PORTABLE SEISMIC ACQUISTION SYSTEM (PSAS) FOR PAVEMENT MASW

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Abstract

A seismic method (e.g., surface- or body-wave method) has been often used in pavement engineering to evaluate such critical constructional parameters as the E-modulus and Poisson's ratio. Conventional method usually uses one or two-channel recording device (e.g., dynamic signal analyzer) for data acquisition whose cost is by no means trivial. In addition, recent applications with the multichannel approach have drastically improved the effectiveness of the seismic method in general and proven a greater potential of the method than ever. A true multichannel approach, however, would require a multichannel recording device (e.g., a 48-channel seismograph) and so-many accelerometers deployed simultaneously. The high-cost aspect of seismic method would make this otherwise-effective method excluded from consideration during the early stage of project planning. Instead, we propose a cheap, compact, and convenient seismic system that can be used with either conventional or multichannel approach. This Portable Seismic Acquisition System (PSAS) consists of a laptop computer, one or two accelerometers, and a hammer. A 16-bit PC-card (PCMCI bus) readily available nowadays is equipped into the computer as a data acquisition board. With this system, the multichannel measurement is simulated through repetitive generation of seismic waves along a linear survey line at different distances from the receiver fixed at a surface point. Data can be processed directly in the field on the same portable computer, only seconds after data acquisition. In combination with the robust dispersion curve analysis by the multichannel approach, this system creates new possibilities for seismic non-destructive testing (NDT) of pavements with on site evaluation. Data acquisition flow chart, signal conditioning, triggering, and other key features of the system are explained. We also present a case of evaluating pavement concrete thickness, E-modulus, and Poisson's ratio directly in the field using the proposed system.

Introduction

Non-destructive testing (NDT) of civil engineering structures is useful in maintenance of old constructions and verification of material properties in new constructions. The determination of thickness and stiffness of concrete and asphalt layers are typical objectives. Seismic techniques are favored in determining *in situ* stiffness properties of materials (Stokoe and Santamarina, 2000). The most widespread of these techniques are Spectral Analysis of Surface Waves (SASW) (Stokoe et al., 1994; Nazarian et al., 1999) and Impact Echo (IE). These techniques are routinely used and have proved useful in several fields of application.

In reflection seismic surveys, multichannel data acquisition and processing techniques are used. The main advantage with the multichannel approach is that different seismic events can be correctly identified and then handled properly (Yilmaz, 1987). This is critical for an object with complex wave propagation. In construction-NDT there is a requirement for fast, flexible and economically efficient measurements with much higher spatial and temporal frequencies, which makes the hardware configuration normally used for ordinary multichannel approach impractical and expensive.

The objective with the system presented herein, is to preserve the advantages gained by multichannel method while reducing the complexity and cost of the data acquisition system. It was designed to be fast enough for on-site data evaluation and still cheap enough to be used in smaller project applications. The data processing is based on Multichannel Analysis of Surface Waves (MASW) (Park et al., 1999) and the data acquisition on Multichannel Simulation with One Receiver (MSOR) (Ryden et al., 2001). In this paper we describe the hardware configuration used and we discuss some critical data acquisition parameters. We also present a case study where the thickness, dynamic Elastic modulus (E) and Poisson's ratio (ν) of a concrete pavement are measured and evaluated directly in the field.

Data Acquisition Method

In the MSOR data acquisition method a multichannel record is obtained with only one receiver. It is fixed at a surface point and receives signals from several hammer impacts at incremental offsets (Ryden et al., 2001). The measuring technique relies on the principle of source and receiver reciprocity. If the data acquisition can be triggered correctly with respect to the hammer impact, all recorded signals can be combined to a multichannel record for velocity calculations. A schematic description of the field set-up is shown in Figure 1.

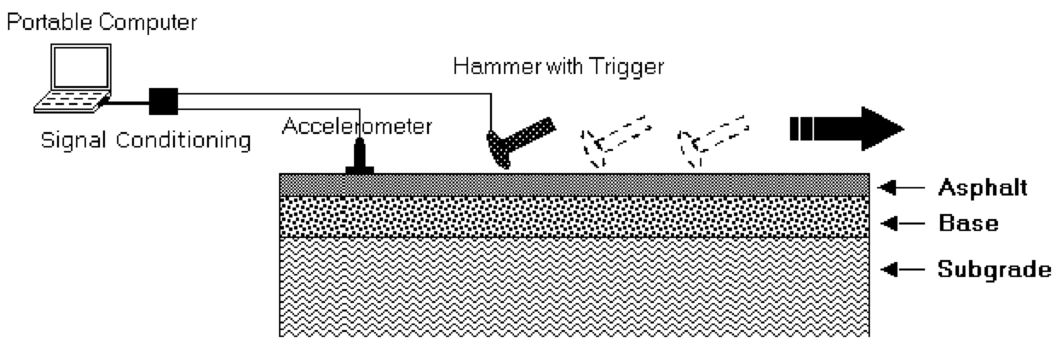

Figure 1. Schematic description of field set-up in the MSOR data acquisition method (Ryden et al., 2002a).

Required Performance of the Data Acquisition System

To resolve properties of the uppermost part of pavement and concrete structures, traditional multichannel seismic equipment cannot be used. For example, it is necessary to generate and record seismic waves of much higher frequencies (>10 kHz) and smaller (<0.05 m) spatial intervals than in reflection seismic surveys. In addition, a true high frequency multichannel system with more than 30 channels will have both practical and economical disadvantages.

In order to perform fast, cost effective measurements the process should be automated to the highest possible degree. That calls for a laptop-based data acquisition-, storage-, conversion-, and processing system. The following paragraphs deals with the required performance of such a system, especially designed for effective MSOR measurements on asphalt or concrete.

Sample Rate and Dynamic Range

Dynamic range is the ratio between the maximum and minimum amplitude level that can be accurately resolved by the recording device (Sheriff, 1991). Due to material damping and geometrical spreading the amplitude of seismic waves drops rapidly with offsets. In addition, surface waves are so strong that they would dominate over all types of body waves. Therefore, a high dynamic range (e.g., 24 bit) has been a critical requirement for the traditional seismic survey for near-surface investigation (Steeples and Miller, 1990) that targets recording of body waves (e.g., reflection) over a wide offset range (e.g., > 100 m). For the pavement applications, however, the strong surface waves are the primary signal and therefore a relatively low (e.g., 16 bit) dynamic range is acceptable. Instead, scale of the survey in the pavement case is micro in comparison to that for the near-surface investigation, indicating the seismic wavelengths be in the micro scale also. In addition, seismic velocities of the pavement material are much faster than in the normal near-surface materials. This combination of the spatial scale and the seismic velocity requires the very-high-frequency (e.g., 30 kHz) seismic waves to be used. In Analog to Digital-A/D conversion there is a trade-off between dynamic range and sample rate; the higher the sampling rate, the lower the dynamic range available. Therefore, an A/D converter with higher sample rate but less dynamic range could be chosen. In Figure 2, the geometrical spreading of seismic waves is illustrated together with the limits of typicall PC-Card (PCMCIA bus) A/D converters under a constant gain level (as of today, 2001). The initial amplitude level at the closest offset is set to a fully saturated 16-bit positive amplitude conversion value. With the assumed noise level (3-bit), in Figure 2, it can be seen that a 16 bit dynamic range gives a sufficient signal to noise (S/N) ratio at 3 m offset.

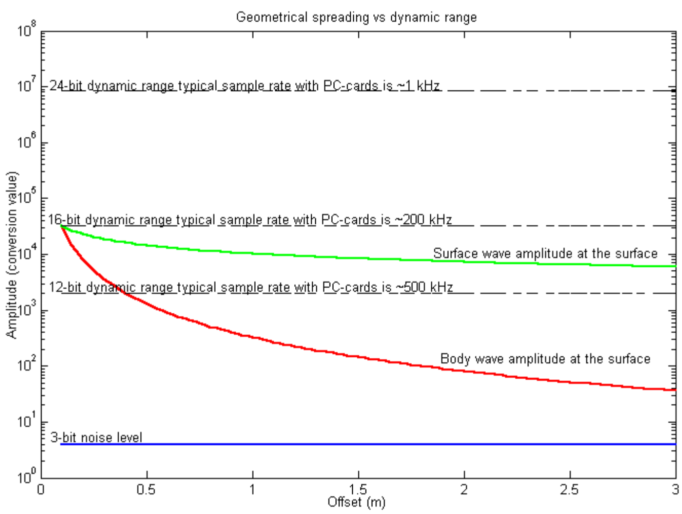

Figure 2. Required dynamic range of A/D conversion with a short survey line length, and a constant gain. The attenuation of seismic waves is calculated from geometrical spreading only. The approximate sample rate at each level of the dynamic range is a typical value for PC-cards (PCMCIA bus) data acquisition cards in 2001.

Source and Receiver Characteristics

The main factor affecting the generated frequency content after an impact is usually the elastic properties of the media. In pavement surveys however, this is a given factor that leaves the source with the only controllable parameters. A high-frequency, broad-band source is necessary to resolve the uppermost properties of the pavement system. An impact source with low mass and small area of impact is expected to generate higher frequencies (Keiswetter and Steeples, 1995) than a large, heavy hammer.

To record the generated high frequencies a high frequency receiver is necessary. Piezo-electric accelerometers are usually used for high frequency measurements. Small accelerometers are available for measurements up to 50 kHz. However there is a trade-off between sensitivity and natural resonance frequency. Large and heavy accelerometers are more sensitive but have a lower natural resonance frequency. 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 frequency limit of the base/coupling/accelerometer system will thereby be lower than the natural frequency of the accelerometer itself. The coupling, then, behaves as a low-pass mechanical filter.

Our experience is that accelerometers for MSOR can be used at a larger frequency range than in measurements of acceleration, i.e. beyond there natural resonance frequency. This is because the level of the signal is not critical, just the relative phase at different offsets.

Triggering

The trigger accuracy is the most important requirement for successful MSOR measurements (Park et al., 2002). Data acquisition from each stroke by the hammer must be synchronized at every impact to the moment of wave generation. With an impact sensor mounted on the hammer there are two main alternatives for a precise trigger system:

1. The impact signal from the hammer could be recorded with pre-triggering. This alternative requires a two channel recording device with an A/D converter running constantly and always keeping the latest samples in a buffer. When the signal from the impact sensor reaches a defined value, the specified number of samples before and after the trigger condition are recorded. After data acquisition all recorded traces can be time shifted and aligned according to the peak amplitude from the hammer signals or any other calculated event. Because both signals are digitized before triggering the trigger accuracy cannot be better than plus minus one sample interval. It may be cumbersome to shift the signals in steps less than one sample.
2. The alternative is to have an analog trigger system that starts data acquisition when the analog signal from the hammer reaches a specified level. This is usually done with a high bandwidth comparator circuit that gives the PC-card a binary logical condition (TTL) signal when the input signal reaches the specified level. Comparator circuits are available with response within a few nanoseconds. The A/D starts conversion when the comparator generates the "go" signal. With this alternative the trigger accuracy can be better than plus minus one sample interval, provided that the impact sensor signal reaches the pre-set level within less than one sample interval.

Hardware Configuration Used in the Data Acquisition System

The recording device used in this study is termed the Portable Seismic Acquisition System (PSAS). It consists of a portable computer equipped with a PC-card, source, receiver and external signal conditioning. A schematic description of hardware components and data flow is presented in Figure 3. With the PSAS system the MSOR method is implemented efficiently, because data are streamed directly to the computer and all impacts can be generated with intervals only fractions of a second apart. For example, a 40-trace record (Figure 4a) was acquired in five minutes. The PSAS system was developed at the Department of Geotechnology, Lund University, and is further described below.

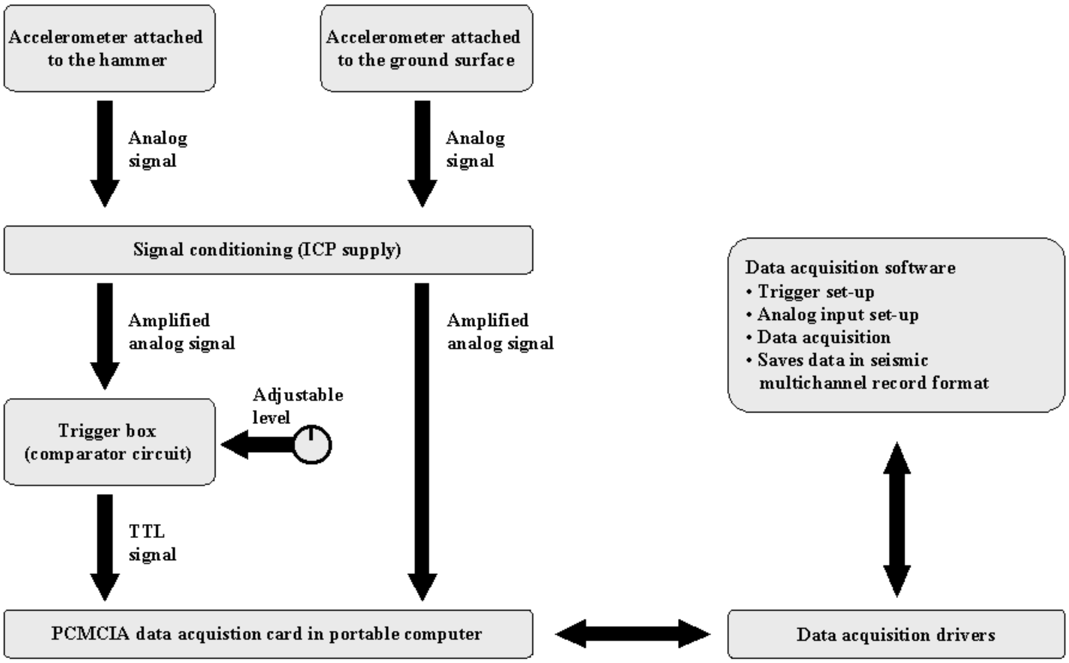

Figure 3. PSAS data acquisition flow-chart with hardware and software components.

Signal Conditioning

Before the signal reaches the A/D converter inside the PC-card, signal conditioning is required. When using accelerometers there are basically two different alternatives. Using a high impedance accelerometer in combination with a charge amplifier or an active low impedance accelerometer. Low impedance accelerometers have a built-in amplifier that needs to be externally powered.

In this system a low impedance integrated circuit piezoelectric (ICP®) accelerometer with a natural resonance frequency of 30 kHz has been used. ICP accelerometers are especially convenient for computer based data acquisition because some data acquisition cards have a built in ICP® supply, e.g. the 2-channel simultaneously sampling 14 bit, 300 kSa/s INES DAQi148, with pre-trig.

The risk of aliasing should be considered. It the frequencies of interest are less than half the sample rate this will take place and corrupt the recorded signals. For a system with much greater bandwidth than the highest occurring frequencies, there is no need for a steep, low-pass, anti-aliasing filter.

PC-card

Today most portable computers have slots for PC-cards (PCMCIA bus). In the last couple of years multifunction data acquisition cards, with sufficient dynamic range and sample rate for seismic NDT of asphalt and concrete structures, has become available. Compared to multi-channel engineering instruments or seismographs these cards are cheap (<$1000), in 2001.

In the system presented herein a PC-card from Measurement Computing™ has been used (PC-CARD-DAS-16/16-AO). This card has a single channel sample rate of 200 kSa/s with a 16-bit dynamic range. From Figure 2 it can be seen that this dynamic range is enough for MSOR measurements without any need to change the gain level. This means that there is no need for additional offset or time dependent amplification of the signal.

Data acquisition can be controlled from a wide range of computer languages. In the system described herein *LabView®* was chosen. A basic MSOR program consists of a loop with trigger set-up, data recording and data presentation for quality control. After the last impact offset is recorded, all individual traces are saved in the Kansas Geological Survey (KGS) seismic data format (SurfSeis manual, 2001) ready to be imported in the *SurfSeis©* (2001) software, especially made for MASW data processing.

Trigger Configuration

To meet the requirements for trigger accuracy in MSOR measurements a fast (5 nano-seconds accuracy) comparator circuit was chosen for the trigger system. This circuit delivers a digital signal for the trigger input channel on the PC-card. The threshold level where the trigger condition should occur, can be manually adjusted with a potentiometer. It should be noticed that this level is very critical for the trigger accuracy and may have to be fine adjusted between measurements. An impact sensor (accelerometer) is mounted on the back of the hammer to generate the trigger signal for the comparator circuit. The accelerometer used here should preferably be a high frequency shock accelerometer.

Another factor motivating this trigger configuration is that only one channel A/D conversion is necessary. As described in the previous paragraph the other alternative requires a two channel recording device and a post-processing algorithm where all traces are shifted to time zero. With the chosen trigger technique used herein there is no need for any trigger post processing (aligning).

Case Study

The presented PSAS data acquisition system was tested at the I-70 highway between Kansas City and Denver. At the specific site a completely new concrete pavement was constructed. The tested section had not yet been opened for traffic. MSOR measurements were conducted with the objective to evaluate the dynamic E-modulus, ν, and thickness of the concrete layer. In the field the true thickness of the concrete was measured to be 0.330 m. The upper base layer was stabilized with cement.

Layout

By following the MSOR method one accelerometer was located at zero offset. The PSAS was set to 200 kSa/s sample rate. While keeping the accelerometer in a fixed spot on the pavement surface, and by incrementing the distance of the impact points from 0.05 m to 2.0 m with 0.05 m separation, data were collected in a walkaway noise analysis format (Dobrin and Savit, 1988) with 40 ms recording time per impact.

Results

The resulting combined or simulated multichannel record, hereafter called the multichannel record, is presented in Figure 4a in offset-time domain. The main wave fronts seen in Figure 4a are low frequency (about 1 kHz) surface waves. In Figure 4b the record is transformed to the frequency-phase velocity domain by using the most current version of the MASW wavefield transformation method (Park et al. 1998; 2000). The transformed image shows how the total seismic energy is distributed between different frequencies and phase velocities. The image of the processed data is actually three-dimensional and the black areas are energy peaks where a maximum can be extracted. The image in Figure 4b shows inverse velocity dispersion up to 32 kHz. The phase velocity is reaching 2200 m/s at frequencies above 7 kHz.

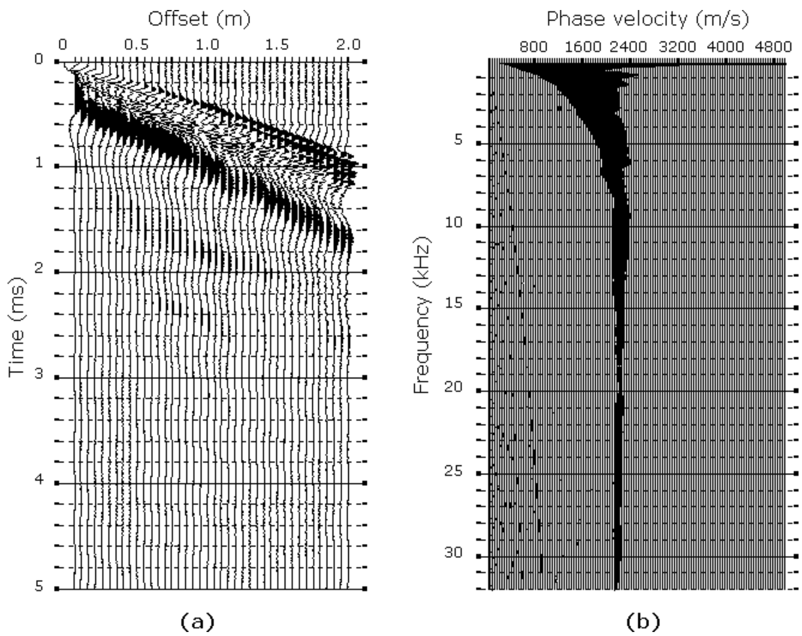

Figure 4. Combined multichannel record (a) in offset time domain. In (b) the time domain record is transformed to phase velocity-frequency domain by using the most current MASW transformation method (Park et al. 1998; 2000). The surface wave dispersion curve is visible as the black curve in (b). The phase velocity is reaching 2200 m/s at frequencies above 7 kHz.

In Figure 5a, the record is showed from 0 to 1.0 ms. The gain is increased so that the weak vertical component of the first arrival wave front is more visible. The linear first arrival velocity can be manually evaluated directly in this image. However a more robust and precise technique based on the semblance concept (Neidell and Taner, 1971) is to objectively analyze best fitting slope, see (b). In the automatic analysis, the best fitting linear velocity is 4140 m/s, this is interpreted as the compression wave V_P velocity of the concrete layer.

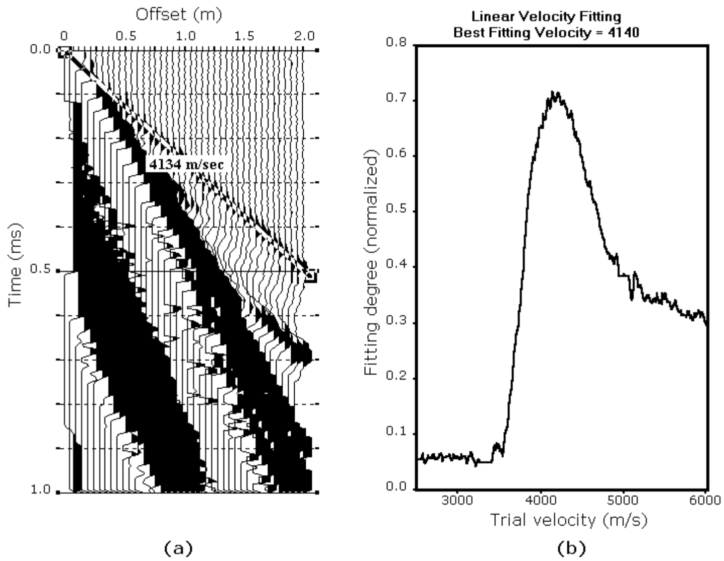

Figure 5. Multichannel record zoomed in on the first arrival, P-wave (a). The best fitting linear velocity (Neidell and Taner, 1971) is 4140 m/s as shown in (b).

From simply observing the fastest surface wave V_R- and V_P-velocity the dynamic E-modulus and Poisson's ratio (ν) of the concrete layer can be calculated from the equations below. The bulk density is assumed to be 2400 kg/m^3. To calculate ν from the V_R and V_P, equation (1) (Nazarian et al., 1999), and (2) are used.

$$V_S = V_R(1.13 - 0.16\upsilon) \tag{1}$$

$$\upsilon = \frac{0.5\alpha^2 - 1}{\alpha^2 - 1} \tag{2}$$

where $\alpha = (V_P/V_S)$. From density (ρ) and the shear wave velocity (V_S), the dynamic shear modulus G can be determined by using

$$G = \rho V_S^2 \tag{3}$$

From G and ν the dynamic E modulus can be determined through

$$E = 2(1+\upsilon)G \tag{4}$$

By using these equations the E-modulus is calculated to 34.0 GPa and ν to 0.22. These equations are all linked through elastic theory (Sheriff and Geldart, 1982). To fully describe an isotropic linear elastic material only two individual material constants are required. Usually these constants are the E-modulus and ν. However, these constants could also be V_P and V_S velocity.

From the SASW test it is known that the wavelength where the highest phase velocities start to drop off in the dispersion curve usually correlates with the thickness of the high velocity top layer (Aouad, 1993). From the cut-off frequency, 7 kHz (Figure 4b), the corresponding wavelength (λ) is 0.314 m, as calculated from

$$\lambda = \frac{V}{f} \tag{5}$$

This thickness is within 5% of the measured true thickness 0.330 m.

Discussion

The presented PSAS system has shown promising results for NDT of concrete pavements. Single sections can be evaluated directly in the field within a couple of minutes. The method also has the potential for complete 2D profiling along the pavement. This will however require an automated system, which is a future possibility.

In the case study presented only the top concrete layer has been evaluated. However, more information about the pavement construction can be obtained from the recorded multi-channel record (Ryden et al., 2002b).

Conclusion

The nature of the MSOR data acquisition technique in combination with the robust MASW data processing method is efficient for a computer based portable seismic acquisition system, PSAS. The PSAS has a much lower cost and less complexity than traditional instruments used for seismic surveys of civil engineering structures. In the presented case study, the dynamic E-modulus, ν, and thickness of a concrete pavement layer could be evaluated directly in the field within a couple of minutes.

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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. Dobrin, M.B., and Savit, C.H., 1988, Introduction to geophysical prospecting, 4th ed.: McGraw-Hill, Inc., New York, 867 pp.
3. Keiswetter, D., and Steeples, D., 1995, A field investigation of source parameters for the sledgehammer: *Geophysics*, 60, 1051-1057.
4. Mark S., and Torben R., 1986, *Piezoelectric Accelerometers and Vibration Preamplifiers*, Bruel and Kjaer, Denmark.
5. Nazarian, S., Yuan, D., and Tandon V., 1999, Structural Field Testing of Flexible Pavement Layers with Seismic Methods for Quality Control, Transp. Res. Rec., 1654, 50-60.
6. Neidell, N.S., and Taner, M.T., 1971, Semblance and other coherency measures for multichannel data: *Geophysics*, 34, 482-497.
7. Park, C.B., Ryden, N., Miller, R.D., and Ulriksen, P., 2002, Time break correction in multi-channel simulation with one receiver (MSOR), Proceedings of the SAGEEP 2002, Las Vegas, NV, February 10-14, 2002.
8. Park, C.B., Miller, R.D., and Xia, J., 2000, Multichannel analysis of surface-wave dispersion: *Geophysics*, in review
9. Park, C.B., Miller, R.D., and Xia, J., 1999, Multichannel analysis of surface waves (MASW): *Geophysics*, 64, 800-808.
10. 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.
11. Ryden, N., Ulriksen, P., Ekdahl, U., Park, C.B., and Miller, R.D., 2002a, Multichannel analysis of seismic waves for layer moduli evaluation of pavements: submitted to the 6th International Conference on the Bearing Capacity of Roads, Railways and Airfields, 24-26 June, Lisboa, Portugal.
12. Ryden, N., Ulriksen, P., Park, C.B., and Miller R.D., 2002b, Branching of dispersion curve in surface wave testing of pavements: Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP 2002), Las Vegas, NV, February 10-14, 2002.
13. Ryden, N., Ulriksen, P., Park, C.B., Miller, R.D., Xia, J., and Ivanov, J., 2001, High frequency MASW for non-destructive testing of pavements-accelerometer approach. Proceedings of the SAGEEP 2001, Denver, Colorado, RBA-5.
14. Sheriff R.E., 1991 *Encyclopedic dictonary of exploration geophysics*, 3rd edition, Society of Exploration Geophysicists, ISBN 1-56080-018-6.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.
15. Sheriff, R.E. and Geldart, L.P., 1982. *Exploration seismology*, volume 1: Cambridge University Press.
16. Steeples, D.W. and Miller, R.D., 1990, Seismic reflection methods applied to engineering, environmental, and groundwater problems, in Geotechnical and environmental geophysics (Investigations in geophysics no. 5), Society of Exploration Geophysicists, Tulsa, Oklahoma, 300 pp.
17. SurfSeis©, 2001, MASW processing software for PC, Kansas Geological Survey, Lawrence, Kansas.
18. 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.
19. Stokoe II, K.H., and Santamarina, J.C., 2000. Seismic-wave-based testing in geotechnical engineering. Proceedings of the GeoEng 2000. Melbourne, Australia.
20. Yilmaz, O., 1987, *Seismic data processing*. Soc. of Explor. Geophys.