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The Impact of Surface-wave Separation on Seismic Survey Design

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SUMMARY

3-D seismic survey design provides an acquisition geometry for obtaining seismic data that enable imaging and amplitude-versus-offset applications of target reflectors with sufficient quality under given economical and operational constraints. However, in land or shallow water environments, surface waves are often dominant and will lower the quality of the final output. The necessity to remove them from the seismic data imposes additional constraints on the acquisition parameters.
Here, we try to understand how the application of surface-wave separation affects the choice of survey parameters and the resulting data quality. Quality is quantified by the signal-to-noise ratio of the seismic data after surface-wave separation or removal. In a case study, we applied surface-wave separation and signal-to-noise ratio estimation to several data sets with different survey parameters. We found that the spatial sampling intervals of the basic subset are the most important ones among the various types of survey parameters. The resulting data quality as a function of the spatial sampling intervals follows a trend curve. Finer spatial sampling intervals lead to better data quality up to a point where the curve flattens and a plateau is reached. The actual shape of the trend curve depends on the method of surface-wave separation.

Introduction

For 3-D seismic surveys, we should choose the survey parameters such that the acquired data are of sufficient quality to achieve the desired objectives in exploration, appraisal and development of oil and gas fields. To obtain high data quality while mitigating survey effort, several authors presented sophisticated approaches to survey design and evaluation. Traditionally, survey design is based on attributes such as fold, offset, azimuth sampling in each bin, as well as their distribution across bins (e.g. Vermeer, 2012). Recent survey-design methods involve the reconstruction of the angle-dependent reflectivity in one or more subsurface points in the target area (e.g. Berkhout et al., 2001). In this way, survey design examines the capability of an acquisition geometry to properly image target reflectors and to allow for amplitude-versus-offset (AVO) analysis of the reflections.

Surface waves in land or shallow-water environments often mask the primary reflections. Therefore, they impose additional requirements on the acquisition geometry, since those should allow for effective surface-wave separation or removal. Many methods for surface-wave separation have been developed. Among those are conventional filtering methods (e.g. Yilmaz, 2001) and data-driven, data-adaptive and model-based methods using a closed-loop approach (e.g. Ishiyama et al., 2014). These and other approaches separate out the surface waves from the seismic data, although some residual may still be present in the result. To analyse the data quality of the result, the signal-to-noise ratio (SNR) can be used as an attribute or quality measure quantifying the effectiveness of surface-wave separation. The residual affects the effectiveness of subsequent stages during processing and reservoir characterization and may impair the resulting data quality. Therefore, survey design should also involve the effectiveness of surface-wave separation for a given acquisition geometry.

For 3-D seismic surveys, the basic survey parameters are the four spatial sampling intervals and apertures of the template geometry (Vermeer, 2012). The four spatial sampling intervals are defined by the receiver and source intervals, each in two sampling directions that are usually orthogonal. The four spatial sampling apertures consist in the receiver and source apertures, oriented in the same way as the above four spatial coordinates. With these survey parameters, we will address the following question in terms of surface-wave separation.

(i) What is the relationship between the survey parameters and the resulting data quality?
(ii) Which types of survey parameters are essential?
(iii) What are optimal values of the essential types of survey parameters for the required data quality?

To answer these questions, we applied surface-wave separation and SNR estimation to several data sets with different survey parameters, and analysed the relationship between the survey parameters and the resulting data quality.

Method

As already mentioned, for 3-D seismic surveys, the relevant survey parameters are the spatial sampling intervals for receivers, Δx_d and Δy_d, and for sources, Δx_s and Δy_s, as well as their respective apertures, X_d and Y_d for the receivers and X_s and Y_s for the sources in the template geometry. Proper spatial sampling can be thought of as the ability to properly reconstruct seismic wavefields. For an orthogonal geometry, the basic subset is a cross-spread gather, where receiver-point and source-point intervals are quite fine (Δx_d and Δy_s for example), whereas receiver-line and source-line intervals are often coarse (Δy_d and Δx_s in this example). Receiver-line and source-line lengths specify the maximum apertures (X_d and Y_s for this basic subset). For an areal geometry, the basic subset is a common-source gather or a common-receiver gather, where receivers are arranged on a densely spaced grid (Δx_d and Δy_d fine) while sources are on a sparsely spaced grid (Δx_s and Δy_s coarse), or vice versa. Receiver-spread widths (X_d and Y_d) specify the maximum apertures in the former case; source-spread widths (X_s and Y_s) in the latter. Two of the four spatial coordinates, the set $\{\Delta x_b, \Delta y_b, X_b, Y_b\}$, specify the spatial sampling of the basic subset. Two other coordinates, the set $\{\Delta x_B, \Delta y_B\}$, specify the spatial redundancy of the basic subsets, i.e., the fold. Their maximum apertures, X_B and Y_B, are usually the same as X_b and Y_b to form the template. For instance, the set $\{\Delta x_d, \Delta y_s, X_d, Y_s\}$ specifies the spatial sampling of a cross-spread gather, i.e., $\{\Delta x_b, \Delta y_b, X_b, Y_b\} = \{\Delta x_d, \Delta y_s, X_d, Y_s\}$, whereas the set $\{\Delta x_s, \Delta y_d\}$ specifies the spatial redundancy of the cross-spread gather, i.e., $\{\Delta x_B, \Delta y_B\} = \{\Delta x_s, \Delta y_d\}$. Here, the x-direction is taken as the in-line direction.

Surface-wave separation is often applied to basic subsets such as 3-D common-shot, 3-D common-receiver and 3-D cross-spread gathers. Therefore, the key set of survey parameters in terms of the surface-wave separation is $\{\Delta x_b, \Delta y_b, X_b, Y_b\}$, specifying the spatial sampling of the basic subset. Consequently, we can define the survey effort, C, as a combined attribute of these survey parameters relative to a reference basic subset as

$$C = \frac{\Delta x_{b\mathrm{ref}}}{\Delta x_b} \frac{\Delta y_{b\mathrm{ref}}}{\Delta y_b} \frac{X_b}{X_{b\mathrm{ref}}} \frac{Y_b}{Y_{b\mathrm{ref}}}, \tag{1}$$

where the subscript ‘ref’ denotes ‘reference’. We also define two attributes in terms of symmetry as

$$A_{\Delta x_b} = \frac{\Delta x_b}{\Delta y_b}, \qquad A_{X_b} = \frac{Y_b}{X_b}, \tag{2}$$

where $A_{\Delta x_b}$ is the aspect ratio of the spatial sampling intervals, and A_{X_b} is the aspect ratio of the spatial sampling apertures.

To estimate surface waves $\hat{\vec{N}}$ and separate them out from seismic data $(\vec{P}+\vec{N})$ to obtain subsurface signals $\hat{\vec{P}}$ with a minimal residual $\Delta\vec{N}$, i.e., $\hat{\vec{P}} = (\vec{P}+\vec{N}) - \hat{\vec{N}} = \vec{P} + \Delta\vec{N}$, many approaches have been developed in processing. Here, the hat symbol $\hat{}$ indicates ‘estimated’. Note that, in this paper, the ‘subsurface signals’ refer to all events except the surface waves, i.e., $\vec{P}$ includes refractions, reflections, surface-related and internal multiples, etc. Here, two of those approaches are considered to obtain seismic data sets after surface-wave separation. The first one (Figure 1b) is the method of 3-D surface-wave estimation and separation using the closed-loop approach (Ishiyama et al., 2014), which we recently developed. The second one (Figure 1c) is a conventional slowness/velocity-based filtering method, in which $(\vec{P}+\vec{N})$ are transformed to a suitable domain, e.g., the $p_x p_y$-f or the $k_x k_y$-f domain, where $\hat{\vec{N}}$ and $\hat{\vec{P}}$ are separated in terms of their apparent slowness/velocity.

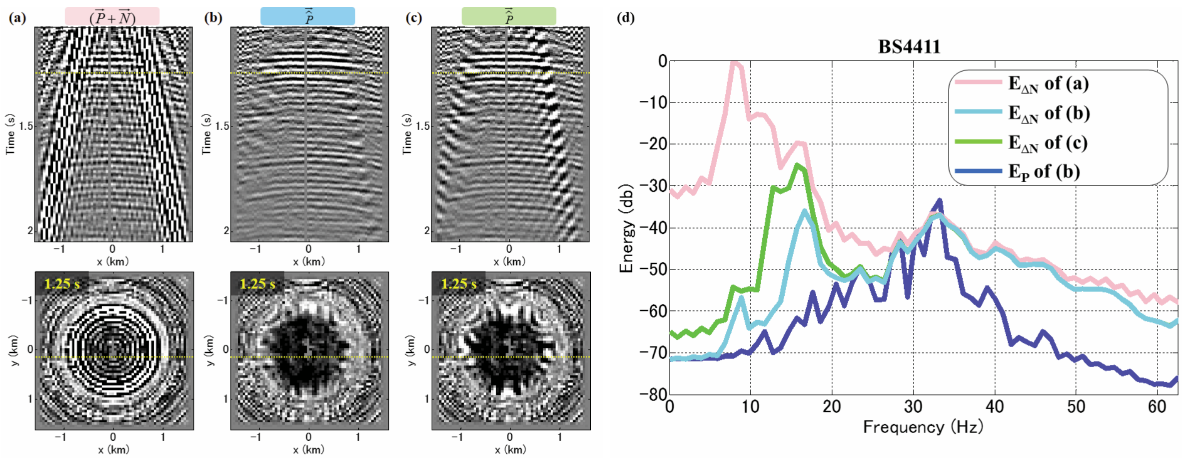

Figure 1 *The energy spectra for a basic subset (BS4411). (a) The raw data set; (b) and (c) the subsurface-signal data sets after the surface-wave separation using our method and the conventional one, with a vertical section at the top and a horizontal time slice at the bottom. A dotted line in the section indicates the position of the slice, and vice versa. (d) The energy spectra. Magenta, cyan and green indicate the surface-wave energy $\mathbf{E}_{\Delta N}$ of the data sets (a), (b) and (c). Blue indicates the subsurface-signal energy $\mathbf{E}_P$ of the data set (b). The SNR is estimated by dividing a representative value of the subsurface-signal energy, such as a spatially summed and averaged value, by that of the surface-wave energy. In this example, the spectra are averaged over a frequency window from 2 Hz to 50 Hz, and the resulting SNR is 0.02 (−32 dB) for $(\vec{P}+\vec{N})$, 0.77 (−2 dB) for $\hat{\vec{P}}$ after the surface-wave separation using our method, and 0.32 (−10 dB) using the conventional one.*

To evaluate the data quality resulting from the surface-wave separation, SNR is used as an attribute. Cross-correlation of successive traces in a seismic data set is used to quantitatively assess the similarity of traces as desired signal (Thomas et al., 1998), i.e., an estimate of the subsurface-signal energy $\mathbf{E}_P$. Autocorrelation of each trace provides an estimate of the total energy $\mathbf{E}_{(P+\Delta N)}$. Therefore, subtracting $\mathbf{E}_P$ from $\mathbf{E}_{(P+\Delta N)}$ provides an estimate of the remaining surface-wave energy $\mathbf{E}_{\Delta N}$. See e.g. Figure 1d.

Case study

We applied the surface-wave separation and the SNR estimation to several data sets (Table 1), obtained by decimating a 3-D OBC hydrophone data originally acquired offshore Abu Dhabi in a shallow-water environment. For the survey effort, we took a reference basic subset with $\{\Delta x_{b\mathrm{ref}}, \Delta y_{b\mathrm{ref}}, X_{b\mathrm{ref}}, Y_{b\mathrm{ref}}\} = \{25\,\mathrm{m}, 25\,\mathrm{m}, 3200\,\mathrm{m}, 3200\,\mathrm{m}\}$. This one is denoted by BS2211.

Geometry	Δx_b (m)	Δy_b (m)	X_b (m)	Y_b (m)	$A_{\Delta x_b}$	A_{X_b}	C	Geometry	Δx_b (m)	Δy_b (m)	X_b (m)	Y_b (m)	$A_{\Delta x_b}$	A_{X_b}	C
BS8811	100	100	3200	3200	1.00	1.00	0.06	BS4421	50	50	6400	3200	1.00	0.50	0.50
BS4411	50	50	3200	3200	1.00	1.00	0.25	BS2211	25	25	3200	3200	1.00	1.00	1.00
BS2811	25	100	3200	3200	0.25	1.00	0.25	BS4422	50	50	6400	6400	1.00	1.00	1.00
BS2411	25	50	3200	3200	0.50	1.00	0.50								

Table 1 *List of the basic subsets.*

Figure 2 shows the SNR as a function of the survey effort C. For the colours of dots, the magenta samples mark the values for the raw data sets $(\vec{P}+\vec{N})$. The subsurface-signal data sets, $\vec{\hat{P}}$, after the surface-wave separation using our method are coloured cyan, whereas using the conventional one are coloured green. The shapes of dots represent the geometries of the basic subsets, see the figure legend. For the magenta samples, SNR is consistently very low due to the dominance of the surface-wave energy. In general, the cyan samples fall in the upper left, and the green samples in the lower right, showing that our method provides a better SNR than the conventional one.

According to the definition of the survey effort, there are two ways to increase the survey effort, one by decreasing the spatial sampling intervals and one by increasing the spatial sampling apertures. Samples surrounded by an outer circle in Figure 2 correspond to cases in which the survey effort is increased by using finer spatial sampling intervals. For these samples, SNR increases with C, in general. For instance, for BS4411, the surface-wave energy is well attenuated and the SNR is consequently improved by the surface-wave separation. Our method provides a better SNR than the conventional one. However, for BS2211, the SNR is improved to the same level with both methods. This is because BS2211 has

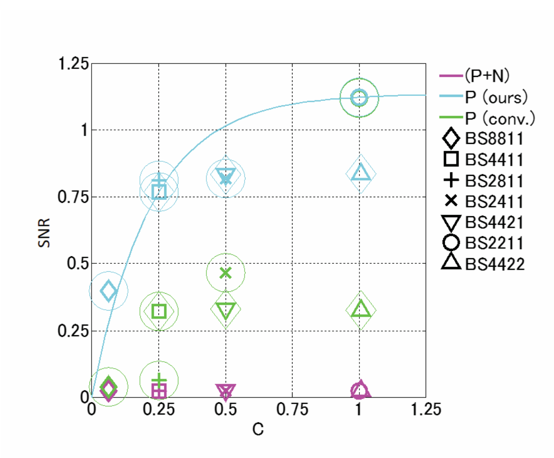

Figure 2 *SNR as a function of survey effort C for the data sets in Table 1. Magenta, cyan and green symbols correspond to the raw data sets, the subsurface-signal data sets after the surface-wave separation using our method and using the conventional one, respectively. Samples surrounded by an outer circle indicate those for which the survey effort is increased by decreasing the spatial sampling intervals. Those marked by an outer diamond have their effort increased by a larger spatial sampling apertures. The cyan line represents a curve obtained by fitting these cyan samples to the equation* $SNR = \alpha(1-e^{-\beta(A_{\Delta x_b})C})$, *where* α *is a constant and* β *generally depends on* $A_{\Delta x_b}$. *In this example,* $\alpha = 1.14$ *and* $\beta = 4.52$, *assuming that* β *is a constant.*

spatial sampling intervals that are sufficiently fine to avoid aliased surface-wave energy. This aliased energy is a main cause of residual surface-wave energy after the surface-wave separation. Therefore, for data sets that do not contain aliased energy, the resulting SNR does not depend so much on the choice of method. In this case, a further decrease of the spatial sampling intervals may generally not lead to a further improvement of SNR. In summary, the spatial sampling intervals are the essential types of survey parameters. Decreasing the spatial sampling intervals increases the resulting data quality up to a plateau that is reached when surface-wave energy is no longer aliased and can be easily removed. This is the main trend in the relationship between the spatial sampling intervals and the resulting data quality. The shape of the trend curve depends on the method of surface-wave separation.

As far as symmetry of the spatial sampling intervals is concerned, BS4411 with $A_{\Delta x_b} = 1$, for instance, is symmetric, while BS2811 with $A_{\Delta x_b} = 0.25$ is not. For the cyan samples (with our method) in Figure 2, the SNR of BS2811 is slightly better than that of BS4411 at the same C. For BS2811, as compared to BS4411, the surface-wave energy is attenuated better in the x-direction and fairly well in the y-direction. This is because BS2811 has a finer spatial sampling interval in the x-direction. Therefore, the degree of asymmetry in the spatial sampling intervals affects the spatial distribution of the pre-stack SNR. This is not the case, however, for the green samples (with the conventional method) of BS4411 and BS2811 in Figure 2. The SNR of BS4411 is better than that of BS2811 at the same C. This is because for BS2811 the surface-wave energy is attenuated very poorly in the y-direction, although well enough in the x-direction. In summary, the degree of asymmetry in the spatial sampling intervals may affect the resulting data quality, positively and negatively deviated from the above main trend according to the situation.

Samples surrounded by an outer diamond in Figure 2 correspond to cases with increasing the survey effort by extending the spatial sampling apertures. For these samples, SNR hardly changes with C. In these cases, the attenuation of the surface-wave energy is similar and the SNR is improved to the same level by the surface-wave separation. This tendency is observed both for our method and the conventional one. In summary, extending the spatial sampling apertures does not contribute to a better data quality in terms of the surface-wave separation. Therefore, the symmetry of the spatial sampling apertures does not matter either.

Conclusions

The capability of acquisition geometry for surface-wave separation can be summarized as follows.

- The spatial sampling intervals of the basic subset are the essential types of survey parameters. Finer spatial sampling intervals improve the resulting data quality, i.e., the SNR, until it levels off on a plateau. The shape of the trend curve depends on the method of surface-wave separation.
- A degree of asymmetry in the spatial sampling intervals affects the spatial distribution of the pre-stack data quality in the basic subset. The pre-stack data quality improves relatively more in the direction of finer sampling.
- Extending the spatial sampling apertures does not lead to an improvement in the resulting data quality. The symmetry of the spatial sampling apertures does not matter either.

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