DETERMINATION OF IN SITU SHEAR WAVE VELOCITIES FROM SPECTRAL ANALYSIS OF SURFACE WAVES

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SUMMARY REPORT 256-2(S)

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Introduction

Pavement life is usually defined as the length of service of the pavement system before maintenance or rehabilitation is required. Estimates of remaining life as well as appropriate remedial measures are based on elastic moduli of the various pavement materials. Young's elastic moduli are used to characterize the stress-strain behavior of the pavement system, which in turn is used to indicate the potential for deterioration and tensile cracking in the surface layer. Numerous methods have been developed to determine elastic moduli in pavement systems in the field. Report 256-2 presents an advance in the state of the art in the application of one of these field methods, a wave propagation method called the Spectral-Analysis-of-Surface-Wave (SASW) method.

Summary of Approach

Criteria which guided development of this method included the constraint of nondestructive testing, accuracy of moduli for all layers regardless of thicknesses, and quickness and efficiency for rapid, extensive testing. To meet these criteria, surface receivers were utilized to monitor Rayleigh wave (R-wave) motion created by a vertical impulse that excites a wide range of frequencies with a single impact and is applied to the pavement surface. Analysis was facilitated by using a portable spectral analyzer to study the magnitude and phase of the frequency content of the recorded wave pulse. A schematic of this arrangement is shown in Fig 1.

For a horizontally layered system such as a pavement site, Rayleigh wave velocity will vary with frequency (wavelength). This variation of wave velocity with frequency (wavelength) is known as dispersion, and a plot of velocity versus wavelength is called a dispersion curve. The dispersion curve is developed from phase information of the cross power spectrum. This information provides the relative phase between two signals (two-channel recorder) at each frequency in the range of frequencies excited in the SASW test. For a travel time equal to the period of the wave, the phase difference is 360 degrees. Thus, for each frequency the travel time between receivers can be calculated by

$$t(f) = \phi(f)/(360\, f) \qquad (1)$$

where

f = frequency,
$t(f)$ = travel time for a given frequency, and
$\phi(f)$ = phase difference in degrees of a given frequency.

The distance between the geophones, X, is a known parameter. Therefore, R-wave velocity at a given frequency is simply calculated by

$$V(f) = X/t(f) \qquad (2)$$

and the corresponding wavelength of the R-wave is equal to

$$L_R(f) = V_R(f)/f \qquad (3)$$

By repeating the procedure outlined by Eqs 1 through 3 for every frequency, the R-wave velocity corresponding to each wavelength is evaluated, and the dispersion curve is determined.

Once the dispersion curve has been determined, velocities for given frequencies are assigned to depths using a wavelength criterion corresponding to an "effective sampling depth" of material properties. Based on comparisons with shear wave

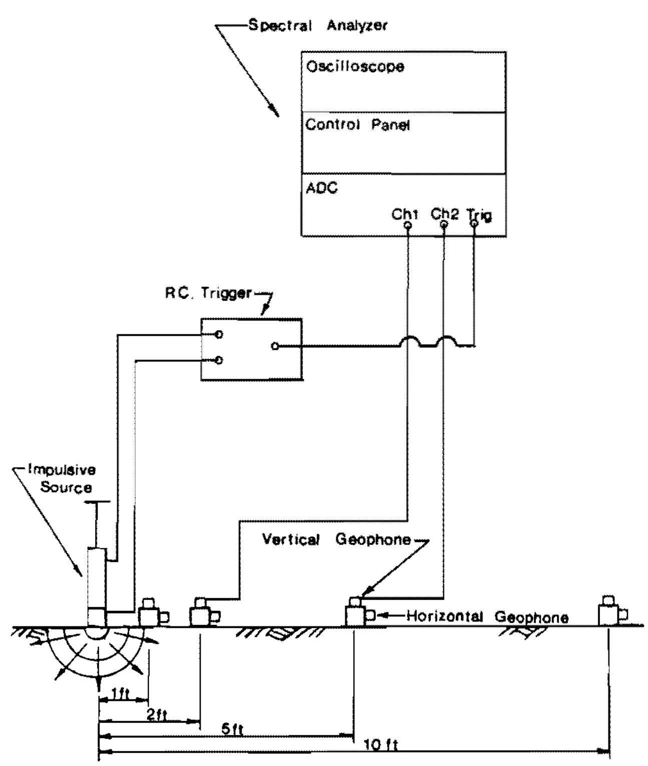


Fig 1. Schematic diagram of experimental arrangement for SASW testing.

velocity profiles from crosshole testing, a depth criterion of $L_R/3$ provided a velocity profile which correlated best with the crosshole profile. Velocities from cross spectrum (surface) measurements did not differ from crosshole velocities by more than 20 percent in the extreme and were typically within less than 10 percent in this work. One such comparison at a flexible pavement site is shown in Fig 2 and is summarized in Table 1.

A comparison of Young's moduli obtained from wave velocities by SASW testing with moduli from deflection measurements using ELSYM5 was performed at the flexible pavement site shown in Fig 2. This comparison is given in Table 2 and indicates that the wave propagation method is a valid way to determine moduli. The differences in moduli ranged up to about 35 percent, which is quite good considering the markedly different approaches of the two methods. It is difficult to say which method is more accurate, although the wave propagation method seems more desirable, since it determines the modulus of each layer directly whereas the deflection method must find moduli by a trial-and-error procedure in which predicted deflections are matched with measured deflections that represent a composite influence of all layers in the pavement system. In addition, it is not clear how well the elastic layer theory incorporated into ELSYM5 applies to low-strain, dynamic (transient) loading.

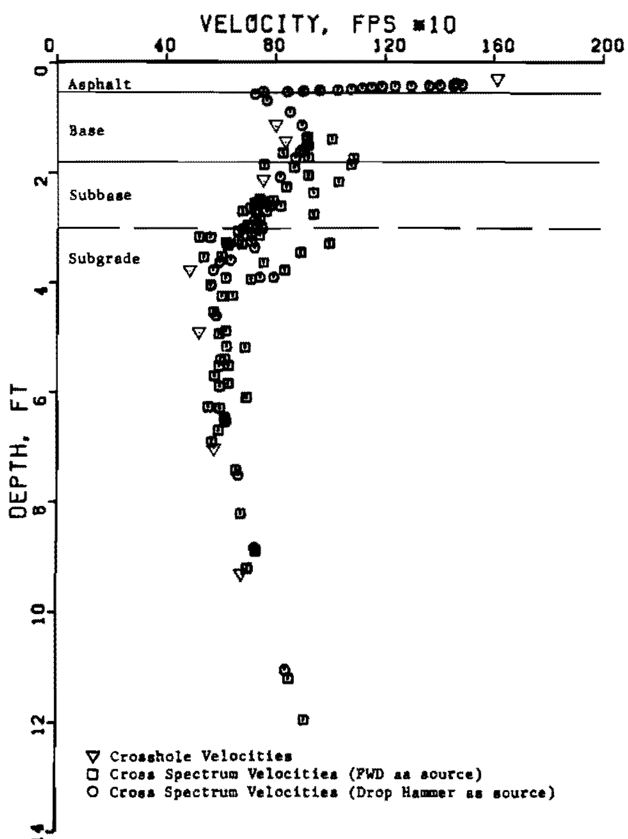


Fig 2. Comparison of crosshole velocities with shear wave velocity profile obtained using SASW measurements.

TABLE 1. COMPARISON BETWEEN S-WAVE VELOCITIES FROM SASW MEASUREMENTS AND FROM CROSSHOLE TESTS

	S-Wave Velocity (fps)		
Material	Cross Spectrum Measurements	Crosshole Tests	Percent Difference
Asphalt	1500	1610	6.8
Base	925	823	12.4
Subbase	740	743	0.4
Subgrade	605	565	7.1

TABLE 2. COMPARISON BETWEEN ELASTIC MODULI CALCULATED FROM WAVE VELOCITIES AND FROM DEFLECTION MEASUREMENTS (ELSYM5)

		Young's Modulus, E (psi)	
Material	Shear Modulus (psi)	Wave Propagation	Deflection Method*
Asphalt	70,000	190,000	250,000
Base	26,000	72,000	108,000
Subbase	16,000	45,000	40,000
Subgrade	9,000	25,000	17,000

* Moduli were backcalculated from fitted deflection basin using elastic theory (ELSYM5).

Conclusions

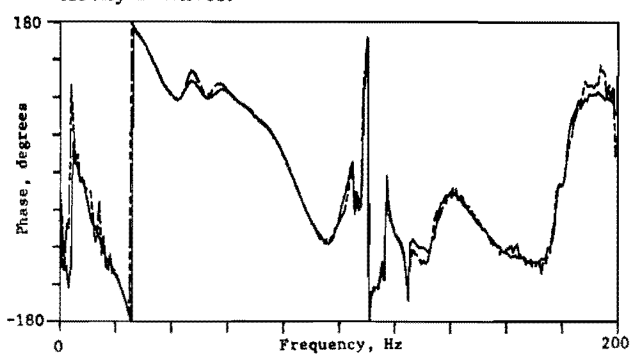
At present, the SASW technique is restricted to using an average velocity, and determination of a velocity profile based on the wavelength criterion is somewhat empirical. The problem of averaging is particularly evident at layer boundaries. Although this empirical approach provides reasonably good correlation with site profiles and crosshole data, it is desirable to incorporate a more rigorous and "accurate" approach for determining the velocity profile from surface measurements. Such an approach involves Rayleigh-wave inversion and extensive numerical techniques to "back out" the velocity (or modulus) profile and to eliminate or minimize problems associated with averaging. This approach could be used to refine the analysis of measurements from surface testing.

In developing the method, several test-related variables, in addition to effective sampling depth, were studied. It was found that several transient events or impacts, should be averaged together to obtain a representative cross spectrum measurement.

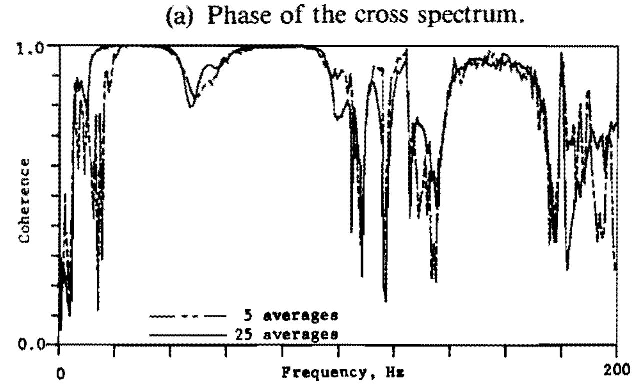
The number of averages may vary somewhat with the reproducibility of the source, but, typically, five averages will provide a representative measurement. Additional averages do not seem to improve the measurement sufficiently to warrant the extra testing time, as illustrated in Fig 3.

Investigation of several sources showed that the stress (or strain) level is not necessarily the critical parameter for selecting an appropriate impact hammer. Selection should be based on the range of frequencies that can be sufficiently excited to sample the site profile adequately. Energy of excitation should not be focused on a few frequencies but should be distributed over all frequencies in the bandwidth. On this basis, a light hammer producing a sharp impulse is much better suited than a large weight which produces a relatively "cushioned" impulse, particularly for testing pavement sites.

Signals recorded with velocity transducers, or geophones, appear to provide valid cross spectrum measurements up to frequencies of at least 3 kHz. Based on tests performed on pavements, vertical geophones provide a more accurate R-wave velocity profile than horizontal geophones. Velocities obtained from measurements using horizontal geophones were generally too high, probably due to the greater sensitivity of horizontal geophones to the higher velocity P-waves.



(a) Phase of the cross spectrum.



(b) Coherence function.

Fig 3. Comparisons of the use of the average of 5 observations with the average of 25 observations to obtain representative spectral measurements.

The spacing of the geophones from the source also is important. In general, an "equally spaced" arrangement, where both the near geophone and the far geophone are located at increasing distances from the source, is more desirable than a "reference" arrangement, where the near geophone is fixed at a location close to the source and only the far geophone is located at increasing distances from the source. The former arrangement provides a more accurate velocity profile, particularly at greater depths (greater wavelengths). The equally spaced arrangement appears to be better than the reference arrangement because the near geophone is located at a sufficient distance from the source, which allows the different frequencies to disperse (by travelling at different velocities) as well as permitting the longer wavelengths to travel through a depth of material which the wave(s) supposedly sampled.

In addition to the cross spectrum function, other functions may be helpful in the analysis of data. The coherence function, shown in Fig 3b, is most definitely needed to assess the range of frequencies over which quality data were obtained for a given measurement. The linear spectrums or autospectrums can indicate which frequencies are adequately excited to measure a good response. Lastly, the transfer function may be used to calculate attenuation properties at a site.

KEY WORDS: Elastic modulus, wave propagation, field testing, flexible pavements, Rayleigh waves, spectral analysis.

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The full text of Research Report No. 256-2 can be obtained from Mr. Phillip L. Wilson, State Planning Engineer, Transportation; Transportation Planning Division, File D-10R; State Department of Highways and Public Transportation; P. O. Box 5051; Austin, Texas 78763.