model. Resolution of the 2-D Vs map is therefore influenced by the receiver spread length (X_T) and the acquisition interval of the record (*dSR*). This combined effect of the spatial averaging by the receiver spread and the spatial interpolation due to the discrete acquisition of 1-D Vs profiles sets the theoretical limit in the horizontal resolution (Figure 4). The practical limit, however, will be greater than this theoretical limit due to the additional smearing effects resulting from the data processing in which a certain degree of error is always unavoidable.

The most critical part of MASW data processing is the accurate extraction of the fundamental-mode (M0) dispersion curve (Park et al., 1999a; Stokoe et al., 1994). The M0 curve is the only reference that the subsequent inversion process uses to find the most probable Vs model matching the curve most closely. A considerable amount of effort has been made to enhance both acquisition and processing accuracy during the last decade of MASW research. In fact, it has been the topic of most intense focus

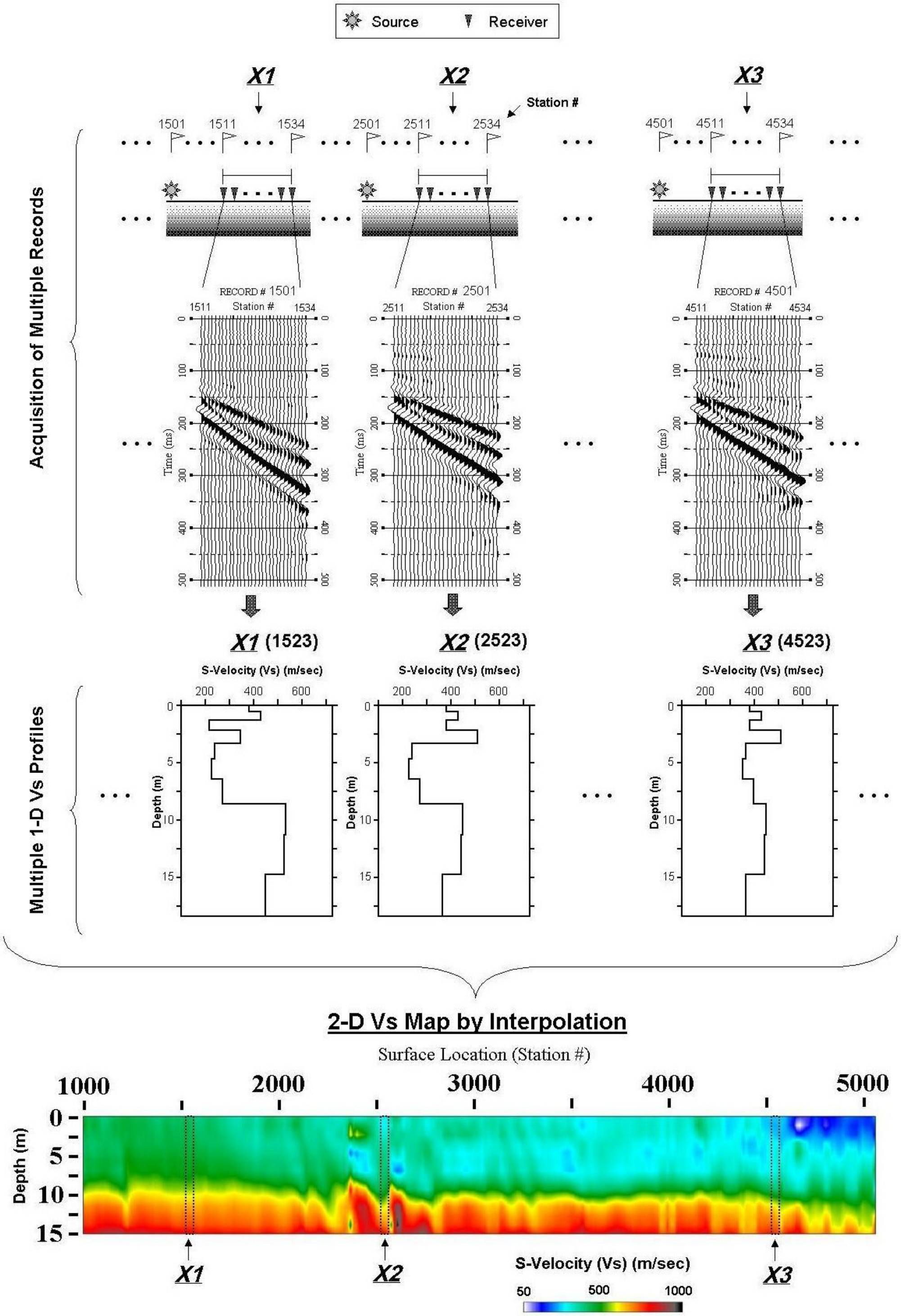


Figure 1. Overall procedure for the 2-D shear-wave velocity map with the MASW survey.

throughout the history of surface wave research for not only engineering applications but also earthquake studies. It has been known with the MASW method that the following field parameters can influence the effectiveness of the M0-curve extraction: dx, X_1, N, and X_T (Park et al., 1998; 2001; 2002). Also, different processing methods can result in different degrees of accuracy: frequency-wavenumber (*f-k*) (Foti et al., 2002), frequency-slowness (*f-p*) (McMechan and Yedlin, 1981), and frequency-phase velocity (*f-c*) (Park et al., 1998) methods. Considering all these acquisition- and processing-related parameters together, it is normally agreed that the receiver spread length (X_T) and the source offset (X_1) are the most influential (Park et al., 1999a; 2001; 2002). X_T needs to be as long as possible because the efficiency of modal separation during the dispersion analysis directly increases with X_T. The long X_T is also favorable to a deeper maximum depth of investigation (Z_{max}) that is proportional to X_T as well (Park et al., 1999a; Stokoe et al., 1994): $Z_{max} = \xi X_T$ $(0.5 \leq \xi \leq 3.0)$. X_1 is usually determined as a certain fraction of X_T: $X_1 = \kappa X_T$ $(0 < \kappa \leq 1)$ (Park et al., 1999a). However, the long X_T is obviously unfavorable to the horizontal resolution because of the spatial averaging effect previously mentioned. Therefore, actual selection of X_T should be made a trade-off from a simultaneous consideration of all three. Contents presented here deal with the topic of horizontal resolution of the MASW method. More specifically, effects of the receiver spread length (X_T), acquisition interval (dSR), and the processing accuracy on the lateral resolution of the 2-D Vs map are explained based on numerical modeling experiments. Illustrations with an actual field data set are difficult to show currently because the true subsurface Vs model cannot be accurately assessed.

The horizontal and vertical resolutions of MASW are usually influenced by different factors. For example, the vertical resolution is known to decrease with depth primarily because phase velocities of surface waves sampling deeper depths are determined by materials of a greater depth range, whereas a similar relationship between the horizontal resolution and wavelength is not so obvious. Also, such processing parameters influencing the vertical resolution as the thickness model and number of layers (Rix and Leipski, 1991) may not be relevant to the horizontal resolution. The issue of vertical resolution with the MASW method needs further investigation and is not an issue to be resolved in this paper. The term "resolution" from here on indicates horizontal resolution unless specifically stated otherwise.

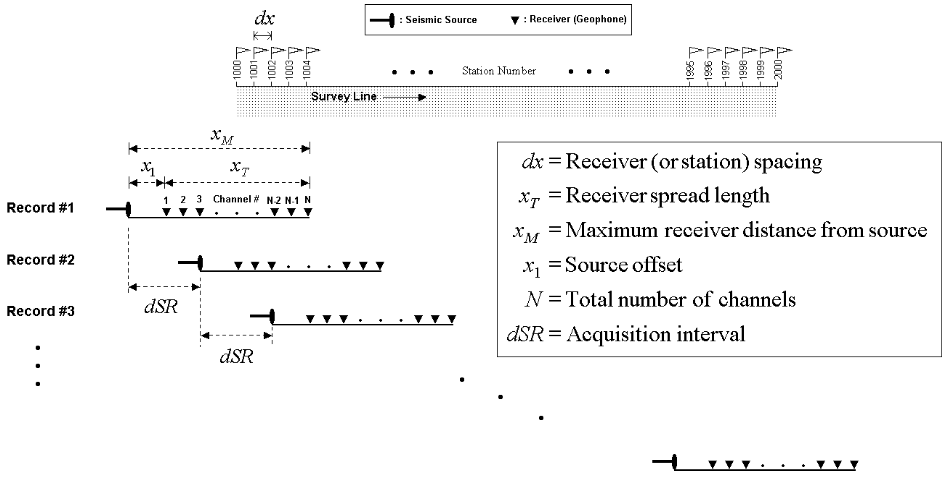


Figure 2. Illustration of the roll-along acquisition method used during the MASW survey.

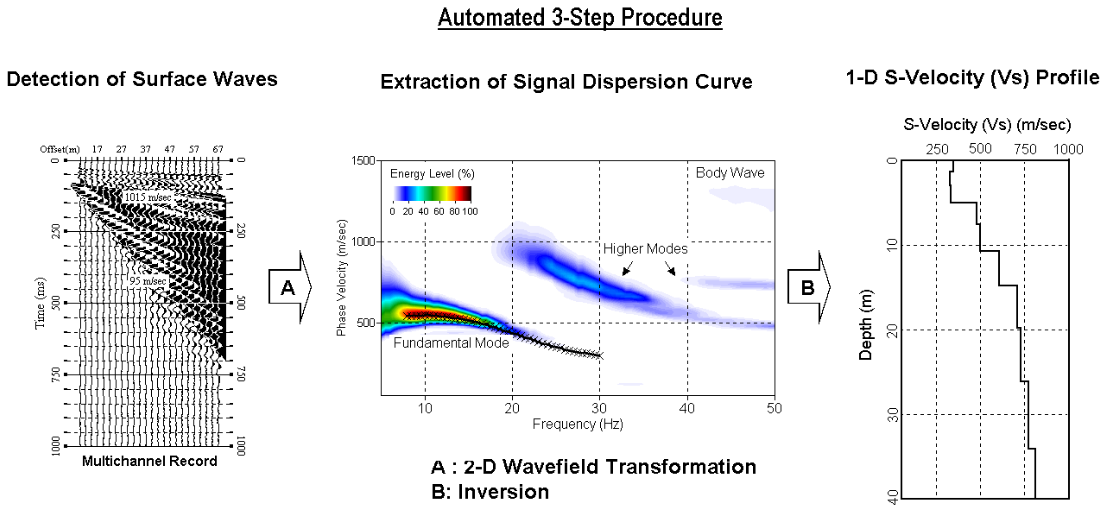


Figure 3. A normal data processing procedure with one field record of the MASW method. The record is first transformed into the dispersion image to extract the fundamental-mode dispersion curve (A). Then, the curve is used as a reference to find a 1-D Vs profile whose theoretical curve matches the extracted (experimental) curve most closely (B).

LENGTH OF RECEIVER SPREAD (X_T) AND ACQUISITION INTERVAL (*dSR*)

A subsurface velocity (Vs) model (Figure 5) is used to illustrate the effect of the receiver spread length (X_T) and the acquisition interval (*dSR*) on the horizontal resolution. All other influencing factors except these two are excluded. The model consists of an undulating interface separating materials of two constant velocities of 150 m/sec (upper) and 300 m/sec (lower) over a surface distance of one thousand stations (1000*dx*). The undulation simulates a sinusoidal curve of varying wavelengths of approximately 200*dx* at the starting station (1000) and 25*dx* at the ending station (2000). First, MASW survey results with X_T of 24*dx* are considered for different acquisition intervals (*dSR*'s) (Figure 5) deduced by the marked triangles at the bottom of each map. Any noticeable change in the resolution does not occur until the acquisition interval (*dSR*=25*dx*) exceeds the spread length used (X_T =24*dx*). For all those smaller intervals (*dSR* < 25*dx*), the entire portion of the interface is restored without any distortion. It appears that such a small acquisition interval (for example, *dSR*=1*dx*) may not improve the resolution but would cost a lot because of the excessive number of records to be collected (Figure 6). As the interval exceeds the spread length used, the distortion starts to occur at the portion of the interface where the undulation has the shortest wavelength (at the end of the line) and then it spreads into the portions of longer wavelengths. The undulation feature is completely lost by the time the interval (*dSR*=200*dx*) exceeds half the longest wavelength of the interface.

Figure 7 shows the same experiment as previously described except for a longer receiver spread length (X_T = 48*dx*). In comparison, the most prominent difference is the distortion already occurring at the most-rapidly-undulating portion of the interface even when the shortest acquisition interval (*dSR*=1*dx*) is used. It is noted that the distortion occurs for those wavelengths shorter than or comparable to the spread length used. Any noticeable increase in distortion does not occur until the interval (*dSR*=50*dx*) exceeds the spread length used (as previously observed with the case of X_T = 24*dx*). After that, the distortion seems to increase in proportion to the acquisition interval.

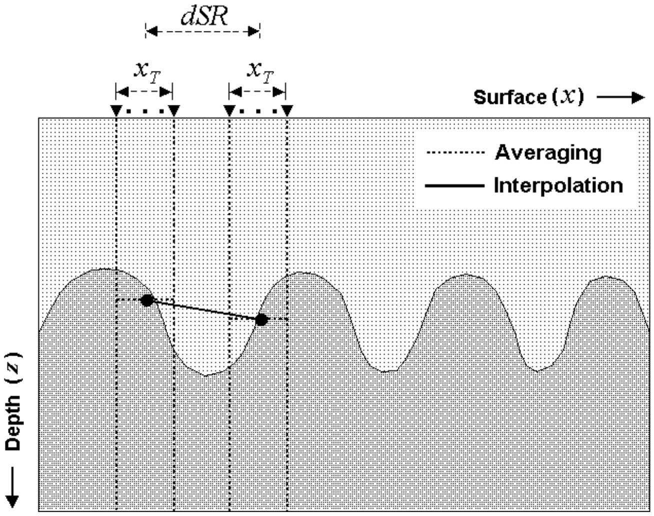


Figure 4. Schematic illustration of the lateral distortion resulting from the spatial averaging by the receiver spread and also from the spatial interpolation due to the finite acquisition interval.

From the above experiments it is obvious that the spread length (X_T) is the first governing factor influencing resolution since it sets the theoretical limit in the horizontal resolution. However, when the acquisition interval exceeds the spread length ($dSR > X_T$), then the governing factor becomes this interval. It appears that an acquisition interval (for example, $1dx$) unnecessarily small may not be beneficial because there is no improvement in resolution. However, the redundant measurements obtained in this case can increase the resolution through a statistical principle of the random-noise reduction as illustrated in the next section.

PROCESSING ACCURACY

Previous consideration of the two acquisition parameters made an implicit assumption that there is no error involved during the processing with perfect dispersion and inversion analyses. A certain degree of error in processing, however, is always unavoidable. For example, phase velocities of M0 curve can be estimated higher than actual values for those frequencies where higher modes occur with significant energy near the fundamental mode. In this case, it is also possible that they are estimated lower depending on their proximity, relative energy ratio, and number of channels used during acquisition of the corresponding record. On the other hand, the inversion process can make a similar type of inaccuracy in the estimated shear-wave velocities, depending on such processing parameters as number of layers, the thickness model, and the specific inversion scheme used (Rix and Leipski, 1991). The non-uniqueness property of inversion can also be an additional source of inaccuracy. At this moment, it seems that no systematic pattern exists in the inaccuracy of the MASW processing. Until the time when a specific pattern is discovered, it is reasonable to assume a random pattern.

Figures 8 and 9 show the experiments in which two different degrees of processing inaccuracy were modeled. In Figure 8, a maximum error of ±10 % was assumed for the calculated Vs values of each layer. In Figure 9, a maximum error of ±25 % was assumed. The actual amount of error comprised a Gaussian distribution within the specified bounds. Both cases were tested with a receiver spread length of $24dx$ for different acquisition intervals. It is now clear that an acquisition interval smaller than the receiver spread can be advantageous. The greater redundancy provided by the smaller acquisition interval can achieve the higher resolution through the statistical error-reduction process.

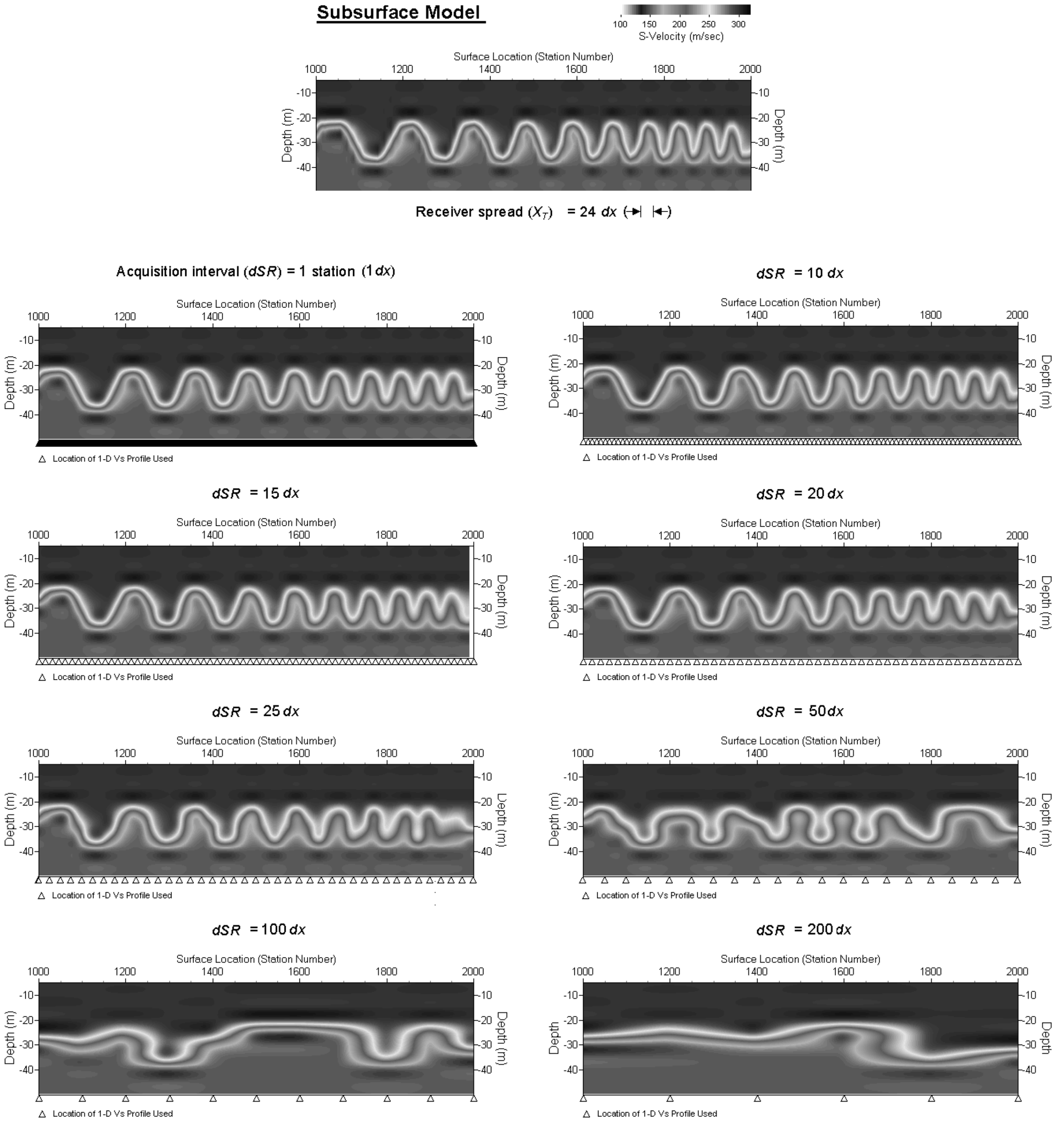


Figure 5. A modeling experiment illustrating variation of horizontal resolution that changes with acquisition interval (*dSR*) for the case of 24-channel receiver spread (X_T). The subsurface velocity model displayed on top consists of an undulating interface of varying wavelengths.

DISCUSSION

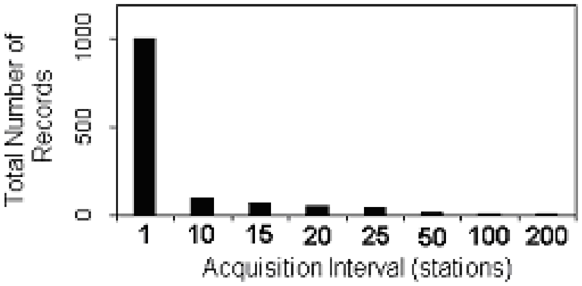


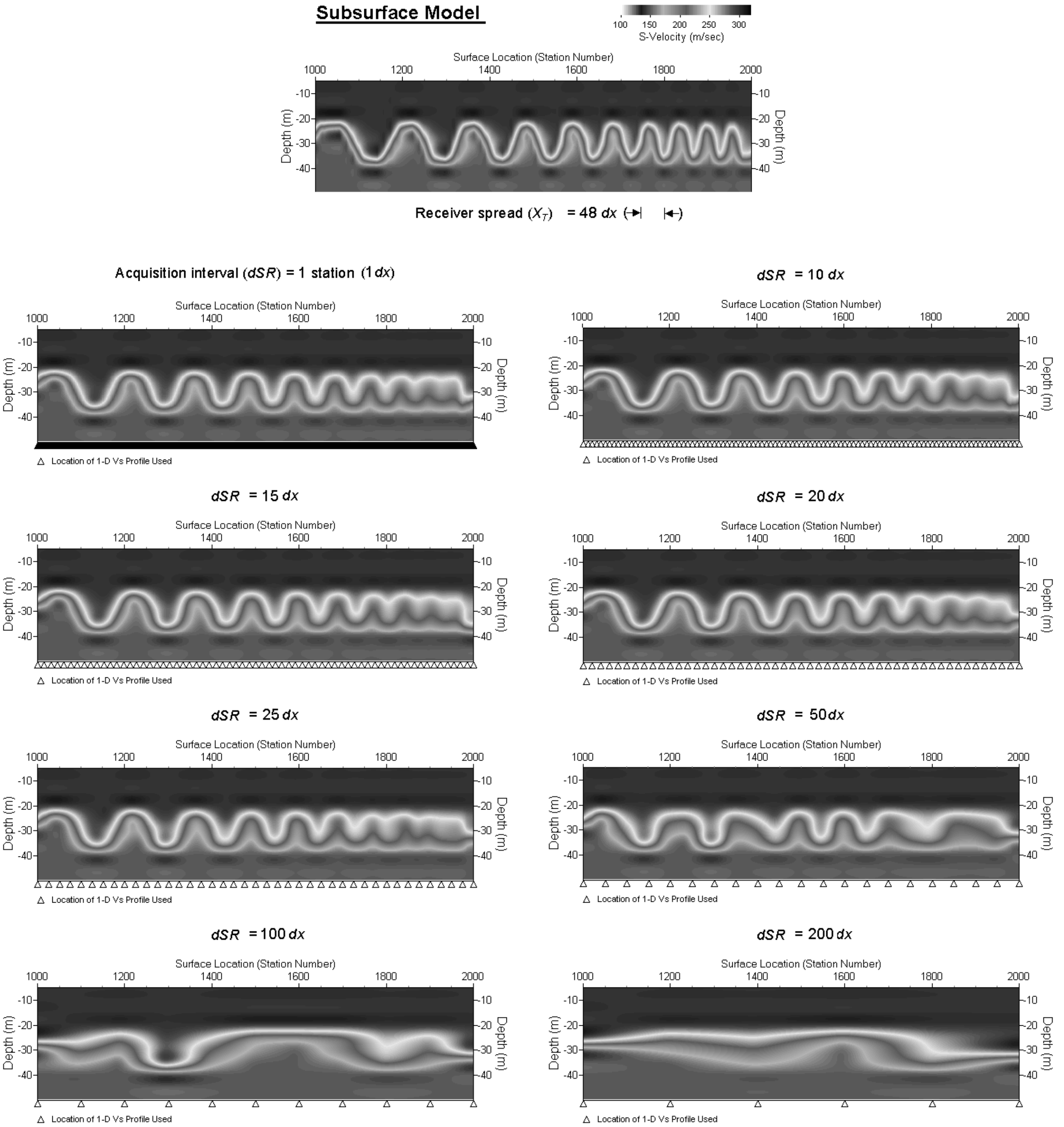
Figure 6. Number of total records needed to survey the entire surface distance (1000*dx*) of the velocity model shown on top of Figure 5. It changes with the acquisition interval.

X_T needs to be as long as possible for the effective modal separation and also for an increased Z_{max}, whereas it needs to be shortest possible to reduce (increase) the spatial averaging (resolution). It is also known that an excessively long X_T will make the higher-mode domination so severe that the modal separation will no longer matter (Park et al., 1999b). For most soil site investigations where Vs is smaller than 500 m/sec in the usual investigation depth range shallower than 30 meters ($Z_{max} \leq 30$ m), X_T of about 10 meters (a rule of thumb) may be a minimum threshold for the wavefield transformation method (Park et al., 1998) to effectively separate the fundamental mode from other higher modes although the details should change with many other parameters including the elastic properties of the subsurface. Then, this (10 m) sets a practical limit in the horizontal resolution with the MASW method. This means that anything in the 2-D Vs map that has a lateral dimension smaller than 10 m (or X_T) should be interpreted with caution, as it can very well be a computation effect. The concept of detection, however, should not be confused with that of the resolution. The horizontal detection limit should be smaller than the resolution limit.

Whenever it is anticipated that the M0-curve extraction can become a formidable task with complicated multi-modal interference, then a smaller acquisition interval has to be used to provide as much redundancy in data as possible.

CONCLUSIONS

The receiver spread length used during acquisition of multichannel records most influences the horizontal resolution of the 2-D Vs map of the MASW method. The lower limit of the resolution becomes approximately the same as the spread length. The spatial acquisition interval between two successive records can be a multiple-station distance, but it should not be greater than the receiver spread length. The smaller interval will be beneficial, especially where there exists a complicated multi-modal interference. For most normal soil site investigations, a 10-m spread length seems to be the minimum distance for the processing scheme to effectively extract the M0 curve, and this would be the practical resolution limit with the MASW method.



Subsurface Model

Receiver spread (X_T) = 48 *dx* (→| |←)

Acquisition interval (*dSR*) = 1 station (1 *dx*)

dSR = 10 *dx*

dSR = 15 *dx*

dSR = 20 *dx*

dSR = 25 *dx*

dSR = 50 *dx*

dSR = 100 *dx*

dSR = 200 *dx*

Figure 7. The same modeling experiment as shown in Figure 5 but using different (twice longer) receiver spread (X_T = 48*dx*).

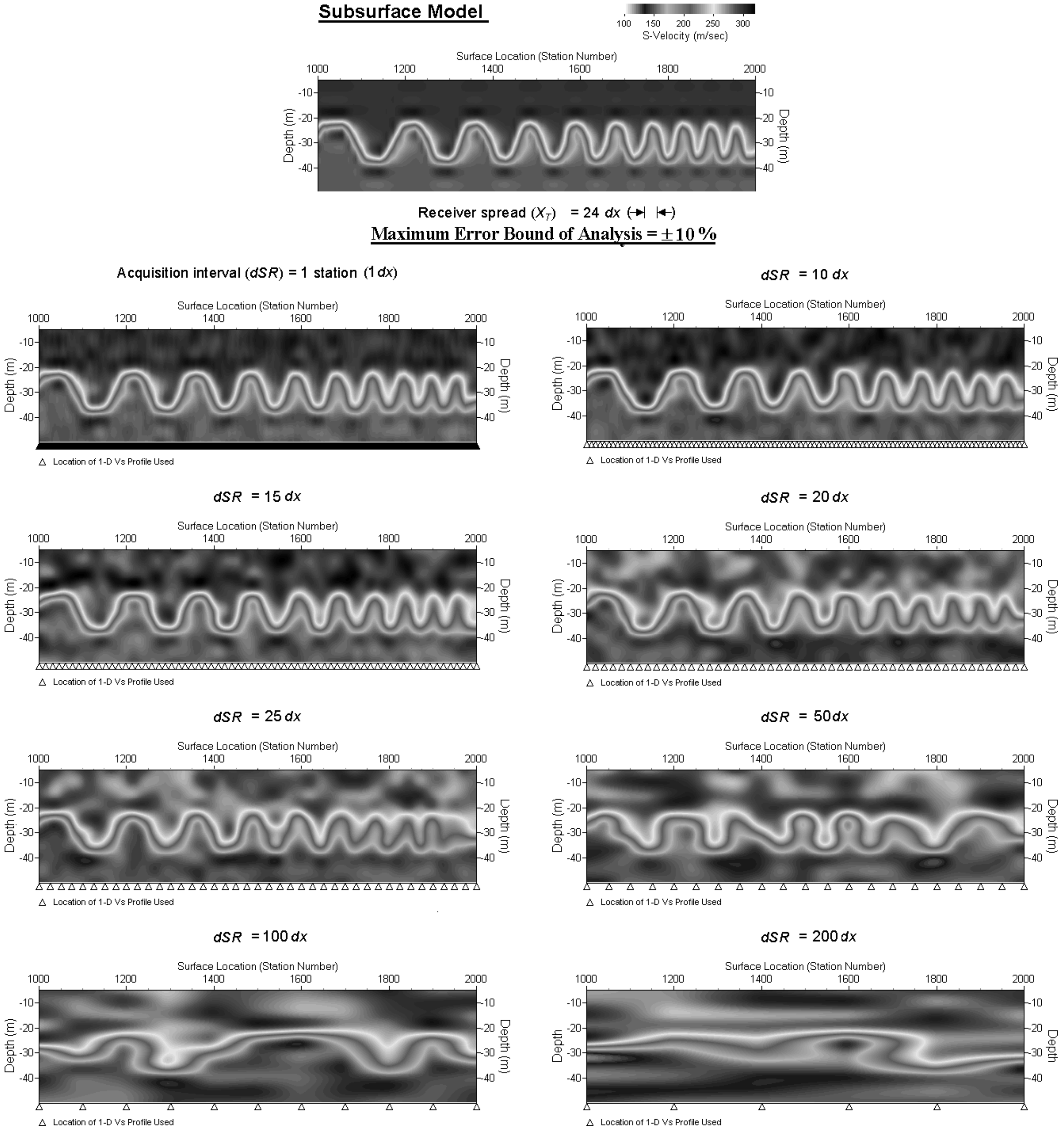


Figure 8. A modeling experiment illustrating the influence of the processing accuracy on the horizontal resolution. Max. ±10% error was introduced into the analysis results. 24-channel receiver spread (X_T) was assumed for all different cases of the acquisition interval.

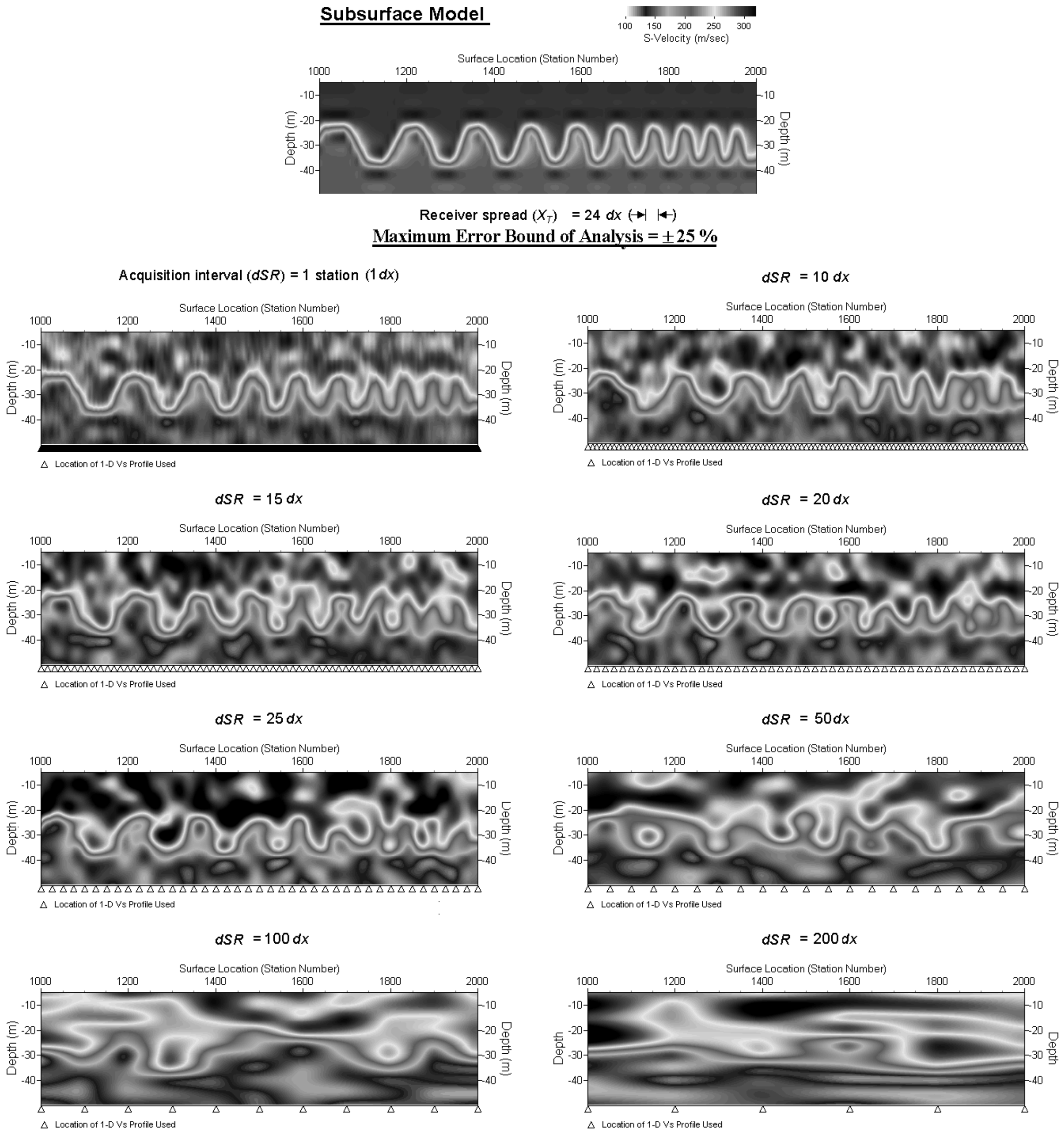


Figure 9. A modeling experiment illustrating the influence of the processing accuracy on the horizontal resolution. Max. ±25% error was introduced into the analysis results. 24-channel receiver spread (X_T) was assumed for all different cases of the acquisition interval.

REFERENCES

Foti, S., L. Sambuelli, L.V. Socco, and C. Strobbia, 2002, Spatial sampling issues in FK analysis of surface waves: Proceedings of the SAGEEP 2002, Las Vegas, Nevada, 12SEI8.

McMechan,G. A., andYedlin, M. J., 1981, Analysis of dispersive waves by wave field transformation: Geophysics, **46**, 869–874.

Park, C.B., Miller, R.D., and Miura, H., 2002, Optimum field parameters of an MASW survey [Exp. Abs.]: SEG-J, Tokyo, May 22-23, 2002.

Park, C.B., Miller, R.D., and Xia, J., 2001, Offset and resolution of dispersion curve in multichannel analysis of surface waves (MSW): Proceedings of the SAGEEP 2001, Denver, Colorado, SSM-4.

Park, C.B., Miller, R.D., and Xia, J., 1999a, Multi-channel analysis of surface waves (MASW): *Geophysics*, v. 64, no. 3, p. 800-808.

Park, C.B., Miller, R.D., Xia, J., Hunter, J.A., and Harris, J.B., 1999b, Higher mode observation by the MASW method [Exp. Abs.]: Soc. Explor. Geophys., p. 524-527.

Park, C.B., Miller, R.D., and Xia, J., 1998, Imaging dispersion curves of surface waves on multi-channel record: [*Expanded Abstract*]: Soc. Explor. Geophys., 1377-1380.

Rix, G. J., and Leipski, E. A., 1991, Accuracy and resolution of surface wave inversion, *in* Bhatia, S. K., and Blaney, G. W., Eds., Recent advances in instrumentation, data acquisition and testing in soil dynamics: Am. Soc. Civil Eng., 17–32.

Stokoe, K. H., II, Wright, G. W., James, A. B., and Jose, M. R., 1994, Characterization of geotechnical sites by SASW method, *in*Woods, R. D., Ed., Geophysical characterization of sites: Oxford Publ.