Analyzing and Filtering Surface-Wave Energy By Muting Shot Gathers

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ABSTRACT

Accurate estimation of the fundamental-mode dispersion curve is the most critical processing step of many shallow surface-wave methods. Use of multichannel analysis of surface waves (MASW), has proven very effective in separating different dispersive events that share the same seismic-frequency range. Yet, under certain circumstances, even when using such a data-redundant method, it may not be possible to separate the fundamental mode of the surface waves from higher modes. Dominant higher surface-wave modes, together with body- and guided waves, can impede the estimation of the fundamental mode. This is especially true when relatively short spread lengths are required for the survey for reasons such as higher lateral-resolution demands or presence of noise at the far offsets.

A simple multichannel processing technique that mutes the interfering seismic waves in the shot records (offset-time \((x-t)\) domain) can be used to analyze and filter noisy surface-wave modes and thus significantly improve the range and resolution of multimodal dispersion curves in the phase-velocity–frequency domain. This is demonstrated on both synthetic and real shot gathers. One shortcoming of the muting method is the estimation of artificially high phase-velocity values at low frequencies. This artifact can be countered by employing dispersion-curve estimation in the same low-frequency range using the unmuted shot records. The proposed muting technique can be beneficial not only for the evaluation of the fundamental mode of the Rayleigh wave, but also for other types of dispersive seismic energy, such as higher Rayleigh-wave modes, Lamb, guided, and Love waves.

Introduction

Most surface-wave methods applied for the characterization of the near surface (<150 ft) involve the evaluation and inversion of the fundamental mode of the Rayleigh wave, such as the multichannel analysis of surface waves (MASW) method (Park et al., 1999; Xia et al., 1999). The process is quite straightforward. First, the fundamental-mode dispersion curve is extracted from a shot record. Then the extracted dispersion curve is inverted to estimate 1-D shear-velocity \((V_s)\) beneath the spread. By using an additional higher-mode dispersion curve (evaluated from the same shot record) in the inversion process, the obtained 1-D \(V_s\) solution can be of greater resolution and more stable (Xia et al., 2003). The multichannel approach to dispersion-curve analysis can not only significantly improve the signal-to-noise ratio \((S/N)\) but it can also improve pattern recognition (Park et al., 1998) for the identification of different types of seismic waves from their arrival and attenuation pattern.

Often it may still not be possible to separate the fundamental mode of the surface-wave from other higher modes due to interference of other type of waves (such as the direct wave, refracted waves, guided waves, air wave) or inadequate acquisition parameters (because of the near- and far-field surface-wave effects [Park et al., 2001] or because of unacceptable lateral variation of the subsurface).

In this paper we demonstrate a method for removing components of the seismic wave-field, mainly higher modes of surface-wave energy (for the purposes of MASW) that appear as noise in the phase-velocity–frequency domain, in which dispersion curves are estimated. After proper muting, the quality and observation range of the desired mode (i.e., fundamental mode) improve significantly.

Method

The essence of this multichannel method for suppressing higher modes is recognizing different apparent-velocity trends of the surface wave on the shot gather and separating them by muting. The basis for the application of the method is eliminating certain arrival-time ranges in the offset-time domain, within which certain wave-field components arrive as a result of their overall propagation velocity. For example, higher mode components are expected to arrive earlier on the shot record because of their greater velocity than the fundamental mode. After the muting, the corresponding phase-velocity–frequency domain will lack the noisy event
different surface-wave velocity trends, which can be
estimated by visually separating the two dispersive
events of the surface-wave, the fundamental mode and a higher mode (Fig. 2a). The fundamental mode can be observed within a narrow frequency range between 9 and 24 Hz (and velocities between 400–600 m/s) while the higher mode dominates a wide frequency range between 25 and 63 Hz (and velocities between 350–800 m/s), and can be observed up to 82 Hz. Efforts to observe the fundamental mode between 25 and 63 Hz by boosting the amplitude of the phase-velocity–frequency spectrum did not bring any success. Thus, the higher-mode energy is significantly higher, and it inhibits the estimation of the fundamental-mode dispersion-curve trend above 24 Hz.

Careful studies of the shot record by boosting the amplitudes (Fig. 1b) reveal two apparent phase-velocity slopes of the surface-wave energy. The two trends can be separated by an imaginary line (along which the two surface-wave patterns notably change) starting at 25 ms on trace one and ending at 400 ms on the last trace. The slope of the separation line is qualitatively determined by visually estimating for best trend separation. The apparent phase-velocity slope above this imaginary line is about 700 m/s, while below it is about 400 m/s. These apparent trends match roughly the dominant phase-velocity observations of the fundamental and higher modes in the phase-velocity–frequency domain (Fig. 2a). Thus, the higher-mode energy, being significantly higher in amplitude than the fundamental-mode energy of the surface wave, can be recognized both in the offset-time (x-t, shot gather) domain (Fig. 1b) and in the phase-velocity–frequency domain (Fig. 2a). By further extrapolating the fundamental-mode trend in the range above 25 Hz, it is reasonable to expect that its corresponding velocity trend would be below 350 m/s. In the same frequency range, the higher-mode velocities range from 800 m/s down to 400 m/s. Such a qualitative observation can be used as a guide for the possibility of applying the muting method. The two surface-wave modes propagate with distinctly different velocities in the frequency range 25–65 Hz.

Muting can be applied along the imaginary line that separates the two different velocity trends (Fig. 1c). Such a muting can practically eliminate the higher-mode energy of the surface wave in the range 25–70 Hz in the phase-velocity–frequency domain and boost the weak fundamental-mode energy within the same frequency range (Fig. 2b). The muting also has completely eliminated the fundamental mode of the surface wave in the range of 9–20 Hz (Fig. 2b). This, however, was expected because the low-frequency components of the fundamental mode have velocities that are in the velocity range of the muted higher mode. This is not a problem because there is an overlapping zone between the 22–26 Hz where the fundamental mode energy is the same before and after muting. This frequency band can be used to tie the two stages of dispersion curve-evaluation. The first stage is the estimation of the phase velocities of the fundamental mode of the surface wave in the low-frequency range without any muting. Higher-mode energy does not develop in this low-frequency zone. The second stage is the muting of the shot gathers from energy dominated by the higher modes and estimating the phase velocities of the fundamental mode of the surface-wave in this frequency range (Fig. 2b), which is no longer dominated by higher modes as in the raw shot gathers. The final step is to combine the two curves into a single dispersion curve using the overlapping zone for confirmation of the evaluation and ignoring the steep velocity-gradient portion (at lower frequencies) of the second curve. The acquired fundamental-mode dispersion curve now spans over a wide frequency range (9–58 Hz).

Muting Analysis of Modeled Surface-wave Data

The purpose of this modeling analysis is to demonstrate that muting is capable of separating the different modes of the surface wave from multimode shot gathers without causing any unacceptable side effects by comparing
Figure 1. Seismic data collected in the Sonoma Desert, Yuma, AZ, USA: a) shot gather number 1095, b) shot gather 1095 with increased gain to observe better the surface-wave energy trends, and c) shot gather 1095 muted along a line that separates different apparent-velocity trends of the surface wave.
Figure 2. Phase-velocity–frequency domain images of: a) shot gather number 1095, b) muted shot gather 1095.
the results with those of single-mode surface-wave shot gathers (for which modeling algorithms such as that of Park et al. [2005] can be used). Using an arbitrary simple earth model (Table 1), three synthetic shot gathers were generated. The first (Fig. 3a) had only the fundamental mode of the surface wave (Fig. 3d), the second (Fig. 3b) had only the 1st higher mode (Fig. 3e), and the third shot gather (Fig. 3c) had both the fundamental and the 1st higher modes (Fig. 3f). The fundamental and the 1st higher modes are well separated above 20 Hz in the phase-velocity–frequency domain (Fig. 3f) and interfere below 20 Hz.

The first step after observing that there is more than one dispersive mode of the surface-wave in the phase-velocity–frequency domain (Fig. 3f) is to determine if there are zones on the shot gather (Fig. 3c) with distinctly different apparent surface-wave phase-velocity trends. A separation line can be determined after careful examinations of the shot gather containing both surface-wave modes. The muting line was chosen to start at the beginning of trace one (about 0 m/s) and end at about 250 m/s of the last trace. Based on the shot-gather trend observations, it is expected that zeroing the data samples above this line (Fig. 4a) would eliminate most of the higher-mode energy in phase-velocity–frequency domain (Fig. 4c) and leave only fundamental-mode surface-wave energy. To check the success of this operation, the fundamental-mode image in the phase-velocity–frequency domain (Fig. 4c) obtained after muting is compared to the image of the modeled shot gather that had fundamental-mode energy only (Fig. 3d). The dispersion-curve images of both shot gathers are practically identical above 17 Hz. In a similar fashion, it is expected that zeroing the data samples below the trend-separation line of the fundamental mode (Fig. 4b) would eliminate most of the fundamental-mode energy in the phase-velocity–frequency domain (Fig. 4d) and leave only higher-mode surface-wave energy. Again, the effectiveness of the shot-gather muting can be verified by comparing the obtained higher-mode image (Fig. 4d) in the phase-velocity–frequency domain with the image of the modeled shot gather that had 1st higher-mode energy only (Fig. 3e). The dispersion-curve images are identical above 18 Hz, consistent with the previous case of looking at the fundamental modes.

This model-muting experiment demonstrates that muting in the shot-gather domain can be used safely to separate fundamental mode from higher modes and vice-versa. However, there are few considerations. We could not pick fundamental-mode energy in the 9–16 Hz range, because this part of the fundamental mode travels with a velocity in the range of 1,000 m/s (Fig. 3d) and appears on the shot record at the same place in terms of traces and time (Fig. 3a) as the higher mode (Fig. 3b). As a result, we muted not only the higher mode but part of the fundamental mode as well. This lack of separation between the fundamental and higher mode velocities is uncommon but does happen. This case was selected for our theoretical example to show that it is possible to mute parts of the fundamental mode as we mute the higher mode.

The fundamental mode has a very steep velocity gradient between 15–18 Hz, which can be discovered after muting. Based on the model experiments, this is concluded to be an artifact of the muting. Therefore, such steep-gradient velocity trend needs to be discarded when analyzing and combining dispersion curve from the two-stage analysis. For that reason, when combining the two Yuma data dispersion curves before and after muting, the up-going steep-gradient trend between 18–25 Hz of the muted-shot dispersion curve (Fig. 2b) was ignored. The steep velocity-gradient artifact can be considered harmless because of the presence of the overlapping zone, which assures the confident merger of the two curves. The example-driven approach of the muting analysis can not exclude the possibility of other types of side effects. Nevertheless, the extensive empirical research (not presented here) in the form of testing the muting technique on numerous data sets with various surface-wave propagation patterns has not revealed or indicated the existence of other possible artifacts.

For studying the effect of the relative accuracy of the muting-line slope, additional records were generated using underestimated and overestimated slopes (Fig. 4a), assuming that the initially applied muting slope is the “correct” one. The fundamental-mode energy of these varying-slope muted shot gathers (Figs. 5a–b) is practically identical to the “correctly” muted shot gather (Fig. 4c). Still, there is some higher-mode energy left at high frequencies in the underestimated-slope muted shot gathers (Fig. 5b), because some of the higher mode is not muted and leaking through.

From a practical point of view, it was not really necessary to apply muting to the multi-mode data (Fig. 3c) because, for the most part, both fundamental and higher modes could be separated well in the phase-velocity–frequency domain (Fig. 3f). However, this model was used as an example of the muting method that can be applied in cases where higher modes are significantly stronger, and the fundamental mode does not have sufficient energy to be observed within the range of the dominant higher mode, as in the case with the Yuma data (Fig. 2a).
Figure 3. Modeling of synthetic seismic data: a) shot gather containing fundamental-mode-only Rayleigh wave, b) shot gather containing higher-mode-only Rayleigh wave, c) shot gather containing both fundamental-mode and higher-mode Rayleigh wave, d) phase-velocity–frequency domain image of the shot gather containing fundamental-mode-only Rayleigh wave, e) phase-velocity–frequency domain image of the shot gather containing higher-mode-only Rayleigh wave, f) phase-velocity–frequency domain image of the shot gather containing both fundamental-mode and higher-mode Rayleigh wave.

Figure 4. Muting applied to the synthetic shot gather containing both fundamental-mode and higher-mode Rayleigh wave: a) muting the higher mode from the shot gather, b) muting fundamental mode from the shot gather, c) phase-velocity–frequency domain image of the higher-mode muted shot gather, and d) phase-velocity–frequency domain transform of the fundamental-mode muted shot gather.
Further Field Data Examples

Fundamental-mode Rayleigh-wave Estimation in Garland, MI

Seismic data were collected at Garland, Michigan. The near-surface geology of the area is known to be dominated by glacial till with some suggestions of boulders. Data were recorded using a Geometrics StrataView seismograph, 48 channels, and 4.5-Hz geophones. Geophone spacing for Line 2 was 2 ft, and the shot offset was 4 ft. After analyzing a shot record (Fig. 6a), it was not possible to extract a clear image of the fundamental mode of the dispersion curve (Fig. 6d). Many irregular events are found in the phase-velocity–frequency domain image. Closer examination of the shot gather reveals two zones with distinctly different apparent velocities. These zones can be separated by an imagery line starting at about 80 ms on trace one and ending at about 260 ms on trace 48. After muting the wave field above this line (Fig. 6b), a very clear image of the fundamental mode of the surface-wave dispersion curve (Fig. 6e) was obtained. In a similar way, after muting below the selected trend-separation line (Fig. 6c), a very clear image of a higher mode was obtained (Fig. 6f). For this particular data set, muting successfully separated the two surface-wave modes (the fundamental mode and a higher mode) that were interfering in the phase-velocity–frequency domain.

The MASW method requires that sufficiently far-offset data be available to separate the fundamental mode from higher modes (Park et al., 2001). However, significant lateral variations along the seismic line or noise from body waves or other sources may not allow the use of the necessary long offsets. For this particular site it was possible to take advantage of using seismic traces positioned at double-space intervals (4 ft), thus providing offsets twice as large as the original (Fig. 7a). With sufficiently far offsets the MASW method provided a clear image of the fundamental mode without any interference with the higher mode (Fig. 7c). This fundamental-mode dispersion curve image is identical to the dispersion curve obtained after muting the noise waves from the half-spread shot of line 2 (Fig. 6e). The main purpose of this comparison with long and short seismic spreads is to demonstrate the effectiveness of the muting method applied on the short spread. In general, longer spreads not only provide better separation of the fundamental mode from higher modes (resolution) but also provide lower frequencies (13–16 Hz for the long spread example) equivalent with increased depth penetration. Shorter spreads, on the other hand, provide higher lateral resolution and higher frequencies, thus greater detail at the shallower parts of the section. In this data example the use of a long spread was effective in suppressing the higher
modes in the phase-velocity–frequency domain. The fundamental mode is dominant and there are only a few hints of higher-mode energy above 35 Hz (Fig. 7c).

Even when using long offsets and strong fundamental-mode energy, muting can be used to improve the fundamental-mode imaging at the high frequencies. After muting the long-offset shot gather (Fig. 7b), the image of the fundamental mode in the phase-velocity–frequency domain (Fig. 7d) has stronger and better-defined energy between 33–44 Hz compared to the image of the shot-gather without muting (Fig. 7c).

Figure 7. Seismic data collected with a long receiver spread in the Garland, MI, USA: a) shot gather number 1001, b) shot gather 1001 muted to remove higher mode along a line that separates different apparent-velocity trends of the surface-wave, c) phase-velocity–frequency domain image of shot gather 1001, d) phase-velocity–frequency domain image of shot gather 1001 muted to remove the higher mode.
Guided P-wave Estimation

Muting can be very useful for estimating guided-wave dispersion curves when the surface-wave energy is very strong. The shot-gather display of the data set from above (Fig. 7a) was boosted to try to observe other non-surface-wave energy (Fig. 8a). Possible guided-wave energy can be observed at the far offsets above 200 ms. The corresponding wide-range phase-velocity–frequency domain display (Fig. 8c) of this shot gather shows only a few possible hints of guided-wave energy between 33–43 Hz and 600–950 m/s.
By examining the shot record it can be estimated that the strongly-dominating surface wave seems to be below a line starting at about 80 ms at trace 1 and ending at about 250 ms at trace 48 (Fig. 8a). After muting all the apparent surface-wave data below this line (Fig. 8b), the phase-velocity–frequency domain image shows strong guided-wave energy between 22–65 Hz (Fig. 8d). Thus, muting can be a very effective tool for analyzing the relatively weaker guided-wave energy.

Fundamental-mode Rayleigh-wave Estimation in Lawrence, KS

Another surface-wave data example was collected at a soccer field in Lawrence, Kansas, USA (Fig. 9a). A 16-lb sledgehammer was used as a source and the geophone spacing was 4 ft (1.2 m). These data were included in our work because of the unique separation of the two surface-wave modes on the shot record and their blurred interference in the phase-velocity–frequency domain.

It is difficult to determine the fundamental-mode energy on the corresponding phase-velocity–frequency domain image (Fig. 9c). There is a portion of strong linear-shaped energy between 31–70 Hz. It can be assumed that this is higher-mode energy and the other two portions of the energy between 18–35 Hz are of the fundamental mode. However, it can also be assumed that the highest-velocity portion at 18–26 Hz and the 31–70 Hz portion are fundamental-mode energy and the short 26–33 Hz low-velocity portion is due to noise, especially as this pattern could be observed only on a few shot records. The rest of the shot records had a strong linear-shaped energy between 18–70 Hz following the 31–70 Hz pattern from Fig. 9c and had a few hints of the short 26–33 Hz low-velocity portion (Fig. 9d).

By carefully studying the wavefield trends on the shot records, one can notice that there are two sectors with distinctly well-separated surface-wave apparent-velocity trends. These trends can be separated by a line starting at about 100 ms on trace 1 and ending at about 500 ms on trace 48. Mutting the data above this line (Fig. 9b) revealed strong low-velocity energy in the phase-velocity–frequency domain (Fig. 9e) overlapping and continuous of the weak low-velocity energy portion at 18–26 Hz on the phase-velocity–frequency domain image of the non-muted data. This analysis allows recognizing this energy as fundamental mode and accepting the first hypothesis that the energy between 18–35 Hz on Fig. 9c of the non-muted data is fundamental mode. As a result, the fundamental-mode dispersion curve was picked in two steps. The first step was to pick the low-frequency range of the fundamental mode on the non-muted data 18–35 Hz (Fig. 9c). The next step was to mute the data and pick the fundamental-mode dispersion curve between 25–50 Hz (Fig. 9e).

Using the overlapping portion between 25–33 Hz, the two curves could be combined (ignoring the steep velocity-gradient portion of the second curve) into one dispersion curve covering the frequency range 18–55 Hz. The high-gradient velocity values at the low frequencies of the second curve were classified as muting artifact and ignored with the assistance of the first curve (from the non-muted shot record) that covered the same frequency range. In such a manner, muting was used not only to improve the dispersion curve picking in the higher-frequency range (35–50 Hz), but it was also used as an analytical tool to recognize the fundamental mode, almost entirely overridden by another higher mode.

The value of this data example is that it illustrates that when identifying different surface-wave modes it may be always useful to use not only the phase-velocity–frequency domain but also the shot-gather domain.

Comparison

The results of the muting technique can be compared with another technique, which filters dispersive events (i.e., higher modes) in the phase-velocity–frequency domain (Park et al., 2002). This technique has proved to be very efficient for filtering dispersive events without introducing artifacts, as compared to the muting technique. However, filtering in the phase-velocity–frequency domain is possible only when the dispersive events that need to be filtered are clearly visible in the phase-velocity–frequency domain, so that it is possible to pick them and then filter them out. This was the case with the Yuma data (Fig. 2a), which were used to test both techniques. Both filtering techniques produced identical fundamental-mode dispersion curves. The availability of automated software for filtering in the phase-velocity–frequency domain made the latter technique a preferred method for filtering higher-modes from the Yuma data set because of its efficiency and reliability. On the other hand, it was not possible to apply filtering in the phase-velocity–frequency domain to data sets for which different dispersive events interfered in the phase-velocity–frequency domain, and it...
was not possible to pick either one of them, such as with the Garland data (Fig. 6d) and the soccer-field data (Fig. 9d). In these cases the muting method was the selected method for filtering. Further comparison of the muting technique with the filtering technique in the phase-velocity–frequency domain on other data sets confirmed the identical dispersion-curve results that both filtering techniques provide. In such a manner, the validity of the muting technique was supported. Additionally, there are two filtering methods available, which can be used depending on the data set. However, the muting method is more intuitive in following what type of apparent surface-wave velocity slopes are being removed from the shot gather. Furthermore, the muting technique is quite simple to apply; is unconditionally applicable (while filtering in the phase-velocity–frequency can be applied successfully only to some data sets), and does not require specialized software. It has proved to be very efficient when testing and optimizing for different surface-wave field parameters.

Conclusions

Fundamental-mode dispersion-curve energy can be boosted in the phase-velocity–frequency domain after examining a multichannel shot record, recognizing and muting harmful higher-mode dispersive energy in the shot-record domain. In such a manner, muting can significantly improve the bandwidth of the fundamental mode and the dispersion-curve picking when using MASW. Muting introduces a high-velocity gradient feature at the low-frequency end of the dispersion curve, which is not present before muting. This artifact can be easily handled by using the dispersion curve from the non-muted data that covers the same frequency range, so the artificially high-velocity values can be ignored and are thus considered harmless.

The effectiveness of the muting technique and its examination for possible errors were analyzed qualitatively by using shot-gather models. However, further work is necessary to study in full all the possible effects of muting on the phase-velocity–frequency domain transform. Extending the research on this muting technique by using an analytical approach can provide more in-depth, useful information about it in the future. Future in-depth analysis will open the door to a broader applicability of this highly useful method.

This wave-field-separation muting technique is valuable not only because it provides a general tool for improvement of dispersion-curve picking, but also because it is a simple and strong processing tool for examining shot records for different types of dispersive energy. It is especially useful when some of the dispersive modes have very strong energy and dominate the rest of the dispersive modes.

This wave-field-separation technique may become useful when analyzing other dispersive components of the seismic-wave field such as higher modes of the surface wave, Lamb waves, and guided waves. The dispersion curves of these waves can be used for further analysis of the wave field such as multimode inversion (Xia et al., 2003), Lamb-wave inversion (Ryden et al., 2004), or inversion of guided waves (Roth and Holliger, 1999).

Additionally, the availability of the muting technique allows us to acquire data with smaller spreads and thus significantly increase the horizontal resolution. For example a small-spread survey can be designed and only few larger-spread shots can be added for quality control. This would ensure that the muting of the smaller-spread data is appropriate and that dispersion-curve processing has results with the same dispersion curves as with the larger-offset data.

Based on the analyzed data, it is our belief that the muting technique is a highly effective and useful method, which can benefit the surface-wave community in both its practical and theoretical dimensions. We hope that this proposed tool will facilitate a significant range of research goals and that its successful and wide implementation will foster further analysis of the related data accumulation.

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