

A Brief Review on Different Surface Wave Methods and Their Applicability for Non- Destructive Evaluation of Pavements

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Abstract

Spectral Analysis of Surface Wave (SASW) method for in-situ non-destructive testing of pavement systems has undergone various improvements since its inception during 1980s. Improvements have been in both data-acquisition (sampling and sensors) as well as in data-processing (forward calculation and inversion algorithm) aspects. However, the two fixed-distance receiver approach being used today has its inherent constraint to separate different modes of wave propagation. Present study explores the relative effectiveness of using SASW and multimodal methods. Precise recording of amplitude value has the potential to further improve the effectiveness and develop the surface wave testing methods. Requirement of using high frequency accelerometers (~10-50 KHz) imply that, factors like attenuation, low signal amplitude, and small wavelength detection command the choice of accelerometer-pavement coupling (APC) system. A suitably chosen APC system improves the accuracy of detected signal by eliminating any significant relative motion, selective detection or attenuation to a large extent. This study compares the two surface wave test approaches with regards to data acquisition, data processing and accuracy. Study highlights the merits/demerits and guidelines for justified application of the two surface wave test approaches for pavement systems.

INTRODUCTION

Surface wave testing determines seismic velocity, a fundamental engineering property of material, at negligible strain levels (Richart *et al.* 1970). It is utilized to determine elastic properties and thicknesses of layers of an existing or newly built pavement system. Surface wave methods for pavement evaluation can be conveniently classified into two types: single-mode methods (Steady state Rayleigh wave; Spectral analysis of surface wave- SASW) and multi-mode methods (Multichannel analysis of surface waves- MASW; Multichannel simulation using one receiver- MSOR, etc.).

Major components of a general surface wave testing and evaluation procedure are: (1) Data acquisition at test surface (2) Experimental dispersion curve (EDC) generation (3) Theoretical dispersion curve (TDC) generation i.e. forward modeling (4) Vertical profile determination i.e. inversion. In some analysis approaches, the last two components of evaluation procedure are replaced by one single equivalent approach (such as Artificial Neural Networks-ANN; Simulated Annealing-SA etc.). SASW is, by far, the most practiced surface wave test method for pavement systems employing the above four components.

Surface wave propagation in pavements

In seismic testing, body-waves namely, longitudinal compression waves (P-waves) and transverse shear waves (S-waves) propagate radially outwards from the source along a hemispherical wavefront and are essentially non-dispersive. It means that various frequency components of the wave travel at same propagation velocity which is a function of engineering properties of the media through which they travel (such as elastic modulus). Thus, propagation velocity of body waves such as P-wave is a unique property of a material.

Seismic surface-waves namely Rayleigh waves (R-wave) and Love waves (L-wave) propagate radially outwards along a cylindrical wavefront. L-waves are horizontally polarized and exist only on a layered strata with shear wave velocity of top layer lower than that of substratum (Richart *et al.* 1970). For a homogeneous elastic half-space, R-wave propagation velocity (V_R) is unique and independent of frequency (Heisey *et al.* 1982). However, in multilayered media, R-waves are essentially dispersive and

*Table 1: Characteristics of seismic waves from a circular footing on a homogeneous, isotropic, elastic half-space (Lamb 1904; Miller and Pursey 1955; Ewing *et al.* 1957)*

Wave type	Relative speed	% of total energy	Decay along free-surface*	Decay along depth*
P-wave	fastest	7	$1/r^2$	$1/r$
S-wave	slower	26	$1/r^2$	$1/r$
R-wave	slowest	67	$1/\sqrt{r}$	$1/\sqrt{r}$

*r - radial distance from the wave source

Table 2: Relation between V_R and V_s for pavement materials

Recommended by	$V_R - V_s$ relation	Remarks
Nazarian <i>et al.</i> (1999)	$V_s = V_R (1.13-0.16v)$	used for pavements
Roesset <i>et al.</i> (1990)	$V_s = V_R (1.135 -0.182v)$	for $v \geq 0.1$
Sanchez-Salinerio <i>et al.</i> (1987)	$V_s = V_R (1.144 -0.194v)$	$V_R/V_s = 0.92$

their velocity is called as phase-velocity (V_{ph}) which is frequency specific (Richart *et al.* 1970). R-waves propagate almost 67% energy (refer Table 1) of a seismic event (such as a hammer-impact) and thus have high amplitude and subjected to less attenuation losses. They exhibit a retrograde-elliptical particle motion (i.e. vertical displacement is about 1.5 times the horizontal displacement) in a vertical plane within one wavelength depth (Richart *et al.* 1970). This is the motion aimed at, to be recorded in the surface-wave methods such as SASW (generally only the vertical component of R-wave motion).

As different wavelength components sweep different depths, the corresponding phase velocities, vary in different layers of a multilayered media (Heukelom and Foster 1960). For pavement materials, V_R is empirically related to S-wave velocity (V_s) by Poisson's ratio, ν (refer Table 2). Thus, the phase-velocity spectrum can be used to develop the dispersion function for the test site which relates V_s to corresponding wavelength component (Nazarian and Stokoe 1986, Park *et al.* 1999). The experimental dispersion curve (EDC) is further used to determine the stiffness modulus (E) profile of the test section using equation (1) through the inversion process (explained later).

$$E = 2 \rho V_s^2 (1 + \nu) \quad (1)$$

where: ρ = mass-density; E = stiffness modulus. Thus, a range of R-wave frequency components propagating in a multi-layered media can provide information on its stiffness profile if the corresponding phase velocities are measured; which is the objective of all surface-wave tests. For wavelengths extending to more than one layer, stiffness of all the involved layers will influence the phase velocity (Richart *et al.* 1970).

R-waves propagate at lower velocity than P or S waves (refer Table 1). For a homogeneous, non-dispersive media, R-wave velocities are a function of P and S wave velocities as given by: (Richart *et al.* 1970)

$$V_R^6 - 8V_s^2 V_R^4 + \left(24 - 16 \frac{V_s^2}{V_p^2} \right) V_s^4 V_R^2 + 16 \left(\frac{V_s^2}{V_p^2} - 1 \right) V_s^6 = 0 \quad (2)$$

For a multilayered dispersive medium, the lowest V_R value represents fundamental mode of R-wave propagation. Higher V_R values represent higher (leaking/jumping) modes of surface waves which are formed by superposition of reflected P and S waves within each layer (Buchen and Ben-Hador 1996). These leaking modes also show dispersive properties, and greatly influence the detected signal and phase values. This concept is the basis behind the multi-mode MASW and MSOR methods.

Following sections first discuss the single and multimode methods in pavement evaluation context along with their respective limitations and merits. Subsequently, specific improvements in various methods with regards to their data acquisition aspects, data processing aspects and accuracy are discussed. Role of accelerometer-pavement coupling (APC) system is also discussed. Lastly, some guidelines for justified application of different methods to pavement systems are presented.

SINGLE MODE METHODS

Application of surface wave propagation theory to testing and evaluation of pavement structure, started in 1950s when steady-state R-wave method (also known as continuous surface wave- CSW method) was introduced (Van der Pol 1951; Jones 1955, 1962; Tokimatsu *et al.* 1992). It utilized a steady-state vibrator as a R-wave source of known frequency, f . A single, vertical-axis, receiver was moved away from source, in small steps, to detect the surface-motion points in phase with the vibrator. Distance between any two such, in-phase points, would represent one wavelength, λ thus giving the phase velocity, ($v=\lambda f$). A chosen V_R - V_s relation (from Table 2) along with equations (1) would then directly give the stiffness values of the layers.

An improvement to Steady state method was the spectral analysis of surface waves (SASW) method (Heisey *et al.* 1982, Nazarian and Stokoe 1986) which introduced a relatively simple, portable and efficient surface wave testing procedure for pavements. Its major highlight was the use of spectral analysis technique for signal processing which made it possible to analyze a range of frequencies with a convenient hammer-impact type surface wave source. It made use of two stationary receivers which eliminated the need to move the single receiver and hence drastically reduced the testing time. Manual masking, forward modeling and inversion procedures were used to generate vertical stiffness profile (explained later). Since then, the SASW method has been vastly examined, tested, improved and adopted for non destructive testing and evaluation of pavement structure (Nazarian *et al.* 1988; Stokoe *et al.* 1994; Nazarian *et al.* 1999).

Limitations of single mode methods

Steady state method was crude in its approach, was time consuming and inadequate in the sense that it was not able to utilize higher frequencies and hence could not give top layer information accurately (Jones 1962). It made use of an assumed value for ratio of wavelength to depth (= 1 to 4) (Heukelom and Foster 1960; Szendrei and Freeme 1970) to directly determine the vertical stiffness profile. It lacked the use of an effective inversion process to backcalculate the elastic properties. Also, only one phase velocity at each frequency was being used. Presence of multiple velocities at same frequencies was reported and attributed to possible existence of higher modes of propagation (Van der Pol 1951; Jones 1955). Presence of some of the high-frequency components were attributed to fundamental mode of anti-symmetric Lamb wave propagation (Vidale 1964; Jones and Thrower 1965) solution for which was verified later (Martincek 1994).

SASW method assumes the presence of only fundamental mode of R-wave propagation. This is reflected in the testing method as the two fixed receiver approach which aims at capturing only one phase-velocity at each frequency. Hence, this earlier limitation of getting only one apparent phase velocity evaluated at each frequency, remained (apparent, as it is a superposition of all types of waves; body and surface). Some other related limitations of the two-receiver SASW approach, causing error and unreliability in pavement characterization, can be identified as follows (Hiltutnen and Woods 1990; Rix and Stokoe 1989; Tokimatsu *et al.* 1992; Al-Hunaidi 1992, Al-Hunaidi and Rainer 1995; Stokoe *et al.* 1994; Ganji *et al.* 1998; Ryden *et al.* 2004; Ryden and Lowe 2004):

- Generated EDC is for superimposed waveform and may have significant influence of leaking modes.
- Dispersion curve was not found continuous with wavelength (Jones 1962; Vidale 1964).
- Viscoelastic nature of asphalt in pavements introduces complex moduli components which are not properly accounted for in the analysis.
- The apparent phase velocity varies with offset distance of receivers (Zywicki 1999). It affects the testing procedure by introduction of near and far-field effects. As a result, test geometry assumes much importance and has to be included in the analysis (Joh 1996).
- Detected signal is contaminated by various types of direct and reflected waves (e.g. P and S waves) from structural boundaries and layer interfaces which are not adequately considered in the analysis.
- Inverse dispersion and sharp S-wave velocity contrast over the pavement layers gives rise to complex modes which are not considered.

Several improvements, aimed at increased accuracy of results from SASW test, have been recommended which generally focus on minimizing the influence of higher modes (Sanchez-Salinerio *et al.* 1987; Gucunski and Woods 1992; Ganji *et al.* 1998; Gucunski *et al.* 2000). At very high frequencies, fundamental mode of R-wave propagation dominates (Ryden and Lowe 2004). This can be cited as the reason as to why the assumed presence and detection of fundamental mode phase-velocity gave, to an extent, useable results in specific situations (Nazarian *et al.* 1999).

MULTI MODE METHODS

MASW technique was first reported in late 1990s (Park *et al.* 1998, 1999, 2001). It makes use of more than two receivers (array of 12 to 48) to detect the higher modes present in the surface waves. Basic testing procedure is essentially the same as of single mode methods. MSOR method for pavement characterization (Ryden *et al.* 2001) is based on MASW technique, and utilizes a single fixed receiver and moving source (or vice versa) to take a number of shot gathers and then use them to simulate multichannel data. A fast testing and analysis procedure makes this method more convenient and efficient than the previous surface wave methods for pavements. Recently, simulated annealing has been applied to MSOR test data for fast, fully automated complete 2-D inversion of wavefield for EDC generation (Ryden and Park 2006). Refraction microtremor (ReMi) method (Louie 2001) is a recent multimode surface wave method, generally used for greater depths (10-100m).

Merits of multi-mode approach

The multi-mode approach attempts to overcome the limitations of single-mode approach. Some of its major advantages can be identified as follows:

- Need for subjective decisions (like masking in SASW) is eliminated due to the automated procedure for dispersion curve extraction.
- Dispersion characterization of full waveform is possible based on propagation velocities and attenuation relations of all seismic waves.
- Sensitivity to noise contamination and near-field effects is minimized due to pattern recognition capability. It also helps in utilizing a broader frequency-band.
- Data acquisition is simpler with respect to accuracy required in test geometry and source impact.
- Low noise sensitivity reduces the need for stacking, making the testing procedure more efficient.
- Multi-mode approach shows relatively good potential for its applicability to different areas of pavement evaluation such as crack detection.

DATA ACQUISITION ASPECTS

Surface wave measurements require one surface of test structure (such as top of asphalt layer) to be accessible for testing. A typical test setup of SASW technique is shown in Figure 1. The receiver converts the physical variable (acceleration) into electrical analog signal which is generally weak and therefore sent to signal conditioning unit. The conditioned signal is then sent to the DAQ-device for analog to digital conversion (ADC). After ADC, DAQ-device sends the signal to laptop computer. MASW and MSOR test

techniques for pavements have a similar basic set up. Discussion on various data acquisition aspects of these testing methods, along with their specific improvements, is presented hereby:

- **Field testing:** It consists of detecting the phase difference between the receivers for each frequency generated. An impact source is used to generate R-waves with a broad frequency band which is sensed by the receivers at known offsets. A number of data sets (time-amplitude data) are obtained for each receiver geometry with the source first on one side of linear receiver array, then on the other (called as forward and reverse configurations respectively).
- **Instrumentation:** Earlier, standalone oscilloscope and/or spectrum-analyzer were used as data acquisition (DAQ) and control system which now have gradually given way to processor based portable DAQ devices, signal-conditioners and laptop-computer. PSPA (Portable Seismic Pavement Analyzer) and SPA (Seismic Pavement Analyzer) for SASW, multichannel seismograms for MASW and PSAS (Portable Seismic Acquisition System) for MSOR are some of the DAQ systems developed for respective testing procedures and also have their own control software. These systems are discussed in detail elsewhere (Nazarian *et al.* 1995; Park *et al.* 1999; Ryden *et al.* 2002).

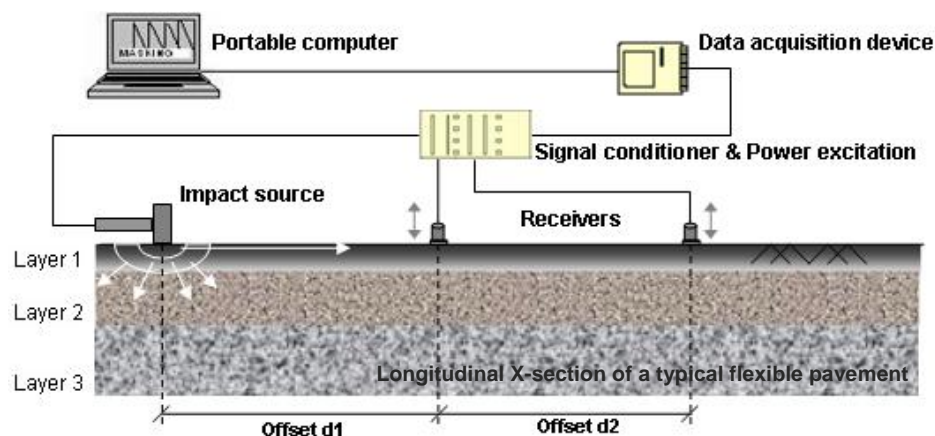


Figure 1. Schematics of a typical SASW test set up

- **Offsets:** Distances between the impact source and the receivers (offset d_1 , d_2 as shown in Figure 1) are varied according to the frequency range and target depth under consideration. Table 3 gives some guidelines for offset selection (called as filter-criteria). Increasing the offsets can reduce the detrimental near-field effects which arise due to prominence of body-waves near the source. However, then lateral geometry and associated boundary reflections gain prominence. Also, the signal-amplitude diminishes (far-field effect). This presents a geometrical constraint for single mode 1D surface-wave methods.
- **Receivers:** Earlier, geophones were being used for pavement testing which had a very limited frequency range ($<1\text{KHz}$) and low sensitivity. Nowadays high frequency accelerometers (10-50 KHz) are available and being used as sensor receivers to get sufficient accuracy in depth profiling. Their high sensitivity makes it possible to record a strong signal which is less vulnerable to influence of noise. In MSOR, a high frequency accelerometer is used as a receiver to simulate high-frequency high-resolution multichannel data which is very difficult to obtain directly using conventional MASW testing due to hardware and portability limitations. Development of high frequency triaxial accelerometers has made it possible to record motion along three axes.
- **Wave Source:** For pavement testing, active sources such as transient-impulse (hammer type) or harmonic (constant frequency) vibrator are generally used. Main consideration in selection of the wave source is the target depth of profiling. For subgrade region (say, 1-3 m), low-frequency, high energy wave source, like sledge hammer with bigger contact surface is more suitable, while a high-frequency, low energy impact source like a carpenter's hammer or steel-ball with smaller impact area is good for top-layer level. Shorter impact duration results in a broader range of excited frequencies. Instrumented impact sources such as a solenoid or a hammer mounted with an accelerometer are generally used nowadays for testing on pavements as they additionally provide good triggering (Nazarian *et al.* 1999; Ryden *et al.* 2002). Geometry of the sensor-array and type of analysis depend

on the type of wave source. With an active source, a linear sensor-array is sufficient for property estimation as the wave-source and propagation direction is known. For passive wave sources such as ambient noise, traffic, etc., the propagation direction is generally unknown and a 2-D array is required (as in ReMi method).

- **Trigger:** A trigger is required to start the data acquisition simultaneously across different receiver channels as soon as the impact is made. It may be an internal software trigger (e.g. rising/falling edge or slope of a signal) or an external contact type/electronic (comparator-circuit) trigger. For MSOR technique, an accurate trigger is a prime necessity to synchronize the signals obtained over various shots with a single receiver (Ryden, *et al.* 2004).
- **Digitization:** Sampling rate and resolution of data acquisition system are determining factors in reliability and correct interpretation of test data. Sampling must be at least twice (called as Nyquist-frequency) and preferably ten times as fast as the highest frequency component in the signal. Under-sampling can result in misrepresentation of the measured signal (called aliasing). Resolution should be at least 16-bit to get a good digitization (Ryden *et al.* 2002). Spectrum analyzer, if being used, should also confirm to these guidelines.

Table 3: Guidelines for offset selection (refer Figure 2 for d_1 and d_2 , λ is the wavelength)

Recommended by	Offset d_1	Offset d_2	Study remarks
Gucunski and Woods (1992)	-	$\lambda < d_2 < 4\lambda$	simulated parametric study
Tokimatsu <i>et al.</i> (1991)	$\lambda/4 \leq (d_1 + d_2/2)$	$\lambda/16 \leq d_2 < \lambda$	valid upto 20m
Hiltunen and Woods (1990)	$d_1 \leq d_2$	-	for pavement site
Roesset <i>et al.</i> (1990)	$\lambda/2 < d_1 < 2\lambda$	$d_1/2 \leq d_2 \leq d_1$	2 layer parametric study
Sanchez-Salinerio <i>et al.</i> (1987)	$d_1 = d_2$	$2\lambda < d_2$	for 3-layer pavement site
Heisey <i>et al.</i> (1982)	$d_1 = d_2$	$\lambda/3 < d_2 < 2\lambda$	for soil sites

DATA PROCESSING ASPECTS

EDC generation

The time domain data sets obtained from testing are averaged together (stacking) to get a more representative data-set which is then transformed to the frequency domain using fast fourier transform (FFT) algorithm. This is done to determine the phase difference between signals from different receivers which is not possible in the time domain.

For SASW method, cross-power-spectrum (CPS) and coherence function of the two accelerometer signals gives their phase spectrum. The wrapped phase spectrum varies from $-\pi$ to π radians and is unwrapped and refined by manual masking technique to determine the travel time of each frequency component between the two receivers. CPS range for which coherence is not close to unity is masked out. The travel time and receiver offset value then gives the V_{ph} spectrum or the dispersion-curve (refer Figure 2). All such dispersion curves for different test offsets and orientations are statistically combined and a representative EDC for the test site is finally generated (Nazarian 1984; Nazarian and Stokoe 1986; Yuan and Nazarian 1993). Earlier, manual masking procedure was very difficult and cumbersome (Nazarian 1984). Nowadays, advanced signal-processing techniques such as exponential windowing, Gaber-spectrum etc. are used which reduce the signal contamination due to noise and reflections from structural boundaries. This has made the masking process relatively much easier and fast (Joh 1996).

For multimode methods, pattern recognition techniques are used (Ryden *et al.* 2004). Specifically, this approach attempts to extract the dispersive properties from multichannel signal by first imaging its 2-D transformed wavefield (frequency-wavenumber or frequency-slowness domain) utilizing pattern-recognition techniques (Park *et al.* 1998). The image gives the dispersion pattern for all modes. The fundamental mode dispersion curve for R-wave is identified and extracted which is more representative of actual wave phenomena being utilized. This is further used in inversion process to give vertical S-wave velocity profile at centre of the receiver spread.

Forward analysis

Using assumed values for thickness, density, V_p (or V_s) and number of layers, the surface motion at receiver locations is determined using surface-wave propagation modeling, and a theoretical dispersion curve (TDC) is generated. It is used in the inversion procedure to generate the vertical S-wave velocity profile. Haskell-Thomson's 1-D plane wave propagator-matrix method (Thomson 1950; Haskell 1953) as corrected by Jones (Jones 1962) became the basis for most of the modeling approaches such as: stiffness-matrix method, linearized stiffness-matrix method etc (Kausel and Roësset 1981). Other modeling approaches utilizing finite-difference (Hossian and Drnevich 1989), Green's functions (Kausel and Peek 1982; Hisada 1994), wavelet transforms (Storme *et al.* 2005), etc. have also been applied and shown to give varying degrees of accuracy of results.

Propagator-matrix method gives surface wave dispersion function as a product of layer matrices. A layer matrix relates displacement and stress components at an interface to those at the next interface and is a function of the wave number and frequency. Product of all such pavement layer matrices relates these components for the free top surface to those for the deepest layer. A determinant search technique is then used to compute values of the wave-number for which the determinant is zero (called as eigenvalues). For pavement profiles, no real eigenvalues exist above a specific maximum frequency. This leads to complex domain computation of eigenvalues and phase-velocities which is a difficult task. Often as an approximation, only the real part of the determinant is considered in the solution.

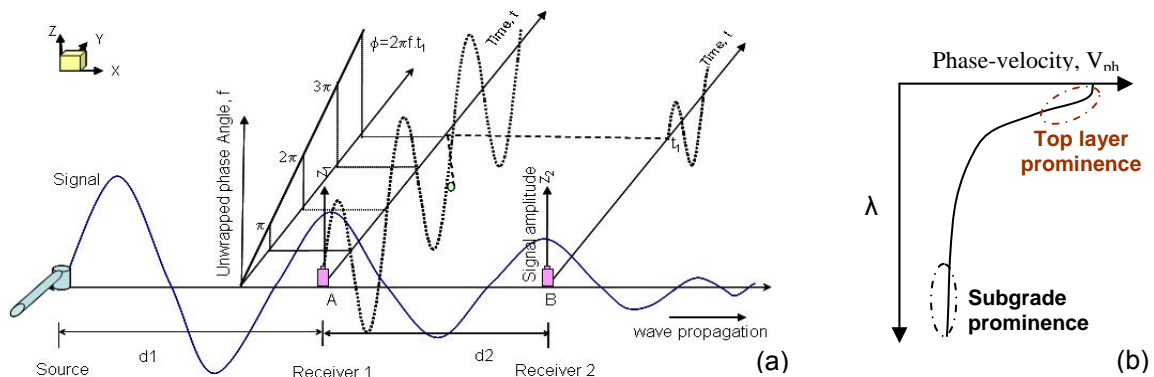


Figure 2: (a) Signal acquisition and phase-difference concept (b) Dispersion-curve

Inversion

The inversion is a process wherein a suitable optimization tool is employed to reduce the difference between EDC and TDC through backcalculation (Yuan and Nazarian 1993). Taking highest frequency, assuming values for mass-density and Poisson's-ratio and using equation (1), stiffness modulus for top most layer can be determined using a theoretical model such as propagator- matrix. Both the modal dispersion curves are compared, and assumed layer property values for TDC are changed till the curves match (for the mode under consideration). The final set of assumed values then give the true S-wave velocity, seismic moduli and depth of layer. Next lower frequency (longer wavelength) has its phase velocity dependence on properties of the first two layers. Thus, the calculated stiffness-modulus of first layer is used to determine properties of the second layer. Similarly, taking smaller frequencies sequentially, properties of all layers are determined. Vertical stiffness profile of the test site is generated as the final outcome.

Analysis tools

Seismic property analyzer (SPA) (Nazarian *et al.* 1995) and WinSASW (Joh 1996) for SASW method and SurfSeis (Park *et al.* 1999) for multi-mode are some of the software tools available for respective analysis procedures. SPA utilizes modified propagator-matrix method and WinSASW is based on dynamic stiffness matrix approach of forward analysis. Various methods for automation of full inversion

process have been proposed till now (Yuan and Nazarian 1993; Ganji, *et al.* 1998). Optimization techniques like ANN (Nazarian *et al.* 2004; Williams and Gucunski 1995; Gucunski *et al.* 2000), Genetic Algorithms (GA) (Al-Hunaidi 1998) and more recently Simulated Annealing (SA) (Beatty *et al.* 2002; Ryden and Park 2006) are also being used for automation of analysis procedure. Generally, all forward analysis methods involving manual masking are time consuming, demand experience of use and show less reliability of results as compared to automated methods.

ACCURACY

Table 4 presents some findings by various researchers on accuracy of results obtained from SASW testing. Usually a combination with other methods such as impulse-echo, falling-weight-deflectometer (FWD), etc. increases the accuracy. To compare SASW results with other similar methods such as FWD, its small-strain measurements can be converted to any strain level using equation (3) (Rix and Stokoe 1989):

$$E_{\epsilon, \text{field}} = E_{\text{seismic}} (E_{\epsilon} / E_{\text{max}})_{\text{lab}} \quad (3)$$

where, E_{seismic} is the in-situ elastic modulus; $(E_{\epsilon} / E_{\text{max}})_{\text{lab}}$ is the normalized elastic modulus determined by resonant-column test in laboratory and $E_{\epsilon, \text{field}}$ is the modulus at the desired strain level, ϵ .

Table 4: Findings on accuracy of results of SASW testing

Reference	SASW result
Nazarian <i>et al.</i> 1999	For AC layers, good agreement with other methods like FWD, seismic moduli (E) are on higher side
Nazarian <i>et al.</i> 1995	20% deviation in backcalculation of PCC thickness using SPA
Al- Hunaidi 1992	For old BC pavements, thickness over predicted by 40%, transducer limitations cited
Rix and Stokoe 1989	for PCC, moduli differed by 10% for top layer to upto 30% for bottom layers
Roesset <i>et al.</i> 1990	moduli correspond to maximum values due to small strains and high frequencies involved, variation of moduli with temperature
Nazarian <i>et al.</i> 1988	moduli differed within 30% for lower layers as compared to FWD results

Role of APC

Precise recording of amplitude value has the potential to further improve the effectiveness and develop the surface wave testing methods. Requirement of using high frequency accelerometers (10-50 KHz; with respective resonant frequencies above 20-60 KHz), imply that, factors like attenuation, low signal amplitude, and small wavelength detection command the choice of accelerometer-pavement coupling (APC) system. APC system puts a limit on the highest recordable frequency by the accelerometer. A suitably chosen APC improves the accuracy of detected signal by eliminating any significant relative motion, selective detection or attenuation to a large extent.

Different APC systems

Various APC systems are available for surface-wave testing of pavements, like, bees-wax, petro-wax, grease, sticky-glue, mounting-stud etc. and even direct contact to surface without coupling agent is also practiced. But there is a need to examine and standardize the choice of a method based on its relative effectiveness (Mark and Torben 1986, Olson 2006, Ryden 2005). This study attempts to compare performances of some of the APC systems, in terms of the precision of data acquired. Testing was done at an existing flexible pavement site at Indian Institute of Technology Kanpur (IITK), India, using same offsets and three different types of commonly available coupling agents, namely: vacuum-grease, petro-wax, high-quality A3 grease. Preliminary results show that for petro-wax, the average value of recorded amplitude is the highest and signal quality is good as indicated by a few of the recorded impulse-response curves given in appendix A. Further testing at more sites is necessary to fully establish the performance of different coupling systems for pavements.

The data acquisition system used for testing has been recently developed at IITK. It consists of a 16-bit USB DAQ card, a signal conditioner with power source, instrumented hammer (accelerometer mounted) and two high-frequency high-resolution (1000mV/g) PCB 352B accelerometers (resonant-frequency >25KHz). System and test set-up is shown in Figure 1. LabVIEW™ software was primarily used for data acquisition and preliminary analysis besides Matlab™. Special feature of this system is its high-portability, ease of use and low power requirements. Problem of excessive laptop and DAQ card heating does not arise as external DAQ card is used.

GUIDELINES FOR JUSTIFIED APPLICATION

Table 5 provides a comparison on some of the characteristics of different surface-wave methods for pavements. Some suggested guidelines for improved performance of surface-wave methods are:

- Combining multiple shot-gathers (stacking) with different offsets and orientation can improve the signal quality. However, it increases the testing time and labor requirements.
- If the offsets are increased, the results will become valid only for a range of higher wavelengths and thus, higher depths. Thus a range of reliable wavelengths should be specified.
- SASW results are expected to be unreliable at locations and times when ambient noise is strong (as on highways, etc.) or where other wave contaminations have strong energy content than the fundamental R-wave mode. As such, it is desirable to do SASW pavement testing at off-peak hours such as early morning or late night. However, multimode methods do not seem to have this limitation (Miller et al. 2000).
- Site specific testing criterion (such as test-geometry, impact source, APC) can improve the signal quality (Stokoe *et al.* 1994).
- At sites where layer-dipping or multiple lateral-reflections are expected, multimode method should be employed for reliable results.
- Multiple sub-layering during forward modeling can improve the accuracy (Kausel and Peek, 1982; Sanchez-Salinero *et al.* 1987), but demands intensive computation requirements.
- The approximate inversion method of assuming a depth to wavelength factor (as in steady state method) can provide a quick initial estimate of depth-profile in the field (Gazetas 1982). This can be used to get approximate E values to be given as input to the inversion routine. Available background information on test site can also be incorporated.
- Multimode data analysis is a complex and involved task which constrains its usability.

Table 5: Characteristics of surface wave methods for pavements

Characteristic	Single mode methods		Multi mode methods	
	Steady state	SASW	MASW	MSOR
Discovered	1950s	early 1980s	late 1990s	early 2000s
Current status	Obsolete	Most practiced	Upcoming	Upcoming
Strengths	-	Top layer evaluation	Subgrade and bedrock evaluation	Full-evaluation; convenient
Frequency range	1Hz – 1 KHz	10Hz – 50KHz	1Hz – 2500Hz	10Hz – 20KHz
Test Geometry	Not fixed	Fixed offsets; precise	Fixed offsets; tolerant	Fixed offsets; precise
Source	EM; mono-frequency	Hammer type, EM; multi-frequency	Hammer type, EM; multi-frequency	Hammer type; multi-frequency
Receiver	Geophone; 1 number	HF accelerometer; 2 numbers	Geophones >2 numbers	HF accelerometer; 1 number
Data acquisition	Spectrum analyzer	Spectrum analyzer/ DAQ card with PC	Multichannel DAQ device with or w/o PC	DAQ device with PC
EDC generation	Direct-calculation	Spectral analysis; (manual)	Pattern-recognition; (automated)	Pattern-recognition, SA; (automated)
TDC generation	NA	Forward modeling	Forward modeling	Forward modeling
Inversion	NA	LS ML, ANN, GA etc.	LS ML, ANN, GA etc.	LS ML, ANN,GA, SA etc.
Analysis tools	-	SPA, WinSASW,etc.	SurfSeis, etc.	SurfSeis, etc.

Note: Electro-mechanical; HF – High Frequency; DAQ card – Data acquisition card; PC – Portable computer; EDC/TDC - Experimental/Theoretical Dispersion Curve; LS ML – Least square Maximum Likelihood; ANN – Artificial Neural Networks; GA – Genetic Algorithms; SA – Simulated Annealing; NA – Not applicable

SUMMARY

Surface wave propagation and dispersion characteristics in multilayered media provide the basis for the single and multi mode evaluation methods for pavement systems. Since the inception of these methods, many specific improvements have taken place in the various aspects related to their testing and data analysis procedures. Different testing methods have their specific merits and limitations. Newer techniques attempt to improve upon the limitations and assumptions of previous methods. A suitably chosen APC system improves the quality of detected signal. Testing with three different APC systems showed that petro-wax gave a superior performance. Knowledge of relative effectiveness of different methods and guidelines to achieve better performance is important for justified application of surface-wave methods to pavement system evaluation.

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Appendix A

Figures (a) to (c) are for type-1 coupling (vacuum grease); Figures (d) to (f) are for type-2 coupling ((Petro-wax) and Figures (g) to (i) are for type-3 coupling (A3 grease).

