SEISMIC INVESTIGATION OF PAVEMENTS BY MASW METHOD — GEOPHONE APPROACH

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Summary

A feasibility test of the multichannel approach to seismic investigation of a pavement system is described. This test followed the procedure normally taken in the multichannel analysis of surface waves (MASW) method by using geophones and a light (8-oz) hammer source. A wavefield transformation of recorded multichannel data shows a strong fundamental-mode dispersion curve image in the frequency range of 30-600 Hz with normal (30-50 Hz) and reverse (50-600 Hz) trends. However, the transformation shows that this fundamental mode disappears quite abruptly and higher modes start to dominate in the higher frequencies up to 2000 Hz. Simultaneous recording of both vertical and horizontal components of seismic wavefields facilitates identification of seismic events. In order to record the horizontally travelling direct (or possibly guided) P-wave event in the uppermost layer, it seems critical to use horizontal phones with longitudinal orientation. Results of test indicate that for an investigation focused into the uppermost layers of a pavement system it is essential to use a different acquisition system that can deal with much higher (> 2000 Hz) frequencies. In addition, complicated and unique elastic properties of pavement systems call for an inter-disciplinary study to develop an effective multichannel seismic method for this area of application.

Introduction

The main objective of non-destructive tests on a pavement system is to estimate the modulus and Poisson's ratio of each layer. These material parameters, together with thickness of the layers, are the main factors determining status and elastic response of the construction. With known external axle loads, fatigue and rutting can be calculated (i.e., remaining life of the construction). Both laboratory and field tests are usually used to determine these material parameters. Seismic methods have been proven very useful for field testing of pavements (Nazarian et al., 1999). These days, seismic methods have drawn even more attention because of their potential in measuring accurate physical material properties. From the seismic velocity, the modulus can be calculated without any empirical relationship. This is essential for analytical pavement design.

The traditional seismic method for this application, however, has been rooted on the simplicity of recording and processing seismic data. Usually only a pair of receivers were used, and it had to be assumed that recorded seismic energy would be dominated by one specific type of seismic wave such as fundamental-mode Rayleigh wave or direct P-wave, depending on the specific method. However, seismic phenomena with a pavement system are usually more complicated than usually thought. For example, there are many different types of seismic waves being generated simultaneously at the time of impact. They can be grouped into body (e.g., direct, refracted, reflected, scattered, guided, and air waves) and surface (e.g., fundamental, higher modes, scattered) waves. Relative dominance of a specific type is a complicated function of many parameters such as seismic source, source point condition, impact strength, distance from source, and the layer model that includes all the elastic parameters of medium. Among these, layer model is the most prevailing factor. It is not only difficult to theoretically predict the seismic response based on a given layer model, but it is usually the layer model that is to be obtained from a seismic test and therefore is not known prior. Considering all these perturbing factors, any traditional method that treats recorded seismic energy being dominated by one desired type can often become extremely dubious.

The multichannel recording method is a pattern recognition method that enables the identification of different types of seismic waves from their arrival and attenuation patterns. With its effectiveness being proven by oil exploration industries over the last several decades, it is a method that assures the most optimum data-acquisition and data-processing parameters. It also enables utilization of the various multichannel processing techniques available to make the recognition more effective under diverse situations.

A pavement system is quite challenging for a seismic survey not only because of the shallow (< 5 ft) target depth, but also because of the unusual seismic velocity structure (Figure 1). The uppermost layer has both S and P velocities significantly higher than those of the underlying layers and each layer has a significant velocity contrast to the overlying (or underlying) layer. Total thickness of a pavement system usually does not exceed several feet. Earlier, it was theoretically predicted (Jones, 1962) that this unique layering of elasticity may result in unusual seismic phenomena in phase velocity and attenuation of surface waves. The unique velocity structure may complicate surface-wave characteristics due to interference from strong higher modes and body waves (Stokoe et al., 1994; Sheu et al., 1988). The dominance of higher mode surface waves has been not only predicted from a theoretical perspective (e.g., Herrmann, 2000; Jones, 1962), but also speculated about during the surface wave measurement by traditional methods. The nature of a pavement system being a well-defined layer model with a significant velocity contrast indicates a possible dominance of body-wave energy from reflection, refraction, and channel (guided) waves (Figure 1). Necessity of unusually high (> 2000 Hz) frequency generation and recording requires a special seismic source, receivers, and field logistics.

At the Kansas Geological Survey (KGS) we have been routinely implementing and researching a unique seismic method called multichannel analysis of surface waves (MASW) (Park et al., 1999) that investigates the shallow (< 150 ft) part of the earth by utilizing Rayleigh-type surface waves. We recently extend this research as a co-project between KGS and the geotechnical department of Lund University, Lund, Sweden, to further develop similar technique to investigate the pavement system. Contents described on this abstract represent preliminary results from our recent experiments as a feasibility test. The goals are to describe both seismic surface- and body-wave phenomena in the pavement system through the multichannel method and to assess limitations with the conventional multichannel method.

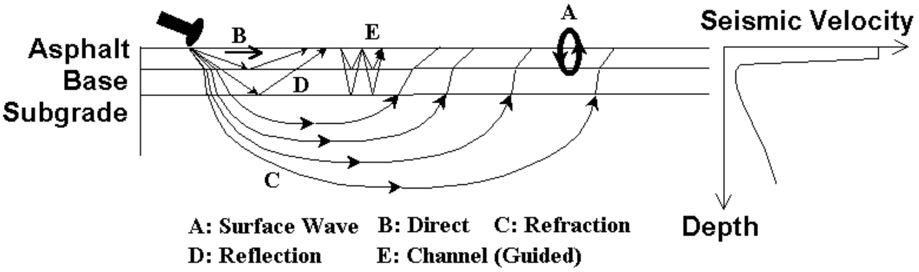

Figure 1. Generalized structure of an asphalt system. Ray paths of various seismic events are also indicated. A generalized seismic velocity structure is displayed on the right.

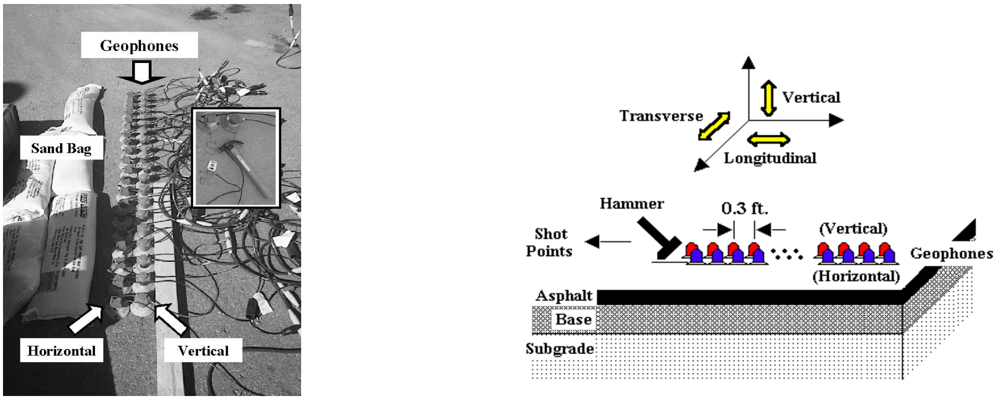

Figure 2. Field setup to acquire both vertical and horizontal (longitudinal and transverse) components of seismic waves on top of an asphalt layer in a KGS parking lot.

Multichannel Multi-Component Recording on Asphalt

One line of twenty 100-Hz vertical phones and another line of twenty 14-Hz horizontal phones were laid out side by side with 0.3 ft geophone spacing on an asphalt parking lot at KGS (Figure 2). Geophone spikes were replaced by conical base plates 0.3-ft in diameter. Each line of geophones was topped by three sand bags weighing about 40 lb each to enhance the coupling. A small (8-oz) carpentry hammer was used as a vertical source. Six different source offsets were used to produce a simulated 120-channel shot gather per each geophone orientation. A sampling interval of 0.062 ms was used to generate 125-ms seismic records by using a Geometrics Strataview (60 channel) seismograph. Horizontal and vertical phones were connected to the 1st-20th and 31st-50th channels of the seismograph, respectively. Figure 3 shows the simulated 120-channel shot gathers for three different geophone orientations: vertical, longitudinal, and transverse. Horizontal phones were first laid out in a longitudinal direction with respect to the receiver line, and then changed into the transverse direction later.

The main purpose of the multicomponent recording was to ensure an accurate identification of seismic events. Furthermore, the thinness and shallowness of the target medium raised speculation that a certain type of body-wave event (e.g., direct P-wave event along an asphalt layer) may consist predominantly of horizontal component in its vibration, whereas others may consist of vertical only (e.g., refraction) or both (e.g., surface wave) components.

The strong vertical (major axis) component of Rayleigh wave is best identified on the vertical shot gather in Figure 3a obtained from the vertical phones along with the reverse trend of its dispersion. The reverse dispersion is identified by the curved-down (decreasing apparent velocity) trend of the surface-wave envelope as offset (apparent frequency) increases (decreases). At far (> 20 ft) offsets an event is seen merging out from the surface-wave envelope that has an apparent velocity of 4500 ft/sec. According to the general velocity structure of a pavement system (Figure 1), occurrence of this refraction is possible only when the seismic P-waves penetrate below the base layer and merge out to the surface only at far offsets.

A relatively weak horizontal (minor axis) component of Rayleigh wave is identified on the longitudinal shot gather in Figure 3b that was obtained from the longitudinally oriented horizontal phones. Contamination by traffic noise from a nearby (about 50 ft away) road is obvious, especially at far offsets, due to the relative weakness of the signal. [Noise contamination at far offsets was still obvious even after a low-cut (< 100 Hz) filter was applied.] The refraction event identified on the vertical shot gather is not seen on this horizontal shot gather as anticipated. Instead, high-frequency (> 1000 Hz) first arrivals are seen at near (< 20 ft) offsets with an apparent velocity of about 9000 ft/sec. This event is interpreted as a direct P-wave event traveling horizontally within the asphalt layer.

The transverse shot gather in Figure 3c shows the weakest surface wave energy. This trend of relative amplitudes at three orthogonal records confirms the identification of surface waves on the previous two shot gathers discussed above. The weak first-arrival event seen at near-offset (< 15 ft) traces has an apparent velocity of 9000 ft/sec and is interpreted as the direct P-wave event observed on the longitudinal record in Figure 3b. Although motion of this event should be perpendicular to the geophone orientation, its horizontal nature seems to have been effective in inducing the transverse component (if minor).

Phase Velocity Analysis by Imaging Method

Each shot gather in Figure 3 was transformed from offset-time (*x-t*) domain into frequency-phase velocity (f-C_f) domain by using a modified version (Park et al., 2000) of the wavefield transformation method by Park et al. (1998). This transformation method makes it possible to observe the frequency-phase velocity relationship of both surface- and body-wave events. This method does not make any assumption on the nature of any seismic event in association with its phase velocity, and therefore the image construction is performed through an objective pattern-recognition skill. Because of the severe noise contamination at far offsets (> 20 ft), only the near-offset traces (first 60 traces) were used for the transformation and the obtained images are displayed in Figure 4. Images were obtained for the frequency and phase velocity ranges up to 2500 Hz and 12000 ft/sec, respectively. Comprehensive interpretation of *x-t* records and their corresponding f-C_f images is displayed in Figure 5.

The f-C_f image (Figure 4a) for the vertical shot gather shows the dispersion of surface waves most prominently. It is noticeable that the quality of the image is directly proportional to the quality of the shot gather (i.e., signal-to-noise ratio). It is shown in the figure that the fundamental mode of surface waves takes most of energy up to the frequency of about 600 Hz, and then higher modes dominate at the higher frequencies (600-2000 Hz). The refraction event at far offsets is imaged only when the corresponding far-offset traces were included in the transformation (Figure 6).

The longitudinal image in Figure 4b shows the same fundamental mode observed in the vertical image, but the higher modes are not so obvious due to the lower signal-to-noise ratio (S/N) of the shot gather. One thing obvious, however, is the distinctive image for the direct P-wave first arrivals in the 1000-1500 Hz range. The resolution of this image is not so high as that of the surface waves because of the higher velocity of the event. In order to achieve the comparable resolution for this part of the image, it would require the further offset range in proportion to the phase velocity ratio (about 9) between this event and the surface-wave event (Park et al., 1998). However, the constant phase velocity of about 9000 ft/sec can be extracted from this image without a significant difficulty.

The transverse image vaguely displays the surface wave dispersion image at lower (< 500 Hz) frequencies. No other image that can be associated with a coherent event on the *x-t* domain is found. Although the first arrivals of 9000 ft/ sec apparent velocity are seen on the shot gather, the corresponding image in the f-C_f domain seems to be lost due to the strong noise.

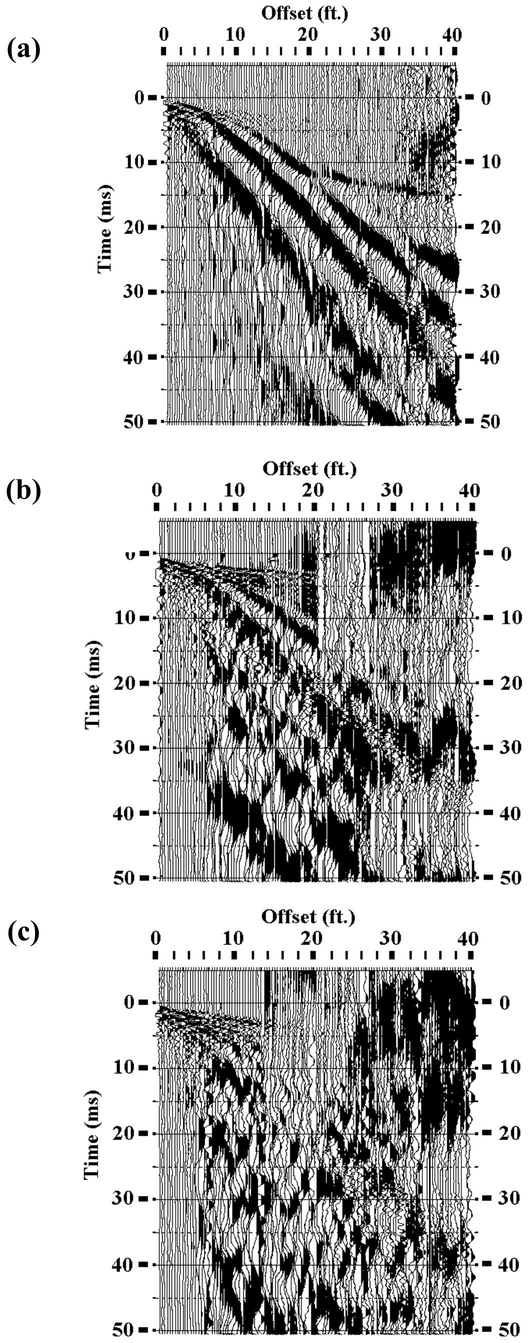

Figure 3. Walkaway records of 120 traces obtained by using (a) vertical, (b) longitudinal, and (c) transverse geophones.

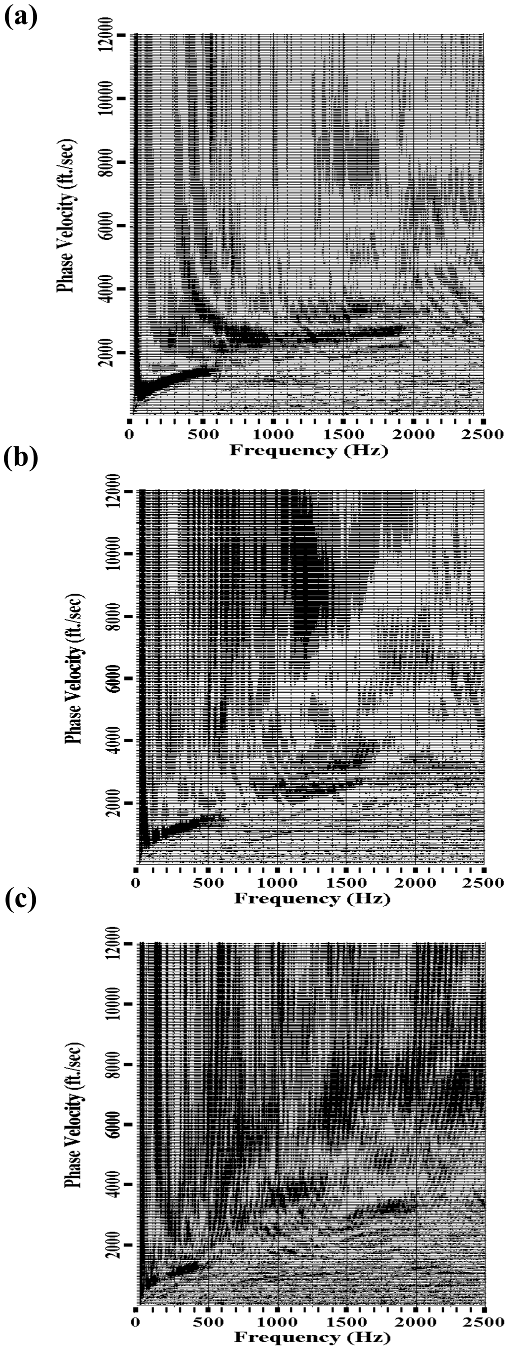

Figure 4. Phase velocity images obtained from near-offset (first 60) traces of corresponding walkaway records in Figure 3.

Analysis of Surface-Wave Event for V_s

A fundamental mode dispersion curve was extracted from the vertical image in Figure 4a for the 30-600 Hz range. Because both normal and reverse dispersion trends exist, the curve was broken into two parts: one (30-50 Hz) with normal trend and the other (50-600Hz) with reverse trend. The normal trend dispersion curve was then inverted with an automated inversion algorithm by Xia et al. (1999) to generate the S-wave velocity (*Vs*) profile for a depth range of 5-20 ft. The reverse trend curve was then used to generate the *Vs* profile for the shallower (< 5 ft) part by using the half-wavelength assumption (Stokoe et al., 1994). The combined profile is displayed in Figure 7. The dotted portion of the profile at depths (< 3 ft) comparable to the pavement system was calculated from the extrapolated part (dotted line) of the dispersion curve indicated in Figure 5b.

Analysis of Body-Wave Event for V_p

A tomographic inversion (Figure 8) of the refraction event on the vertical shot gather was performed to generate a P-wave velocity (V_p) profile shown in Figure 7 for the depth range investigated from the surface wave analysis (Ivanov et al., 2000). An initial *Vp* model prepared from the *Vs* profile by assuming a constant Poisson's ratio (0.45) made the inversion process converge to the final solution in a fast and stable manner. This joint inversion also has the advantage that it minimizes the risk of the non-uniqueness problem inherent to all types of seismic inversion (Ivanov et al., 2000).

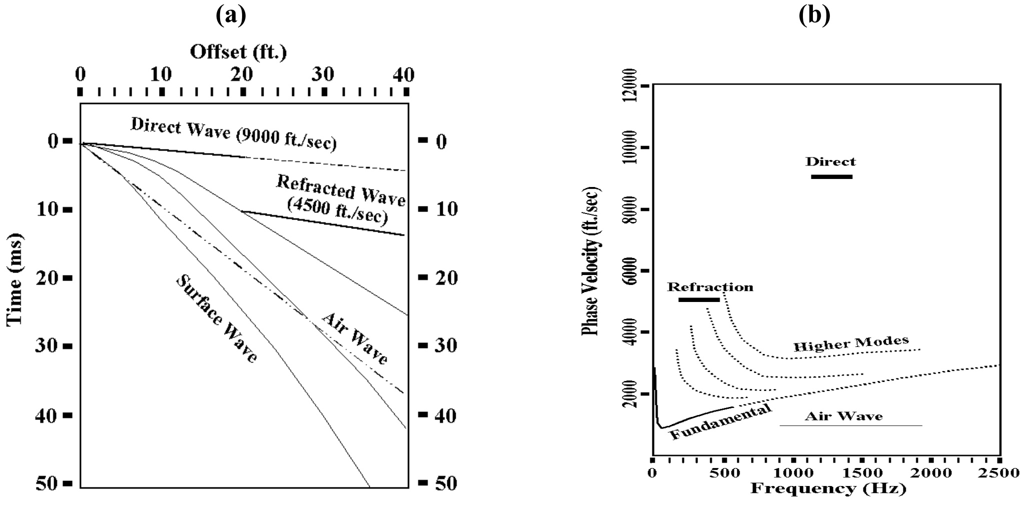

Figure 5. A comprehensive interpretation of both body- and surface-wave events (a) on the offset-time (*x*-*t*) records in Figure 3, and (b) on the frequency-phase velocity (f-C_f) images in Figure 4.

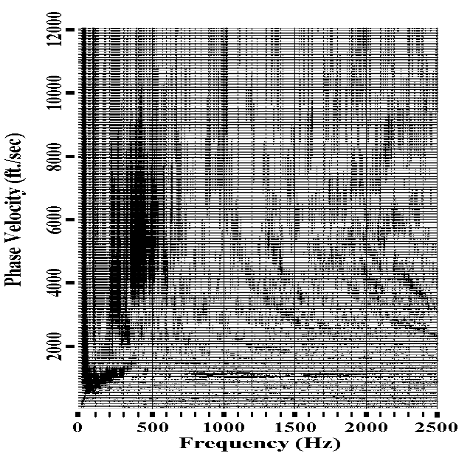

Figure 6. Phase velocity image of far-offset traces (last 60 traces) of the vertical record in Figure 3a.

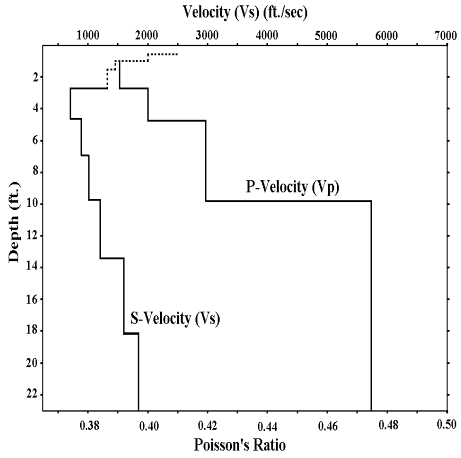

Figure 7. S-wave and P-wave velocity profiles obtained from the inversion of surface- and body-wave events, respectively.

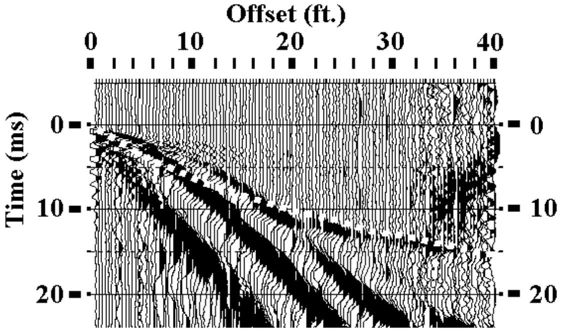

Figure 8. The first-arrival times of P-wave refractions superimposed on the vertical record for the velocity (*Vp*) model displayed in Figure 7 that was calculated through a tomographic inversion.

Discussions

Disappearance of fundamental mode and then dominance of higher mode surface waves occurs at those high frequencies where the wavelength of the fundamental mode becomes a few feet and the corresponding penetrating depth becomes comparable to the depth of subgrade. It seems that this can be attributed to a theoretical prediction that the fundamental mode does not exist near the asphalt (or concrete) layer where seismic velocity increases extremely but many higher modes can be generated (Herrmann, 1999; Ryden, 1999). This may also be related to another phenomenon called the frequency gap (Jones, 1997). These associations, however, need to be based on further studies carried on several more pavement sites. With the theoretical aspect and the experimental observation made from this study, it is highly possible that the phase velocity calculation by the conventional two-receiver method should yield the values for the higher modes for this high (or even higher) frequency range. However, as theory tells that all the modes should converge asymptotically in their dispersion pattern as frequency becomes very high (e.g., > 5 kHz), the calculated values may not deviate significantly. There is no doubt that a more detailed and reliable analysis of this phenomenon requires a seismic survey with a frequency range (> 2000 Hz) beyond that investigated in this study. This sets the limitation with this traditional seismic method using geophones.

Although the first-arrival event observed on the horizontal (longitudinal and transverse) records was interpreted as direct P-wave arrivals, its more accurate nature is not yet clear. It could be a guided P-wave event trapped inside the uppermost layer(s) or be a combination of direct and guided P-wave arrivals. However, if it were the guided-wave event, then it is not clear why it is missing on the vertical record. Also, reflection from the interface between base and subgrade might have interfered with the aforementioned arrivals. Again, for a more accurate analysis of these body-wave events it is inevitable that you will move beyond the limitation with the traditional method.

During the tomographic inversion of the refraction event observed on the vertical records, existence of the asphalt layer was ignored because the algorithm was based upon the calculation of only the first arrivals (Stork and Clayton, 1991). Considering the exceedingly fast P-wave velocity and the thinness (< 0.5 ft) of the asphalt layer, the ignorance may not have affected the inversion result of the *Vp* profile significantly. However, it seems that the severe ray bending at the bottom of the asphalt layer due to the excessive velocity contrast should have been accounted for during the calculation of offset-dependent arrival times.

In addition to the complexity in pattern of both surface- and body-wave events, there are other factors that may need to be accounted for during the acquisition and processing. For example, surface-wave velocity (and also V_p) in the asphalt material changes with temperature by a noticeable degree (Figure 9) (Ryden, 1999; Olson, 1998). It is also known that the V_p may change with frequency by a measurable amount. There are a lot more features and issues to be addressed and discussed than those covered in this abstract. We decide, however, to put it off until we come up with a data set that contains seismic events in a few tens of kilohertz range. Until then, all the attempts to explain these unfamiliar seismic features would involve excessive speculations. We anticipate that a prototype of such an acquisition system being currently developed at the geotechnical department of Lund University, Lund, Sweden, will be ready within next several months.

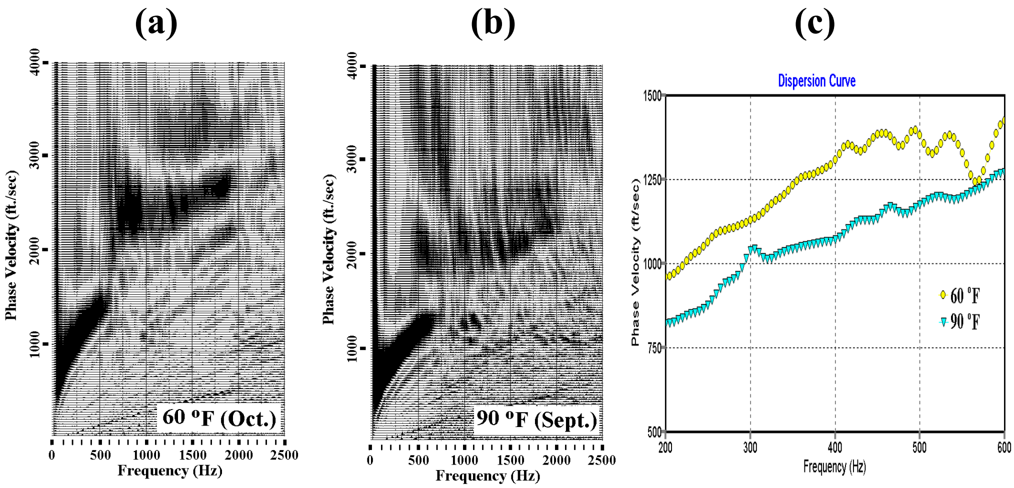

Figure 9. Dispersion curve images of vertical records obtained under different temperatures; (a) 60, and (b) 90 degrees in Fahrenheit. Picked dispersion curves are shown in (c). This variation in phase velocity with temperature was caused by the temperature-dependent elastic property of the asphalt material.

Conclusions

Higher modes of surface waves dominate at the shallowest depth range comparable to asphalt (or concrete) and base layers. Calculation of phase velocities of the surface waves penetrating this superficial part of a pavement system should yield values of the higher modes, not the fundamental mode. The deviation may not be unacceptably large as all the modes converge in their dispersion pattern at this short wavelength. It turns out that multi-component recording can be very useful for a reliable identification of complicated seismic events in a pavement system.

Acknowledgments

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