HIGH FREQUENCY MASW FOR NON-DESTRUCTIVE TESTING OF PAVEMENTS—ACCELEROMETER APPROACH

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Abstract

The dispersive nature of surface waves in pavement systems is imaged through a multichannel approach using one accelerometer as receiver and multiple shot points. The image obtained from a wavefield transformation method shows multimodal dispersion curves up to 10 kHz.

We present results from a simplified MASW data acquisition method applied to a pavement surface. The method can simulate an arbitrary number of channels. The sensor separation can be chosen arbitrarily small. In these experiments, the upper frequency limit is 10 kHz, which can be increased by the exchange of one sensor. The method is tested by one manual and one automated procedure. Both rely on source-receiver reciprocity. The automated procedure is regarded as necessary when a large number of channels is combined with a small sensor separation. The manual method will not provide the necessary accuracy and endurance for that kind of measurement, but is promising for less complicated setups. We present recommendations for high frequency measurements on pavements.

In the subsequent data processing, we follow the procedure of multichannel analysis of surface waves - MASW. It has recently been developed as a geophysical method for near-surface investigation. We demonstrate that the MASW technique can identify detailed aspects of the high frequency total wave-field of both surface and body-wave events.

Results of dispersion curve extraction indicate that higher modes of surface waves are dominating at depths associated with the transition between the asphalt and the base layer. However, the deviation from the fundamental mode is not large because all modes are converging in an asymptotic manner with increasing frequency.

The study indicates that the MASW method is a fast and cost efficient method for measuring pavement stiffness parameters.

Introduction

From a geotechnical point of view the objective of non-destructive testing (NDT) on pavements is to determine the Young’s modulus, E and Poisson’s ratio, ν for each layer in the construction. These material parameters together with the thickness of the layers are the main factors determining status and elastic response of the construction. The parameters can be used to calculate allowable loads and rehabilitation needs for existing pavement structures. Both laboratory and field tests are usually conducted to determine these parameters. Seismic methods have proved useful for field testing of pavements (Nazarian et al., 1999). Today, the seismic methods draw even more attention because of their potential in measuring accurately physical material properties. From the seismic velocity, the modulus can be calculated without any empirical relations. This is an essential step in order to move towards analytical pavement design and performance based specifications. There are several seismic NDT methods available for testing of pavements. However, the main concepts of these “traditional” methods are not based on the multichannel recording concept that utilizes pattern-recognition techniques, since long adopted in geophysical seismic surveys.

Recent studies indicate that the seismic phenomena associated with the pavement system are more complicated than normally assumed. Body waves (direct, guided, refracted, and reflected) and higher mode surface waves may interfere with the fundamental mode surface wave (Stokoe et al., 1994; Herrmann, 2000). For example, fluctuations in the surface wave dispersion curve have been explained as effects from reflected body waves (Sheu et al., 1988). To study these phenomena further a larger part of the wavefield than normally utilized must be acquired and processed. This implies high frequency multichannel data acquisition.

High Frequency Data Acquisition

In this section, critical data acquisition parameters associated with high frequency measurements on asphalt or concrete are discussed. The high frequency acquisition system described here is similar to a reflection seismic survey setup. It consists of a seismic source, receiver(s) and a recording device.

To record high frequency multichannel data on a pavement surface, a few practical issues have to be addressed. A multichannel seismograph can only be used with geophones that yield a strong electric signal. To record multichannel data with frequencies in the ultrasonic range, high frequency receivers (accelerometers) with a low electric charge signal have to be used. In addition, the sample rate has to be high to achieve the necessary resolution to resolve thin (<0.5 m) layers of a pavement system. The cost for a system with a large number of simultaneously acquired channels will be high. This is mainly due to the required fast simultaneous sampling of the channels which implies individual A/D converters and amplifiers for each channel. Practical problems associated with receiver attachment, calibration and spacing may occur. It might be necessary to have smaller spacing between the receivers than the actual size of each receiver. Because of these difficulties, a preliminary study has been initiated. The objective has been to record multichannel shot gathers with only one receiver. Either the source or the receiver can be moved manually or by a scanner device, relying on the principle of reciprocity, see Figure 1.

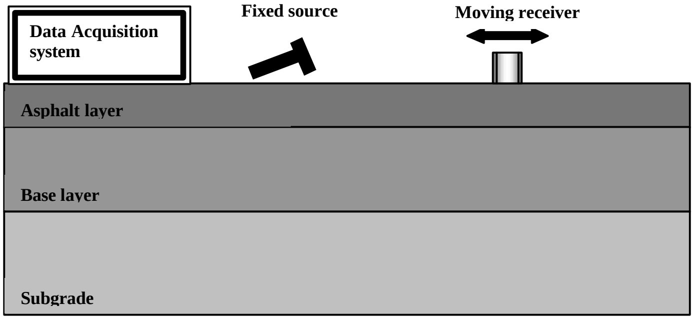


Figure 1. Schematic figure of field set up with fixed source and moving receiver.

Sources

The frequency content, from an impulse source striking a specific material, usually changes with mass and area of the striking element. These are controllable parameters although a more dominating factor usually is the elasticity of the medium near the impact point. An impact source with less mass and a smaller area is expected to generate higher frequencies (Keiswetter and Steeples, 1995).

In this study, impact sources have been used. Several differently sized hammers and three electromechanical devices have been used as impulse sources. The electromechanical sources have been controlled from an external power supply with adjustable power and time window. The objective with the source study has been to optimize frequency content, bandwidth, energy and repeatability. The electromechanical sources showed best repeatability, but currently provides too little energy. A small (0.5 kg) rounded head hammer showed best field performance.

Receivers

Accelerometers were used as high frequency receivers. In contrast to the geophone, the accelerometer has a piezoelectric element that responds with an electric charge variation when it is dynamically loaded by the seismic mass under an external influence of vibration. The practical upper frequency limit for an accelerometer is the resonance frequency. In this test, the denomination of the different accelerometers is their specified natural resonance frequencies.

The accelerometer attachment, the coupling, is critical for the measured bandwidth. If the accelerometer is poorly attached to the structure this introduces an additional compliance between the base and the structure (Mark and Torben, 1986). The lower practical limit of the base/coupling/accelerometer system will hereby be lower than the natural frequency of the accelerometer itself. Hence, the coupling behaves as a low-pass mechanical filter, see Figure 2.

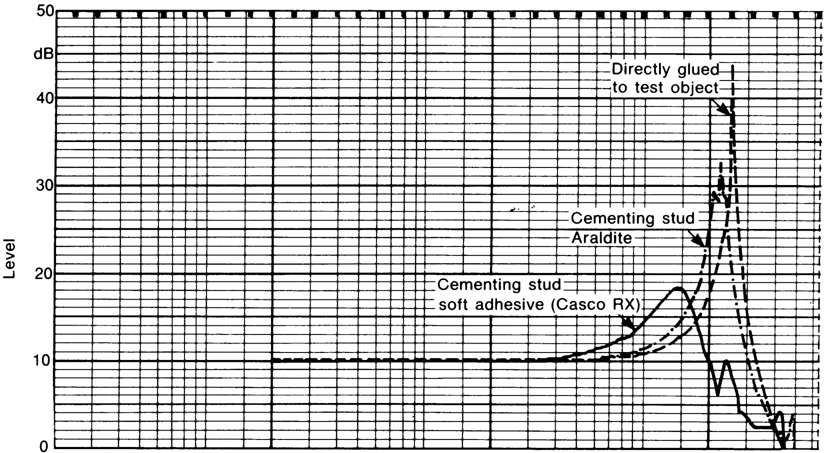


Figure 2. **Typical frequency responses of an accelerometer attached with different methods (Mark and Torben, 1986).**

Accelerometers with natural resonance frequencies of 30 and 54 kHz, respectively, have been studied. The objective was to study coupling resonance frequency and sensitivity of the attached accelerometer. The coupling proved to be a critical parameter and therefore this topic was studied closely. The tested attachment methods were glue, grease, threaded stud, and applied force by weight and air-pressure. Sticky grease or glue showed best result in this test. Both methods tend to fill in the rough surface of a pavement and increase the contact coupling area. Typically, the 54 kHz accelerometer showed higher linear frequency response but less amplitude sensitivity. The 30 kHz accelerometer attached with grease performed best in the field.

Data Recording

To achieve the high sample rate and high dynamic range required in this study, an HP35665A Dynamic Signal Analyzer (DSA) has been used as recording device rather than a seismograph. The DSA was limited to 2048 samples per trace. The maximum sample rate for one channel data acquisition was 250 kSa/s.

A prerequisite to be able to record multichannel shot gathers with only one receiver is an accurate trigger. Two main trigger alternatives were tested, an accelerometer attached to the impact device and electrical contact closure on impact. So far, the accelerometer has been found to be superior, and has consequently been used in most tests.

Computerized scanner system

In order to speed up the acquisition of multichannel records and to overcome random errors by a human operator, a scanner system was designed. The scanner system was made from three main components: the DSA above, operating as a controller running instrument Basic, the linear scanner bar with servo motor and control unit, and the electromechanical impact source with its power supply, see Figure 3. Using the scanner, the measurement process could be automated and syncronized to the analyzer measurements.

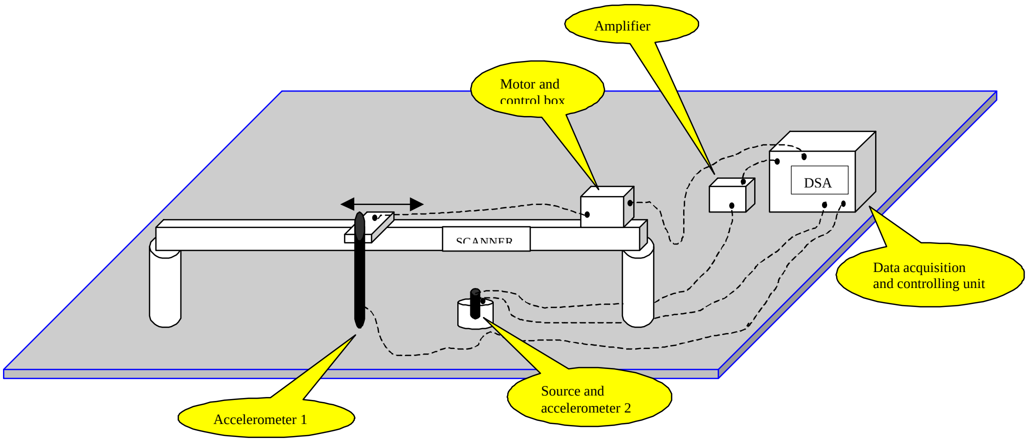
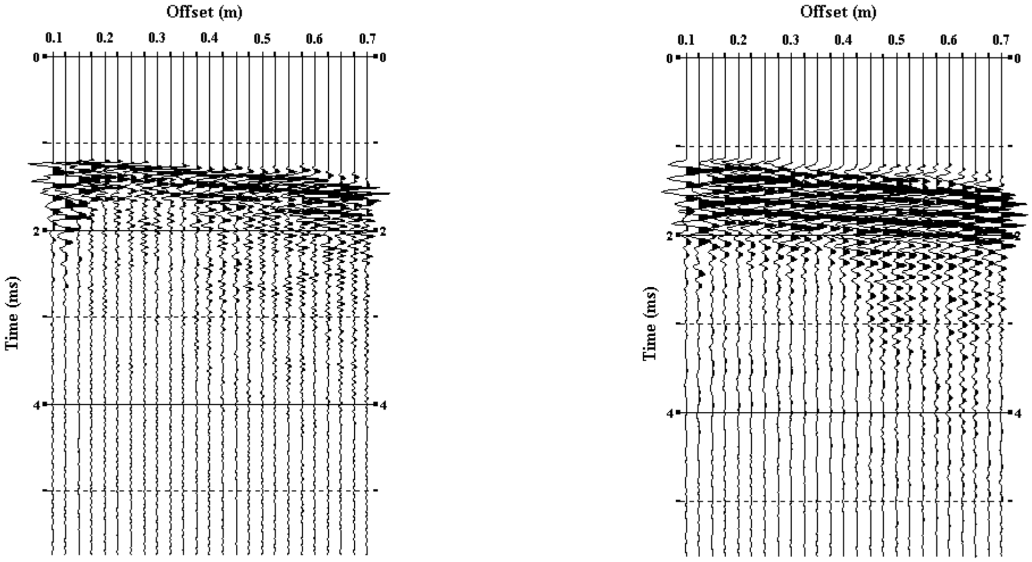


Figure 3. **Schematic figure of the scanner system.**

The available electromechanical sources performed well on a concrete slab inside a laboratory hall at LTH, the Lund Institute of Technology. Outdoors, on a pavement surface, these sources proved to be too weak to overcome the strong attenuation in the asphalt material in a noisy environment. Therefore, for field experiments, the manual approach had to be used together with the small hammer. However, the scanner approach shows great potential for fast and automated data acquisition. With the high-resolution scanner, an arbitrary number of channels can be simulated, each with an arbitrarily small possible station separation. The accurately controlled system might also be critical for vertical stacking or coded impact sources to increase signal-to-noise ratio (S/N) (Park et al., 1996). Figure 4 shows a multichannel record automatically collected with the scanner system and one of the electromechanical impact sources.



(a) (b)

Figure 4. **Automatic simulation of a multichannel record using the scanner system. Data was recorded on a concrete slab with both vertical (a) and horizontal (b) accelerometers. The source (small, 0.1 kg, electromechanical source) has been moved from 100 mm to 700 mm offset in 25 mm increments. Both records show a first arrival event of 4100 m/s, which is a reasonable P-wave velocity of concrete.**

Multichannel Processing for Dispersion Curve Extraction

At the Kansas Geological Survey (KGS) a unique seismic method called multichannel analysis of surface waves (MASW) (Park et al., 1999), has been developed. The method utilizes multichannel shot gathers for detailed surface wave analysis. The shot gather is 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. The method does not make any assumption on the nature of any seismic event in association with its phase velocity, and therefore the construction of the frequency-phase velocity image is performed through an objective pattern-recognition technique. With this technique applied to pavements, energy distribution between different types of wave propagation can be closely studied. In addition, fundamental and higher mode dispersion curves from surface waves can be extracted. The multichannel approach provides a possibility to record the total wave field of both surface- and body-wave events.

Multichannel Records

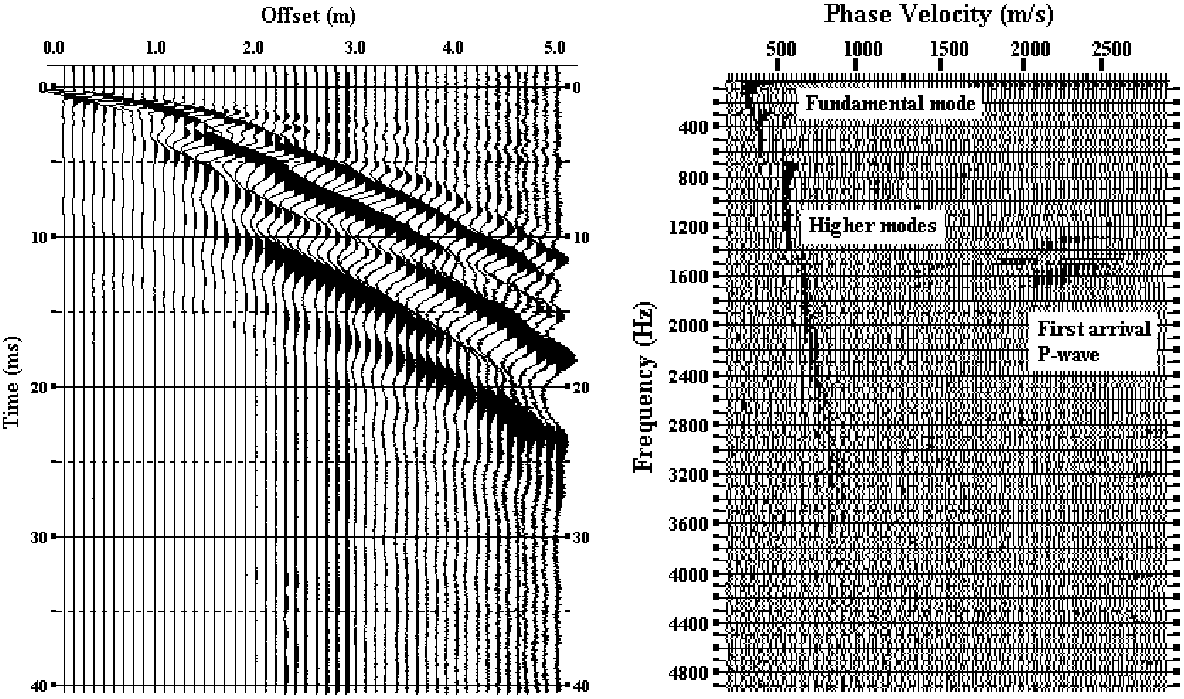
For evaluation purposes, two manual, one receiver/multiple source point records were acquired on two different pavement sites. The first measurement was made at a parking lot at Lund Institute of Technology, the LTH test site. At this site, the asphalt layer was thin and the base layer was not well defined in terms of thickness or material content. To study seismic events on a different pavement profile, a more recently constructed pavement was also tested, the PEAB test site. At this site, both thicknesses and materials for the different layers were well defined. Further, the pavement had not yet been opened for traffic, hence the top asphalt layer was in top condition without rutting or joints. The layering of the two pavement systems is presented in Table 1.

Table 1. The Layering of the pavement construction at the two test sites.

Layer	LTH test site	PEAB test site
Asphalt thickness (m)	~0.050	0.095
Base thickness (m)	~0.400	0.780
Subgrade material	clay till	clay till

At the LTH test site one 30 kHz accelerometer was attached vertically with grease at zero offset. The DSA was set to 62.5 ms record length and 33.3 kSa/s sample rate. A 0.5 kg hammer with a rounded metal head was used as impulse source. An accelerometer was attached to the hammer for triggering. While keeping the accelerometer fixed, and by changing the impact points of the source from offset 0.1 m to 5.0 m with 0.1 m impact interval, data were collected in a walkaway noise analysis format (Dobrin and Savit, 1988). The asphalt temperature was 10 degrees Celsius throughout the measurement.

The resulting multichannel record in *x-t* domain is presented in Figure 5a. At near offsets (0.1 to 1.0 m) high amplitude first arrivals are identified. Around 2.0 m offset the strong first arrivals are attenuated and eventually disappear, and the lower frequency surface waves start to dominate the seismic events. The first arrival velocity is 2400 m/s in the *x-t* domain. In Figure 5b, the record is transformed to frequency-phase velocity domain, by using the modified version (Park et al., 2000) of the MASW wave field transformation method (Park et al., 1998). The image shows three main frequency-phase branches. They are interpreted as being the fundamental mode surface wave dispersion curve for the lowest frequencies, and as the first and second higher mode dispersion curves associated with the higher frequencies. All three branches seem to converge in an asymptotic manner. This trend has been anticipated by theory (Jones, 1962), but has never been observed until now. The P-wave energy can also be identified in the image as the black spot around 1.5 kHz and 2400 m/s.

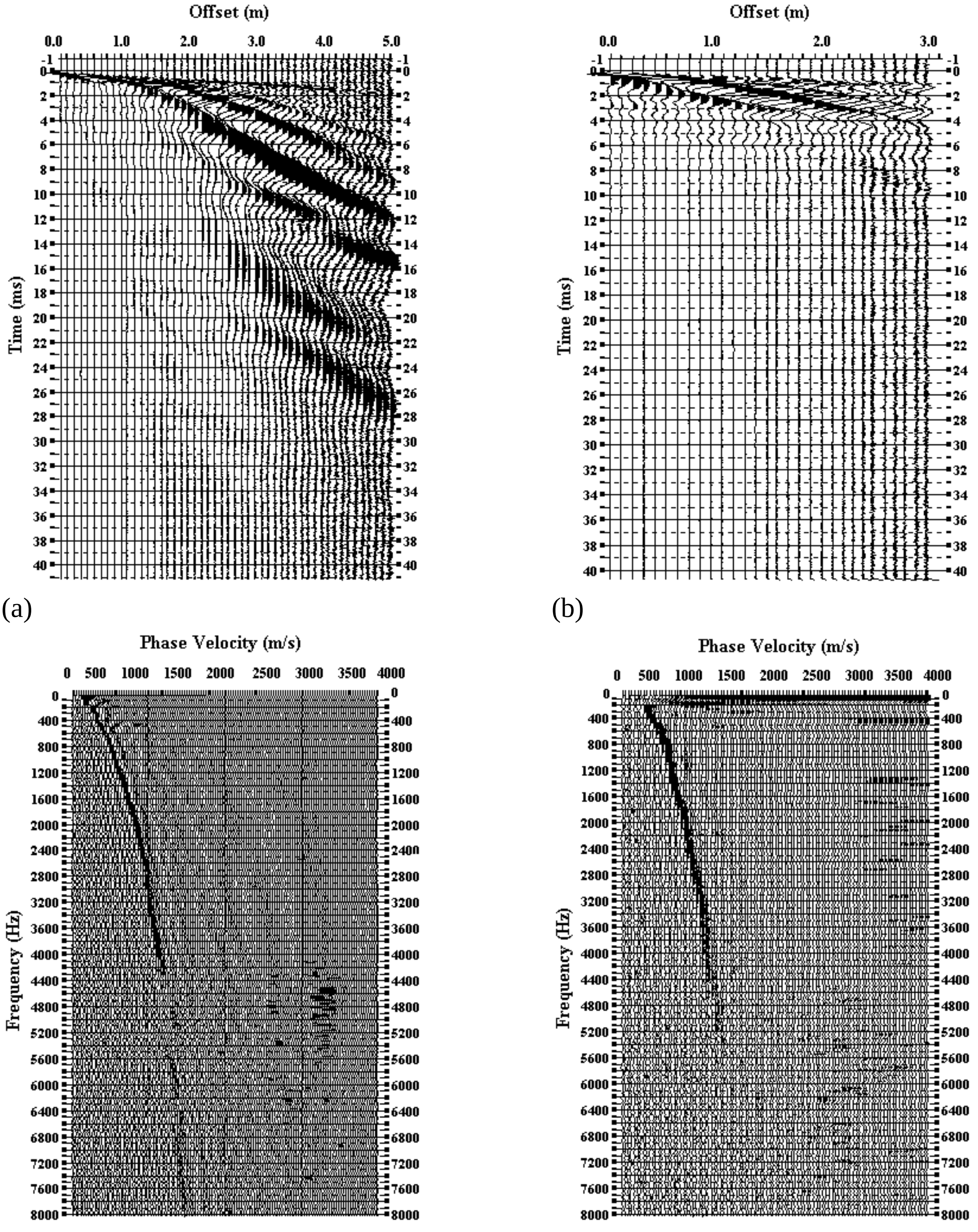


(a) (b)

Figure 5. **Multichannel record obtained by using a light (0.5 kg) hammer (a) and dispersion curve image (b) from the LTH test site.**

At the PEAB test site a 30 kHz accelerometer was used first vertically and then horizontally. The horizontal component was recorded in an attempt to verify the assumption that the first observed seismic event is a P-wave. All other data acquisition parameters were kept constant, and as in the measurement from the LTH test site. The temperature of the asphalt layer was 8 degrees Celsius during the measurement.

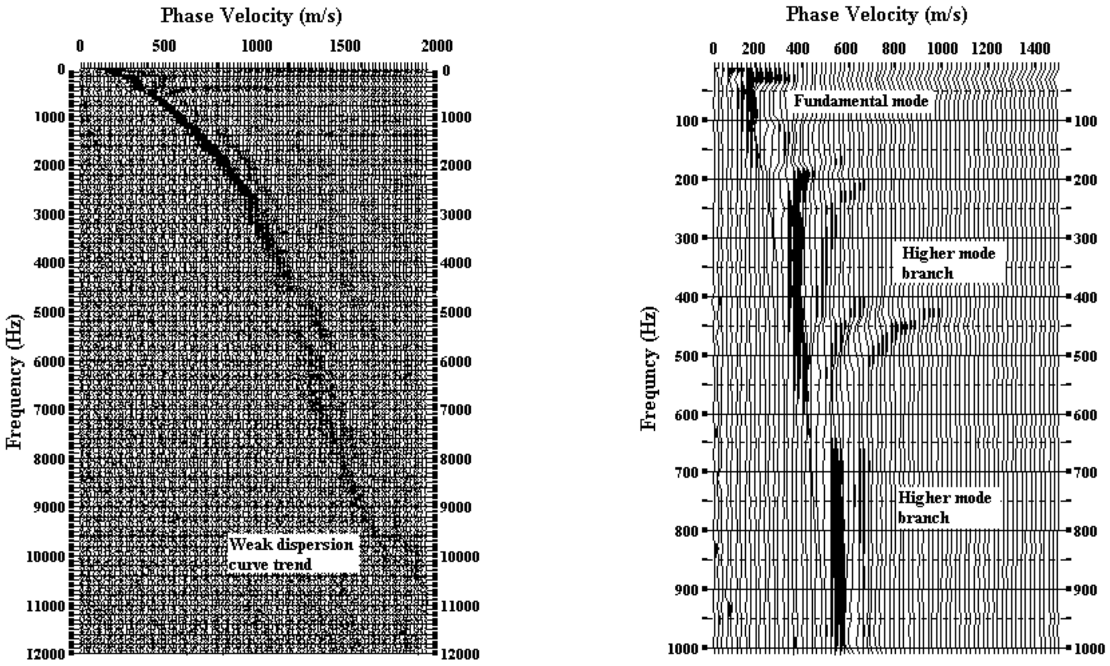
In Figure 6 both vertical and horizontal component records are displayed. Note that the horizontal record only extends to 3.0 m offset. This limitation was due to too low S/N ratio for longer offsets. At this site the first arrivals are slightly easier to identify and earlier compared to the LTH test site. In both the vertical and horizontal records, the interpreted first arrival velocity is 3200 m/s, which is higher than the velocity at the LTH test site (2400 m/s). The higher velocity is reasonable because of the thicker and newer asphalt at the PEAB test site. In Figure 6, corresponding phase velocity-frequency images are presented. A clear dispersion curve is present in both the vertical and horizontal component images. These results show similar trends as the dispersion curves from the LTH test site. The different modes are not as readily separated in the image from the PEAB test site as in the image from the LTH test site, Figure 5b. Figure 7b, shows a smaller frequency range of the same record. In this image, the different modes are more visible. In Figure 7a, a wider frequency range is plotted. The image shows a weak dispersion curve trend up to 10 kHz. The first arrival event identified in the shot gathers is also visible in the phase velocity image around 3200 m/s and 5 kHz, see Figure 6 (c).



(a) (b)

(c) (d)

Figure 6. **Multichannel record from vertical component (a), corresponding horizontal component (b), dispersion curve image from vertical component (c) and dispersion curve image from horizontal component (d). Data were collected at the PEAB test site.**



(a) (b)

Figure 7. **Dispersion curve image with a wide frequency range (a) and smaller frequency range (b) compared to Figure 6.**

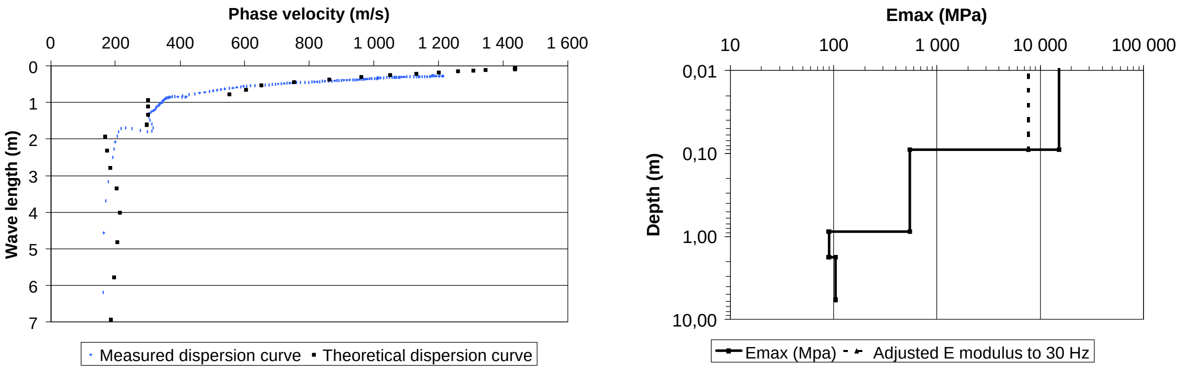
In order to illustrate how the dispersion curve images are converted to material parameters for pavement design, the E-modulus profile was calculated for the PEAB test site. In Figure 8a, the dispersion curve has been extracted from the maximums in the phase velocity image in Figure 6c. The dispersion curve is now presented in the velocity-wave length domain. The forward modeling software WinSASW (from the University of Texas at Austin) has been used to find a model with a matching theoretical dispersion curve. The matching model in terms of layer thicknesses, S-wave velocities, densities and Poisson's ratios, is presented in Table 2. By using the well known equations

$$G_{\max} = r v_s^2 \qquad (1)$$

$$E = 2G(1+n) \qquad (2)$$

where G = shear modulus,
r = density,
v_S = shear (S) - wave velocity,
E = Young's modulus, and
n = Poisson's ratio,

the E-modulus can be calculated from the model parameters. An E-modulus profile calculated in this way is shown in Figure 8b. The E-modulus for an asphalt layer is both temperature and frequency dependent (Daniel and Kim, 1998). The modulus presented here is therefore valid only for the in-situ temperature during the measurements (8°C). For comparison with, for example, the Falling Weight Deflectometer (FWD), the modulus has to be adjusted to a lower frequency. The dotted line in Figure 8b represents the adjusted asphalt modulus for 30 Hz. The modulus is reduced from 15 300 MPa to 7 600 MPa according to the temperature dependent adjustment factor presented by (Aouad, 1993).



(a) (b)

Figure 8. **The extracted dispersion curve from the PEAB test site with corresponding theoretical dispersion curve (a), and calculated E modulus-depth profile (b). The dotted line in (b) represents the asphalt modulus adjusted to a lower frequency level (30 Hz) according to (Aouad, 1993).**

Table 2. Model used in the calculated theoretical dispersion curve.

Thickness (m)	S-wave velocity (m/s)	Poisson's ratio	Density (t/m^3)
0.095	1537	0.35	2.40
0.780	330	0.35	2.10
0.900	130	0.40	1.90
4.000	140	0.40	1.90

Discussion

The main objective of this study was to describe critical data acquisition parameters for the pavement system and to investigate the main seismic events associated with this special case. Evaluation of Young's modulus is presented as an example of how to use the obtained results. To reach the full potential of the MASW method applied to pavement testing, and to achive acceptance among users, extensive comparisons with traditional field and laboratory methods are necessary.

This preliminary study suffers from some limitations in data acquisition. Higher sample rate, larger dynamic range and an improved S/N may possibly improve the measurements significantly. Once the stage of acquiring higher (>10 kHz) frequencies with higher S/N is reached not only surface-wave but also body-wave (e.g., reflection, refraction, guided waves, etc.) analysis using various schemes of the multichannel processing will provide additional key information such as thickness and P-wave velocity (V_p) of individual layers in the pavement system. At the Department of Geotechnology, Lund Institute of Technology, a specialized system for high frequency MASW is under development. This project is carried out as a cooperation between the Department and the Kansas Geological Survey (KGS).

In addition, the processing techniques may have to be refined for applications to pavement systems. Long offsets are critical for discriminating different modes of surface waves with a high resolution (Park et al., 1998). However, for a pavement system, the high frequencies are quickly attenuated, and the target depth is so shallow that excessive offsets are impractical. To overcome low S/N ratio during the measurements, vertical stacking or a coded impact technique (Park et al., 1996) might be necessary.

Conclusion

It is clear that a pavement system requires a unique data acquisition system and technique of operation. Receiver coupling, high frequency, high-energy source and fast data acquisition, are critical parameters for successful MASW on pavements. Results indicate that it might not be necessary to use a true multichannel recording system. A simple and cost effective approach with only one receiver has shown promising results. Acquisition of very-high-frequency seismic waves gives a better understanding of the seismic phenomena in a pavement system. In addition, both fundamental mode and higher mode dispersion curves can be accurately extracted as well as P-wave velocity (Vp) information of the uppermost layer. This will give more information from the seismic measurements and improve the resolution in the inversion models used to calculate shear wave velocity with depth profiles. This is a critical step in the proceeding towards a refined seismic NDT technique for pavements.

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References

1. Aouad M.F., 1993, Evaluation of Flexible Pavements and Subgrades Using the Spectral-Analysis-of-Surface-Waves (SASW) Method, Ph.D Dissertation, The University of Texas at Austin.
2. Daniel J.S., Kim Y.R., 1998, Relationships among rate dependent stiffness of asphalt concrete using laboratory and field test methods, Transportation Research Board, Paper no 980266, Washington DC.
3. Dobrin, M.B., and Savit, C.H., 1988, Introduction to geophysical prospecting, 4th ed.: McGraw-Hill, Inc., New York, 867 pp.
4. Herrmann R., 2000, SASW synthetics, retrieved on June 20, from World Wide Web: http://www.eas.slu.edu/People/RBHerrmann/NILS.
5. Jones R., 1962, Surface wave technique for measuring the elastic properties and thickness of roads: theoretical development, Brit. J. Appl. Phys., 13, pp 21-29.
6. Keiswetter, D., and Steeples, D., 1995, A field investigation of source parameters for the sledgehammer: Geophysics, 60, 1051-1057.
7. Mark S., Torben R., 1986, Piezoelectric Accelerometers and Vibration Preamplifiers, Bruel and Kjaer, Denmark.
8. Nazarian S., Yuan D., and Tandon V., 1999, Structural Field Testing of Flexible Pavement Layers with Seismic Methods for Quality Control, Transportation research record 1654, pp 50-60.
9. Park, C.B., Miller, R.D., and Xia, J., 2000, Multichannel analysis of surface-wave dispersion: Geophysics, in review.
10. Park, C.B., Miller, R.D., and Xia, J., 1999, Multichannel analysis of surface waves (MASW): Geophysics, 64, 800-808.
11. Park, C.B., Miller, R.D., and Xia, J., 1998, Imaging dispersion curves of surface waves on multi-channel record: Technical Program with biographies, SEG, 68th Annual Meeting, New Orleans, Louisiana, 1377-1380.
12. Park, C.B., Miller, R.D., Steeples, D., and Black, R., 1996, Swept impact seismic technique (SIST): Geophysics, 61, 1789-1803.
13. Sheu J.C., Stokoe K.H., and Roesset J.M., 1988, Effect of Reflected Waves in SASW Testing of Pavements, Transportation research record 1196, pp 51-61
14. Stokoe II, K.H., Wright, G.W., James, A.B., and Jose, M.R., 1994, Characterization of geotechnical sites by SASW method, in Geophysical characterization of sites, ISSMFE Technical Committee #10, edited by R.D. Woods, Oxford Publishers, New Delhi.