TIME BREAK CORRECTION
IN MULTICHANNEL SIMULATION WITH ONE RECEIVER (MSOR)

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Abstract

Recent investigations in the seismic evaluation of pavement systems indicates that the multichannel approach is indispensable. This is because of the complicated seismic phenomenon that originates from the unique seismic setting of a pavement system. A true multichannel survey would be a formidable task that would require an expensive multichannel (e.g., 48 channel) recording device and so-many receivers with complicated wiring deployed in a small area on the pavement. Instead, the multichannel simulation with one receiver (MSOR) approach can produce a simulated multichannel record by using only one receiver and a single (or two) channel recording device readily available for various types of engineering measurements. For this approach to be an effective alternative, a consistent timing of wave generation at each impact is the most critical condition to be met. Considering the necessary accuracy of tens of microseconds to deal with seismic waves in the range of kilohertz, it seems that a certain degree of inconsistency in time break can always occur in spite of a carefully designed timing mechanism. For a given inconsistency, extraction of the dispersion curve for surface waves is adversely affected most in the high frequencies and least in the low frequencies, making the lower frequencies still useful. This low-frequency dispersion information is then used to construct an impulsive surface wave event that should align perfectly at zero time if there were no time break inconsistency. The appropriate amount of time break correction can therefore be assessed from the amount of misalignment. The correction procedure may continue in an iterative manner because the extractable bandwidth of the dispersion curve would extend after each correction.

Introduction

The surface wave method is often used for elastic modulus evaluation of pavement system (Stokoe et al., 1994; Nazarian et al., 1999). The conventional method for this type of application employs the two-receiver approach and the dispersion curve is constructed from the phase-lag calculation of many pairs of Fourier-transformed seismic traces that are carefully prepared through both field-acquisition and data-conditioning steps. In spite of many of its successful applications, difficulties in the extraction of dispersion curves have been reported (Al-Hunaidi, 1992).

Ryden et al. (2002a; 2002b; 2001) and Park et al. (2002a; 2001a; 2001b) have shown that the seismic phenomenon over the pavement system is more complicated than normally assumed by the conventional method and that the multichannel approach is indispensable for getting accurate and reliable results. They also indicate that the difficulties with conventional methods can be significantly alleviated with a multichannel approach. The multichannel survey, however, would normally require a multi-channel (e.g., 48-channel) recording device and so-many receivers deployed simultaneously on the surface. This means a high survey cost unaffordable for many small-budget geotechnical projects. Instead, Ryden et al. (2001) introduced an alternative approach that can simulate the multichannel recording by using a single (or two) channel recording device and one receiver. This multichannel simulation with one receiver (MSOR) approach generates multiple seismic measurements (traces) with one accelerometer attached to a fixed point on the pavement surface and multiple impacts delivered at

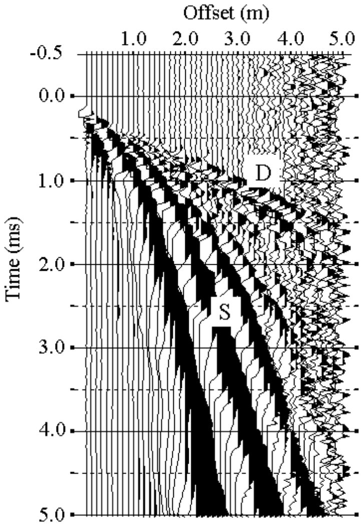

Figure 1. A typical simulated multichannel record (Ryden et al., 2001) obtained over an asphalt pavement through the multichannel simulation with one receiver (MSOR) approach. Direct arrivals of compressional waves (D) are separated from surface waves (S) only at far offsets (> 2.0 m) where ambient noise usually dominates.

successively increasing distance from the receiver. The simulated multichannel record is constructed by combining all these traces together.

For MSOR to be an alternative to the true multichannel method, there are several conditions that must be met (Ryden et al., 2002a; 2002c; 2001). Among them the accurate timing of wave generation (i.e., time break) is most critical. This is because the inconsistency in time break would perturb the arriving pattern of seismic waves, and degrade the fundamental advantage with the multichannel method, the pattern recognition. If there is a strong first-arrival event (e.g., direct body waves) whose arrival pattern is linear with a known slope (i.e., velocity), then the correction of the inconsistency is a trivial task. However, the offset range for a pavement survey is usually within a few meters and direct-wave events occur in a mixture with strong surface-wave trains (Figure 1). In addition, the complicated wave phenomenon near source point further inhibits the coherent direct arrivals. This phenomenon has been commonly referred to as the near-field effect by practitioners of the conventional method (Stokoe et al., 1994). At far offsets (e.g., > 2.0 m) where it would separate from surface waves, the energy level of direct-wave events often drop so significantly that ambient noise usually dominates (Figure 1). It seems that the weak nature of the direct arrivals could also be related to the predominantly horizontal motion of the wave disturbance in direct waves (Park et al., 2001a; 2001b).

For a given inconsistency, the degree of the perturbation influencing the dispersion-curve analysis is directly proportional to the frequency. In consequence, the dispersion curve extraction that is difficult at high frequencies is still quite possible for the lower frequencies. These low frequencies of surface waves can be collapsed through the frequency-variant linear move out (FV-LMO) correction (Park et al., 1998b) into an impulsive event that should perfectly align along the zero time line if there was no inconsistency. The amount of inconsistency can then be determined by calculating the amount of misalignment.

Advantages with the Multichannel Method

The multichannel analysis of surface waves (MASW) method (Park et al., 1999; Xia et al., 1999; Miller et al., 1999) was originally developed as a seismic tool to investigate Vs properties of near-surface (< 50 m) materials, including normal soil sites. The MASW method was recently applied to pavement evaluation in a collaborative research project between the Kansas Geological Survey (KGS) and Department of Geotechnology, Lund University, Sweden. Preliminary results from the research indicate that seismic phenomena over the pavement system are unusually complicated due to the unusual seismic setting of the pavement layers, and that the conventional method is incapable of handling all these complications. The results also showed that most difficulties experienced with the conventional method are due first, to the oversimplification of the seismic phenomena, and second, to ineffective signal extraction. The multichannel method is a pattern-recognition method that can delineate the complexity of seismic characteristics through the coherency measurement in velocity and attenuation of different types of seismic waves (e.g., multimodal surface waves, various types of body waves, and a wide range of ambient noise). As a consequence, the effectiveness and reliability of signal extraction are maximized. This is illustrated through a synthetic experiment (shown in Figure 2). A multichannel record contains surface waves whose dispersion curve mimics a common trend normally observed with a pavement system. In addition, it contains a considerable amount of random noise as well as several traces that indicate bad coupling at the receiver (or source). (Compare Figure 2a with its noise-free version shown in Figure 4a.) When a proper pattern-recognition technique (Park et al., 1998a) is applied to extract the dispersion information underlying the severe noise, the information is fully recovered (Figure 2b). Random noise is only one among many types of noise interfering with the signal during seismic measurement. The multichannel method maintains the same degree of robustness in discrimination against other types of noise as well (Park et al., 1999).

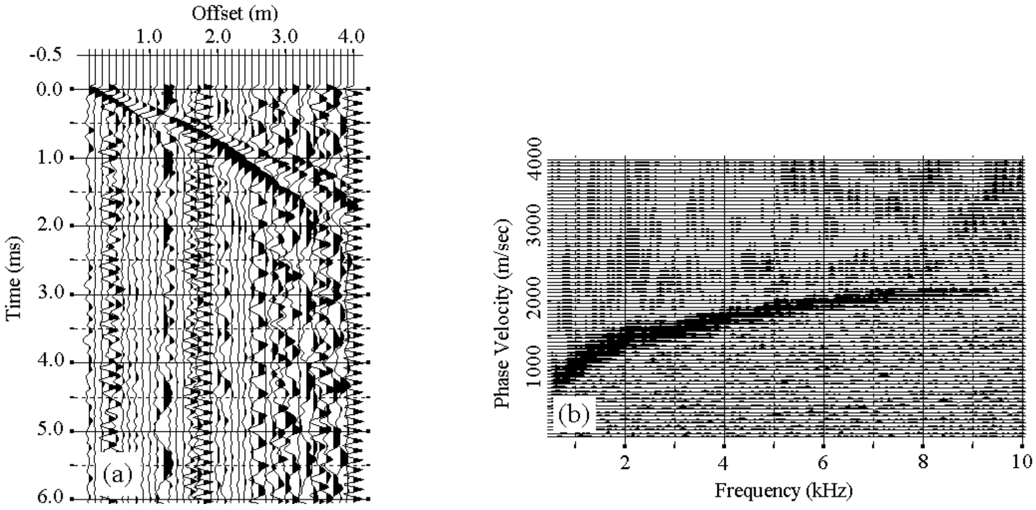

Figure 2. (a) A synthetic multichannel record containing a typical surface wave signature over a pavement as well as strong noise and several traces of bad coupling, and (b) its wavefield transformation (Park et al., 1998a) showing that the correct image of a dispersion curve has been extracted in spite of the severe noise.

Multichannel Simulation with One Receiver (MSOR)

The multichannel survey, however, requires a multichannel (e.g., 48-channel) recording device and so-many receivers deployed simultaneously in a small area. This would indicate a formidable survey expense not affordable to low-budget projects, and also inconvenient in the field with many components and complicated wiring deployed in a small area. The MSOR approach by Ryden et al. (2001) alleviates these problems. With only one receiver (an accelerometer) attached to a fixed point on the pavement surface, a multiple number of impacts are delivered with a successive increment of distance from the receiver point (Figure 3), and a simulated multichannel record is constructed by combining all the individual measurements or seismic traces. However, for this approach to become an alternative to the true multichannel method, there are several conditions to be met: reproducibility of identical seismic waves at each impact, no source static, and accurate timing of wave generation (i.e., time break). In this paper we will deal with the issue of time break. Other issues are discussed in Ryden et al. (2002a; 2002b; 2002c; 2001) as well as future publications.

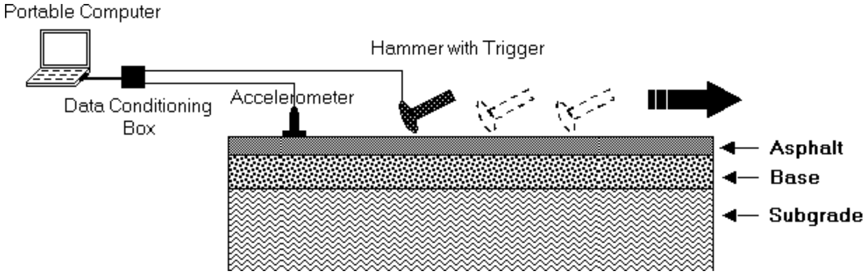

Figure 3. A typical field setup and procedure for the multichannel simulation with one receiver approach (from Ryden et al., 2002a).

Time Break Correction

Several factors may contribute to the inconsistent time break: sensor type, impact mode, and surface condition. Different sensors have different sensitivities and therefore may result in different degrees of inconsistency. For example, a common, commercially available hammer switch has a more reliable consistency than a simple custom-made contact closure. The impact mode means the way an impact is delivered: strong versus weak or straight versus slant, etc. A rough surface may result in inconsistent time breaks as well as a source static problem. In addition, a local anomaly such as a small piece of gravel sitting at or right below the impact point may cause an abnormal action-reaction between the hammer and the impacting surface, generating an abnormal time break.

The inconsistent time break degrades the effectiveness of pattern recognition in extracting the dispersion curve of surface waves, as illustrated from a synthetic experiment in Figure 4. The record in Figure 4a represents a case of perfect time break (or a true multichannel case). The two records in Figures 4b and 4c represent cases having different degrees of inconsistency. Random inconsistency between ±0.025 ms and ±0.050 ms were introduced in Figures 4b and 4c, respectively. It is obvious that the degree of perturbation in the extracted dispersion curve image (Park et al., 1998a) is directly proportional to degree of inconsistency. In both cases, however, the lower frequency portions (< 6 kHz and < 3 kHz, respectively) of the curve have been correctly extracted (Figures 4e and 4f). This indicates

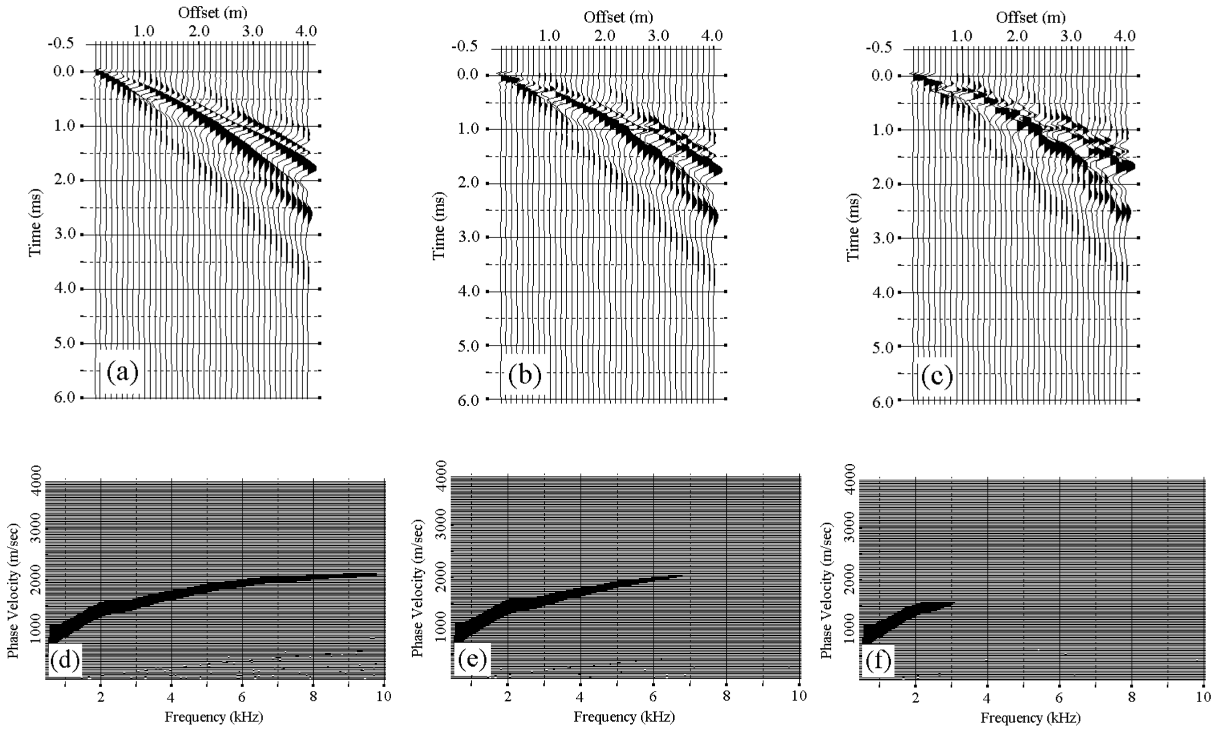

Figure 4. Synthetic multichannel record with a typical signature of surface waves over pavement with (a) none, (b) ±0.025 ms, and (c) ±0.050 ms inconsistency in time break. Corresponding dispersion curve images (Park et al., 1998a) are shown in (d), (e), and (f), respectively.

that this part of the dispersion curve can be used to construct an event from which the amount of time break inconsistency can be determined. This is further explained below using real field data sets.

A simulated multichannel record (Figure 5a) was obtained from a MSOR survey over an asphalt parking lot at the KGS. A 30-kHz accelerometer was attached on top of the asphalt surface with high-density lubricating grease. Using a light (0.25 kg) carpenter hammer, sixty impacts were delivered along a 3-m linear survey line with 0.05-m increment. A 0.1-m long bolt with 0.01-m diameter was used as a coupling device between asphalt surface and hammer. A portable seismic acquisition system (PSAS) (Ryden et al., 2002c) consisting of a laptop computer equipped with a 16-bit PC-card (PCMCI bus) was used to record data. Ryden et al. (2001) investigated various types of time break sensors and achieved an accuracy much higher than that illustrated by field data examples used in this paper. However, as mentioned previously, the sensor is not the only cause of the time break inconsistency and there is always the possibility of running into a problematic situation caused by things other than the sensor. The data in Figure 5a were acquired using a hammer switch that is used during normal near-surface seismic investigations and hence readily available.

The low coherency of a surface wave event indicates that the data suffer from a time break inconsistency. This is noticeable when it is compared with the synthetic data in Figure 4c. However, the dispersion-curve image shows that correct information can be extracted up to 1.5 kHz (Figure 5b). The broken part of the image near 0.4 kHz originated from the branching phenomenon of seismic waves (Ryden et al., 2002b; Vidale, 1964; Jones, 1962). The branch represents the elastic discontinuity between base and underlying soil. The phase velocity information extracted from the image in the 0.4-1.5 kHz range was then used for the frequency-variant linear move out (FV-LMO) correction (Park et al., 1998b; 2002b) to produce the section in Figure 5c. The FV-LMO correction collapses the

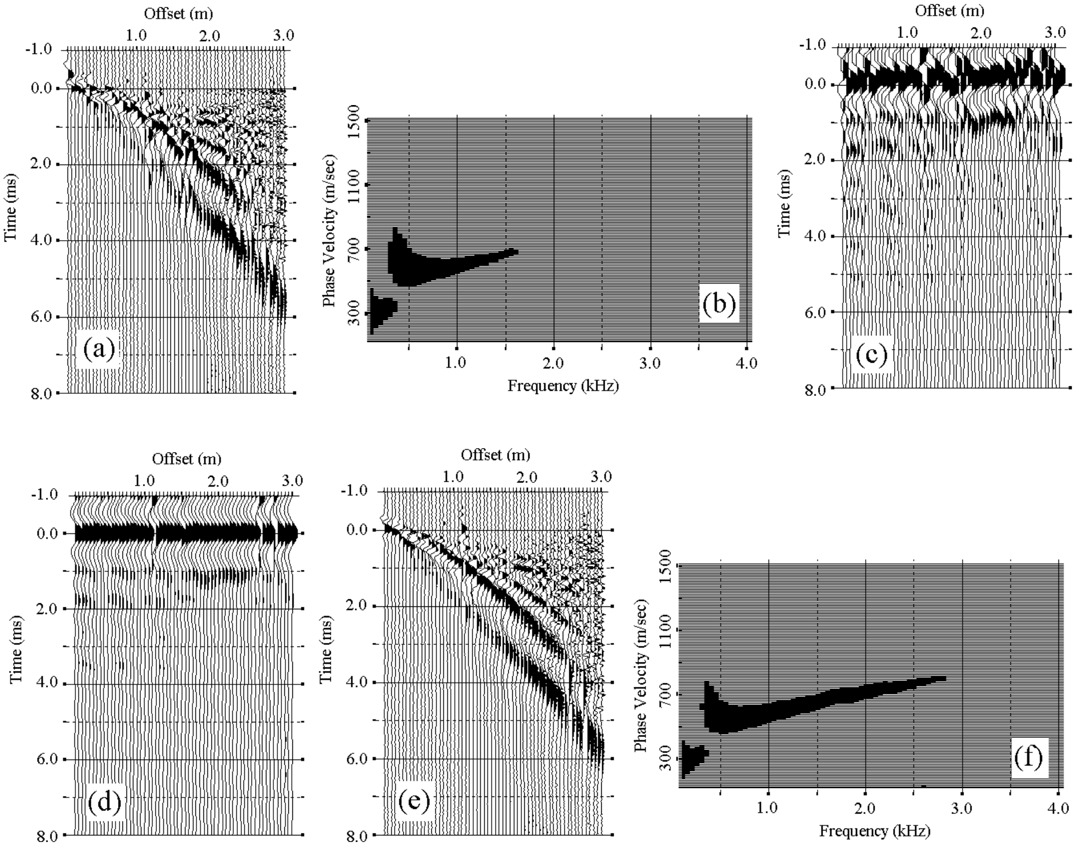

Figure 5. (a) A field record obtained over an asphalt parking lot at KGS through the MSOR approach, (b) its dispersion curve image, (c) frequency-variant linear move out (FV-LMO) correction applied to (a) using the dispersion curve extracted from (b), (d) record of (c) after correction of the time break inconsistency has been made, (e) record of (a) after the same time break correction, and (f) the dispersion curve image of (e).

dispersed train of surface waves into an impulsive form that should appear at time zero if there were no time break inconsistency. As indicated by the irregular arrival pattern of the collapsed waves in Figure 5c, the inconsistency in time break is obvious. In order to assess the absolute shift of arrival time, the exact phase information of the source wave should be known. Dispersion curve analysis, however, does not require strict accuracy in the absolute arrival time (Park et al., 2001c). Instead, the overall consistency in time break for all the constituent traces is most critical. In consequence, one arbitrary trace (second trace) among all the sixty traces with FV-LMO correction was chosen as a pilot trace to be cross-correlated with all other traces. The cross correlation gives the relative amount of time shift needed for a trace being examined to match the pilot trace most closely. Figure 5d shows this relative time-break correction. Most of the traces are now well aligned. Three traces (one in the middle and two at the far offsets) are still not aligned due to the bounds (±0.5 ms) imposed during the cross correlation. Time lags calculated from the cross correlation were then used to apply the static shift to the corresponding traces. The new section with this static correction now shows a significant recovery of the surface wave coherency (Figure 5e). The dispersion curve image of this record (Figure 5f) indicates that extraction is now possible up to 3.0 kHz.

At this stage, another iteration of the procedure outlined above may be applied to further enhance the time break consistency. This is because bandwidth of the extractable signal has now been enlarged and extended to higher frequencies, indicating that the cross-correlation operation can achieve even better accuracy than determined in the first application of the procedure. Another section (Figure 6a) of

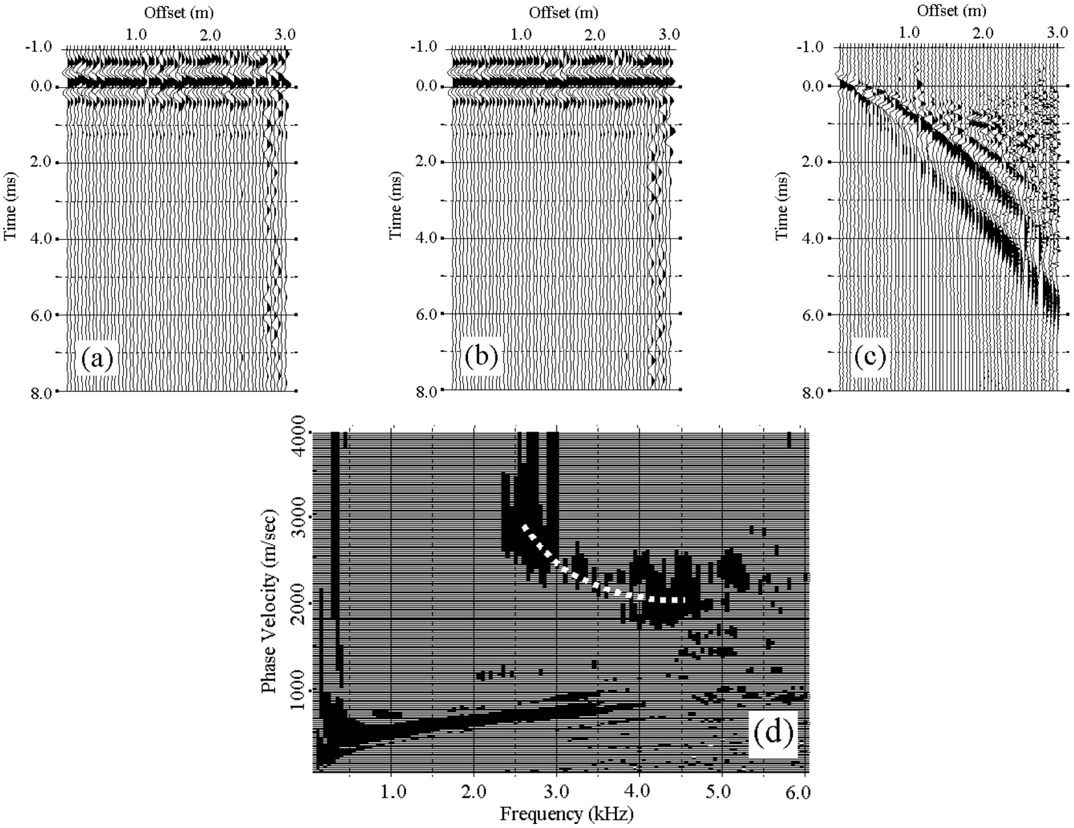

Figure 6. (a) Record in Figure 5e after another FV-LMO correction has been made using the dispersion curve extracted from Figure 5f, (b) time break inconsistency has been corrected from (a), (c) record in Figure 5e after the correction of inconsistency has been made, and (d) its image of the dispersion curve. A seismic longitudinal mode has been marked by a dotted line in (d).

FV-LMO correction made by using the extended dispersion curve of 0.4-3.0 kHz shows a noticeable amount (about ±0.2 ms) of the inconsistency still remaining. Subsequent cross-correlation significantly alleviates this remaining inconsistency (Figure 6b). This new set of cross-correlation lags are then used for another static correction made to the record of Figure 5e, and the resultant record is shown in Figure 6c. On visual comparison of Figures 5e and 6c, no change or improvement is noticeable. However, the dispersion image (Figure 6d) of the new section reveals an improvement of the surface wave coherency at frequencies up to 4.0 kHz. Also, the seismic longitudinal mode (Jones, 1962; Park et al., 2002a) is better imaged. The seismic longitudinal mode can give information about thickness and seismic velocities (both P- and S-wave velocity) of the uppermost layer.

Another MSOR record acquired over a concrete pavement at KGS is displayed in Figure 7a. This data set was obtained by using one of the most reliable time break sensors tested by Ryden et al. (2001; 2002c). The dispersion curve image of this record (Figure 7b) shows an excellent trend of phase velocity gradually increasing up to about 2200 m/sec and then leveling flat at frequencies higher than 10 kHz. In spite of the overall superior quality of this time break, a further enhancement operation was attempted with the dispersion information in 0.5-10 kHz range. The image (Figure 7c) obtained from the enhanced record now reveals the seismic longitudinal mode more clearly.

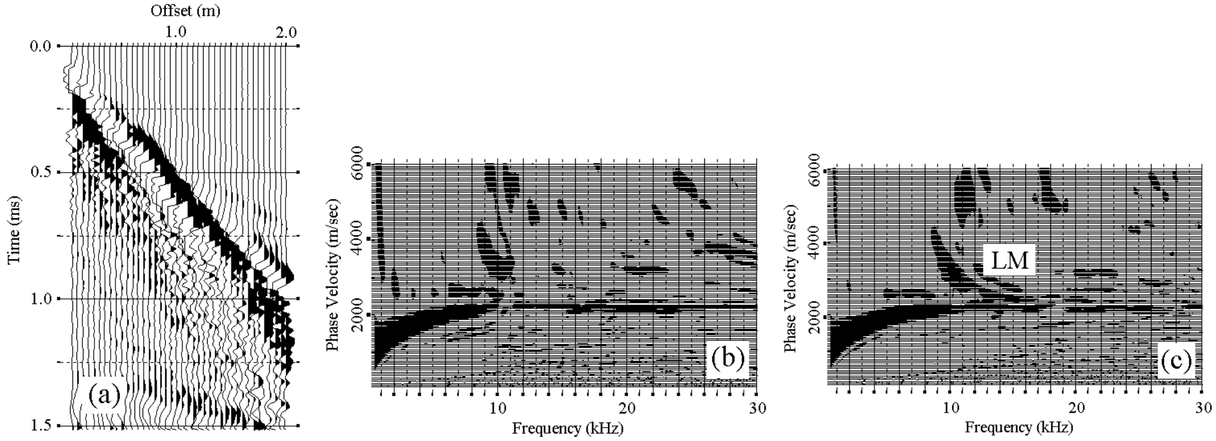

Figure 7. (a) An MSOR field record obtained over a concrete pavement at KGS, and its dispersion curve images (b) without, and (c) with the time break correction made by using the dispersion curve of 0.5-10 kHz in (b). The seismic longitudinal mode (LM) is better imaged in (c).

Discussions and Conclusions

Although the time break correction principles presented in this paper are straightforward, a certain type of pre-conditioning of data is occasionally necessary before the FV-LMO correction or the cross-correlation operation is applied. For example, if there is a significant amount of noise energy within the frequency band of the preliminary dispersion curve to be used for the FV-LMO correction, the noise energy may contribute to misalignment along the zero time line. If the noise has a coherency in its arrival pattern like back- or side-scattered waves, then its contribution will be obvious, as the overall shape of alignment would slope gradually up or down (or slowly undulating) depending on its origin. In this case, the noise event needs to be attenuated by using the velocity (or f-k) filtering method before FV-LMO correction. It is also important to apply band-pass filtering with the same band as the dispersion curve before the FV-LMO correction is made. Otherwise, all the energy outside this frequency band will act as noise.

It has been implicitly assumed that the survey site can be treated as a layered model without any significant horizontal variation in its elastic properties. This will be the case for most pavement applications. Small-scale variations (e.g., roughness of a pavement surface) may cause an apparent inconsistency in time break (even in the case of a true multichannel recording). This would be an example of a surface static problem. In this case, the presented method can be used as a static-correction method.

The following conclusions are made from this study:

1. Time break inconsistency introduced during a MSOR survey diminishes an important pattern of surface waves that is utilized during the dispersion curve extraction by the multichannel-processing method. From the processing perspective, it acts as a high-cut filter.
2. Low-frequency components of surface waves that are least affected by the time break inconsistency and usually have the highest signal-to-noise ratio (S/N) can be used to repair the inconsistency through a combined procedure of frequency-variant linear move out (FV-LMO) correction followed by a cross-correlation.

Acknowledgments

We thank Mary Brohammer for her assistance in preparation of this manuscript.

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