Use of Spectral Analysis of Surface Waves Method for Determination of Moduli and Thicknesses of Pavement Systems

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The spectral analysis of surface waves (SASW) method is a nondestructive method for determining moduli and thicknesses of pavement systems. By means of a transient impact on the surface of a pavement system (or soil deposit), a group of waves with different frequencies is transmitted to the medium. Seismic wave velocities and, eventually, elastic moduli and thicknesses of the various layers in the pavement system are determined from analysis of the phase information for each frequency determined between two receivers located on the surface. The method has several advantages: it is nondestructive, has a unique solution, and is capable of full automation. The results of three series of tests performed on TX-71 near Columbus, Texas, are presented. Testing was performed on an asphaltic concrete pavement, a continuously reinforced concrete pavement, and a natural soil occupying the median at the site. Elastic moduli determined by using the SASW method are compared with those determined by means of crosshole seismic tests and Dynaflect measurements. Moduli determined by the SASW method are in agreement with those from crosshole tests, whereas moduli back-calculated from Dynaflect measurements compare rather unfavorably with moduli determined by the other two methods.

Many different methods have been proposed for evaluating the elastic properties of pavement systems. These methods can be categorized in four groups: static deflection, steady-state dynamic deflection, impact load response, and wave propagation. An in-depth review of these methods has been presented by Lytton, Moore, and Mahoney (1) and Hoar (2). The methods apply either a static or a dynamic load to the system being tested. One disadvantage of methods involving static loading is that they have a nonunique solution. In addition, only a summation of the overall stiffness of the pavement system is measured, and breaking down this summation into properties of the different layers involves considerable judgment. Dynamic methods such as the Dynaflect and the falling weight deflectometer are more promising, but the equipment is expensive and again a nonunique solution is obtained. In addition, dynamic tests involve wave propagation testing, but static loading is assumed in analyzing the data obtained from these tests. The assumption of static loading for a wave propagation test can result, at a minimum, in significant differences between actual and assumed stress distributions.

In this paper, the spectral analysis of surface waves (SASW) method for determination of moduli and thicknesses of pavement systems is discussed. The SASW method is a wave propagation method that has been under development for some time (3-5). New refinements in collecting and analyzing the data are presented here along with several case histories that illustrate the value of the method and the uniqueness of the solution.

EVALUATION OF ELASTIC PROPERTIES FROM WAVE VELOCITY

Wave motion created by a disturbance on an elastic half-space can be described by two kinds of waves: body and surface waves (6). Body waves consist of shear (S) and compression (P) waves. The Young's modulus (E), shear modulus (G), and Poisson's ratio (ν) of a material are commonly expressed in terms of the wave velocities as

$$E = \rho(1+\nu)(1-2\nu)V_p^2/(1-\nu) \tag{1}$$

$$G = \rho V_s^2 \tag{2}$$

and

$$\nu = [0.5(V_p/V_s)^2 - 1]/[(V_p/V_s)^2 - 1] \tag{3}$$

where

V_p = compression wave velocity,
ρ = mass density, and
V_s = shear wave velocity.

The second kind of wave associated with an elastic half-space is a surface wave, also called a Rayleigh wave (R-wave) (7). R-wave velocity (V_R) is constant in a homogeneous half-space and is independent of frequency. Each frequency (f) has a corresponding wave length (L_R) according to

$$V_R = fL_R \tag{4}$$

R-wave and S-wave velocities are related by Poisson's ratio. Although the ratio of R-wave to S-wave velocity increases as Poisson's ratio increases, the change in this ratio is not significant, and it can be assumed that it is approximately equal to 0.90 without introducing an error larger than 5 percent.

DESCRIPTION OF SASW METHOD

The SASW method is a powerful and potentially economical method of evaluating the elastic properties of pavement systems as well as natural soil deposits. As a result, the method can be used to solve problems in which moduli are used directly, such as in overlay designs, or indirectly, such as in controlling the quality of compaction of pavement materials during construction.

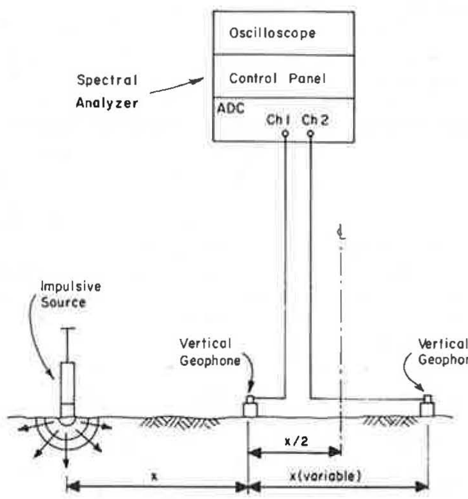
The SASW method is a nondestructive test method in which both the source and the receivers are placed on the pavement surface. R-waves at low strain levels are then generated and detected. The method has the advantages of repeatability, high accuracy, no boreholes, and a simple setup and test procedure. In addition, a continuous profile of site properties can be determined, including modulus values and layer thicknesses, only limited judgment is required to reduce the data, and the method is capable of being fully automated. The main disadvantage at this point is that testing is not performed rapidly. For example, it took about 2 hr to test each of the three sites presented here as case histories. However, once testing is completely automated, it should be possible to test a site in a matter of minutes.

At each site, the investigation consists of three phases: field testing, determination of the R-wave dispersion curve, and inversion of the R-wave dispersion curve. These phases are discussed in the following paragraphs.

Field Testing

The test setup is shown in Figure 1. The setup con-

Figure 1. Experimental arrangement for SASW tests.



sists of an impulsive source, two vertical geophones (velocity transducers), and a transient event recorder-analyzer.

Impulsive Source

The source must be capable of transiently generating R-waves over a wide range in frequencies with an amplitude that can be detected by the geophones. Simultaneously, the source should generate minimal P- and S-wave energy. For the testing described in this paper, a 2-lb sledge hammer and chisel were used as the source when the spacing between the source and the first receiver was less than about 4 ft. When this spacing became greater than 4 ft, 8- and 15-lb sledge hammers were used at a maximum spacing of 16 ft.

Location of Receivers (Geophone Array)

Factors that affect appropriate receiver spacing include (a) the velocity of the material, (b) the depth of the investigation, (c) the range of frequencies, (d) the attenuation properties of the medium, and (e) the sensitivity of the instrumentation. Based on studies at several soil sites, Heisey, Stokoe, and Meyer (5) suggested that the distance between receivers (x) should be less than two wavelengths and greater than one-third of a wavelength. This relation can be expressed as

$$L_R/3 < x < 2L_R \tag{5}$$

This relation was used in analyzing all data presented in this paper.

In addition to the factors cited above, Nazarian and Stokoe (8) have shown that different geometries of the setup can affect the results. The two most common types of geometric arrangements for source and receivers in seismic testing are the common source-receiver (CSR) geometry and the common midpoint (CMP) geometry. In the CSR geometry, either the source or the receivers are fixed in one location and the other is moved during the test. In the CMP geometry, both source and receivers are moved the same distance about an imaginary centerline. For a medium consisting of a stack of horizontal layers with lateral homogeneity, the results of the tests performed with both methods are identical. If the layers are not horizontal or the seismic properties of any layer vary laterally, the CMP geometry is preferred because velocities are averaged over the testing range. However, if only a single CMP experiment is performed, there is no way to determine the dip of the layers.

In using the SASW method, the area between the receivers is important and the properties of the materials between the source and the near receiver have little effect on the results. Thus, the imaginary centerline in the CMP method is located between the receivers. The two receivers are moved away from the imaginary centerline at an equal pace, and the source is moved so that the distance between the source and the near receiver is equal to the distance between the two receivers. This geometry of source and receivers is called common receivers midpoint (CRMP) geometry and is shown in Figure 1.

Nazarian and Stokoe (8) have shown that use of the CRMP geometry in SASW tests significantly reduces scatter in the data at shallow depths. An additional advantage of the CRMP geometry is that, by reversing the location of the source while keeping the receiver location fixed and by averaging the records from these direct and reversed tests, the effect of any internal phase between the two geophones can be eliminated.

Recording Device

A convenient device for spectral analysis of surface waves is a Fourier spectral analyzer. A Fourier analyzer is a digital oscilloscope that, by means of a microprocessor attached to it, can perform directly in either the time or the frequency domain. Fourier analysis is a powerful tool in the decomposition of complicated transient waveforms into a group of simple harmonic waveforms. The benefit of being able to view the frequency-domain data in the field cannot be overemphasized.

Determination of R-Wave Dispersion Curve

The variation of wave velocity with frequency (or 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°. Thus, for each frequency the travel time between receivers can be calculated by

$$t(f) = \phi(f)/(360f) \tag{6}$$

where

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

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

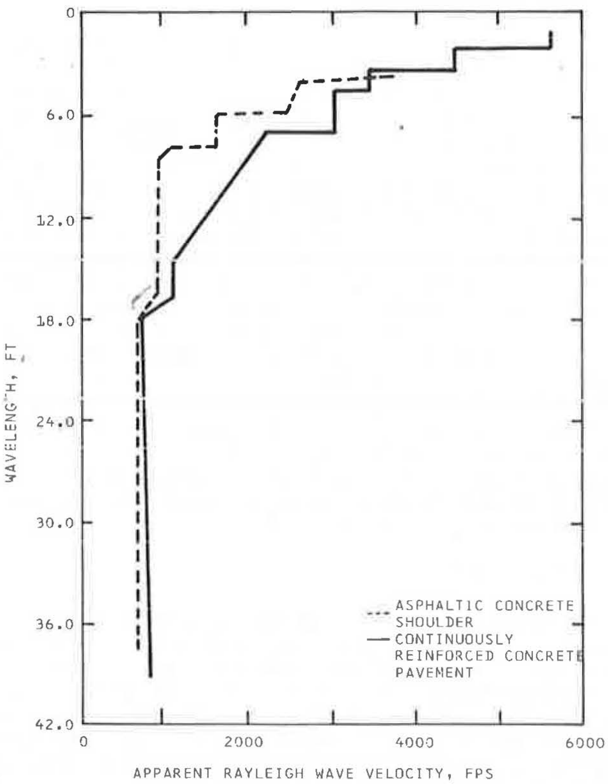
$$V_R(f) = x/t(f) \tag{7}$$

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

$$L_R(f) = V_R(f)/f \tag{8}$$

By repeating the procedure outlined by Equation 6 through 8 for every frequency, the R-wave velocity

Figure 2. Comparison of dispersion curves under adjacent ACP and CRCP sections.



corresponding to each wavelength is evaluated and the dispersion curve is determined.

R-wave velocities determined by this method are not actual velocities for the layers but apparent velocities. The existence of a layer with a higher or lower velocity at the surface of the medium affects the measurement of the velocities for the underlying layers. Thus, a method for evaluating actual R-wave velocities from apparent R-wave velocities is necessary in SASW testing.

Inversion of R-Wave Dispersion Curve

Inversion of the R-wave dispersion curve--or simply inversion--is the procedure of determining the actual propagation velocities at different depths from the dispersion curve. Inversion consists of determining the depth of each layer and the S-wave velocity for each layer from the apparent R-wave velocity versus wavelength.

In a layered medium in which there is no significant contrast in velocities for the layers, the apparent and actual R-wave velocities are approximately equal. But if one or more layers have significantly different properties, the apparent and actual R-wave velocities will be substantially different. This is especially true in a pavement system in which the stiffness of the materials can differ greatly. For example, in the case of a continuously reinforced concrete pavement (CRCP), the elastic properties of the concrete are typically many times greater than those of other materials. For this system, the apparent R-wave velocities of the underlying layers would be falsely high. Conversely, at a soil site where there may be significant seasonal precipitation, the first few feet of ground are softer in the wet season, and the apparent R-wave velocities of the underlying layers determined during this season would be too low.

To demonstrate this effect, the dispersion curves for adjacent asphaltic concrete pavement (ACP) and CRCP sections are shown in Figure 2. Although the properties of these two pavement surfaces are different, it is presumed that the subbase and the natural soil beneath the pavements are the same because the systems are within a few feet of each other. However, the two dispersion curves for the deposits beneath the pavement surfaces do not agree: the apparent R-wave velocities associated with the materials beneath the CRCP section are consistently higher than those beneath the ACP section.

In the preliminary investigation of the SASW method, Heisey, Stokoe, and Meyer (5) considered that the effective depth of sampling is equal to one-third of a wavelength. [Other work suggests that this is a reasonable approximation, especially at soil sites (9)]. Heisey, Stokoe, and Meyer also assumed that the apparent and actual R-wave velocities for each wavelength were equal. This crude inversion method is applicable to soil sites with relatively uniform, thick layers, and they successfully applied this method to several soil sites.

A refinement in the inversion process has been developed in this research based on Haskell's matrix for elastic surface waves in a multilayered solid media (10). To simplify the process of inversion, the following assumptions were made:

1. The layers are horizontal.
2. The velocity of each layer is constant and does not vary with depth.
3. The layers are homogeneous and linearly elastic.
4. The effective sampling depth is equal to one-third of the wavelength.
5. The apparent and actual velocities of the top layer are equal.

From item 4 the depths of all layers are known, and from item 5 the actual R-wave velocity of the top layer is available. By assuming that the wavefront passes through the overlying layers at the velocities determined for those layers, the R-wave velocity profile can be constructed from top to bottom sequentially. Because of the simplifying assumptions used, this refined inversion process does not function accurately under certain conditions. It is not yet possible to handle either (a) relatively thin layers (relative to the thickness of the other layers) when there is considerable variation in the properties of the overlying layer or (b) layers in which the velocity varies with depth. However, the inversion process is under continuous development and improvement.

COLUMBUS, TEXAS, EXPERIMENT

The SASW method was used on three pavement sections with different layerings near Columbus, Texas. This was the first time that the SASW method had been used to evaluate the elastic properties of a concrete pavement system.

Site

The site was located near Columbus, Texas, on TX-71 about a half-mile south of the TX-71 overpass on US-90. This section consists of two southbound lanes of CRCP, each 12 ft wide, a 4-ft-wide asphaltic concrete shoulder, and a natural soil median.

In August 1981 a preliminary set of SASW tests was conducted on all three sections (CRCP, ACP, and median) by Heisey. In March 1982 a second set of tests was performed at approximately the same location. In conjunction with the second set of tests, a series of crosshole seismic tests was performed under the asphaltic concrete shoulder and median. Due to the lack of appropriate drilling equipment, no crosshole tests could be conducted under the CRCP section. A third set of SASW tests was also performed in May 1982 on the CRCP section to study further the reproducibility of the results.

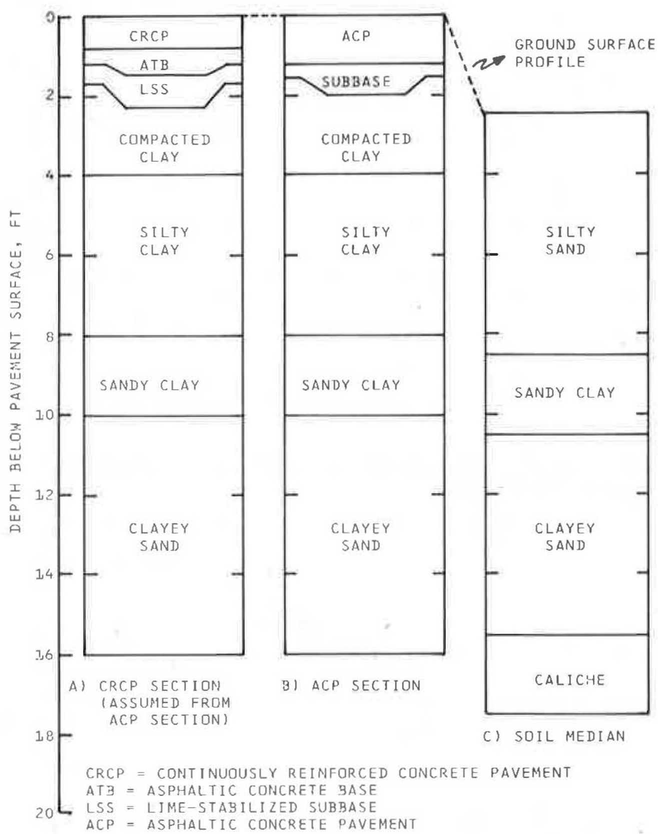
Material profiles for the ACP and soil median sections determined from the boreholes drilled for crosshole seismic tests are shown in Figure 3. It is assumed that the soil profiles under the CRCP and ACP sections are identical below the subbase. The assumed profile for the CRCP section is also shown in Figure 3.

Setup and Procedure

The general configuration of the source, receivers, and recording equipment is shown in Figure 1. Vertical geophones with a natural frequency of about 8 Hz were used as receivers. The CRMP geometry was used for testing in March and May 1982. The pattern of these tests is shown in Figure 4. The distance between the geophones ranged from 1 to 16 ft, and reversed tests were performed. The closer spacings were necessary to determine properties at the shallower depths and the larger spacings for deeper layers.

A CSR geometry was used for testing in August 1981. In this case the location of the source was held fixed and the receivers were moved. Receivers and receiver spacings were the same as in the 1982 tests. However, reversed testing was not performed in 1981.

Figure 3. Material profile at each test section.



Results

The primary objective of the tests performed by the SASW method was to evaluate the elastic properties and thicknesses of the different layers of the ACP and CRCP sections. Because this method has been used very little on pavement sections, the reproducibility of the results with different operators and different conditions was of concern. Thus, the first series of tests was conducted by Heisey in August 1981, and the next two series were performed in March and May 1982. In addition, the SASW method was used for the first time on a CRCP section.

Soil Median

Average dispersion curves from the two sets of tests performed in August 1981 and March 1982 are shown in Figure 5. It can be seen that there is no major difference in the results for wavelengths longer than 10 ft and a maximum difference of 8 percent at a wavelength of about 36 ft. Determination of the average dispersion curve from the data for August 1981 was somewhat difficult because of scatter in the data. In addition, extensive precipitation occurred on the day before testing in March 1982, which caused the first few feet of the median to be quite soft and resulted in a significant drop in the elastic properties of the near-surface material.

ACP Section

Average dispersion curves for the experiments conducted on the ACP section in 1981 and 1982 are shown in Figure 6. The thicknesses and apparent R-wave velocities for different layers from the 1981 and 1982 tests are in agreement, and no significant differences can be detected in the average dispersion curves. The relative difference between the two curves does not exceed 6 percent. Because the fre-

Figure 4. Pattern of SASW tests used in March and May 1982.

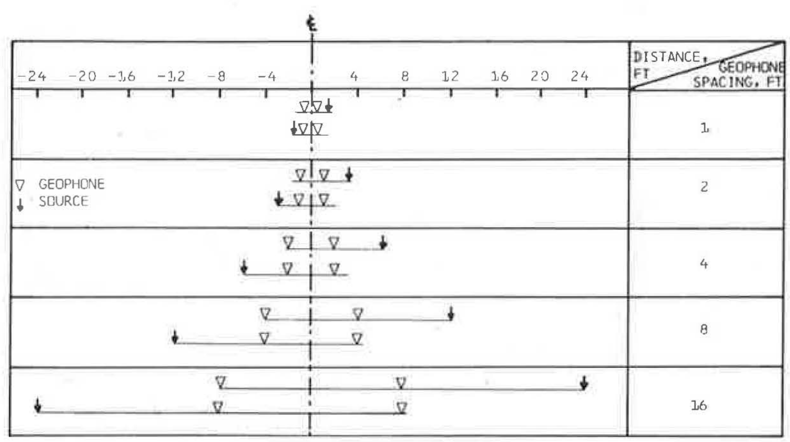


Figure 5. Average dispersion curves determined in August 1981 and March 1982 for natural soil (median).

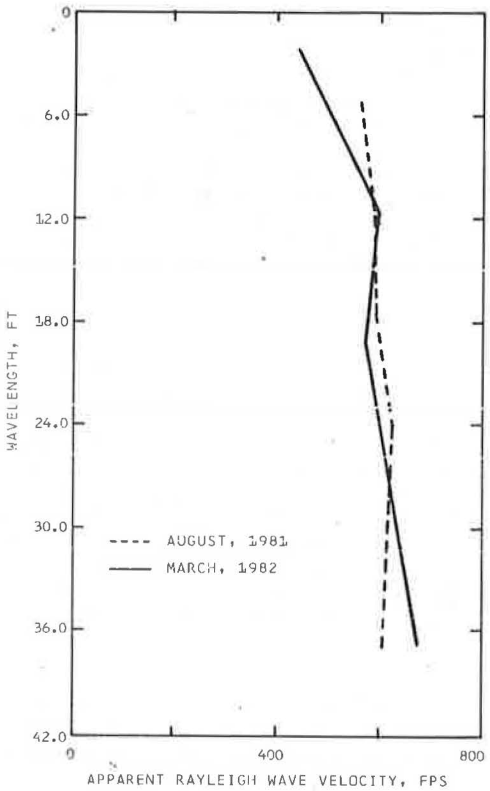


Figure 6. Average dispersion curves determined in August 1981 and March 1982 for asphaltic concrete shoulder.

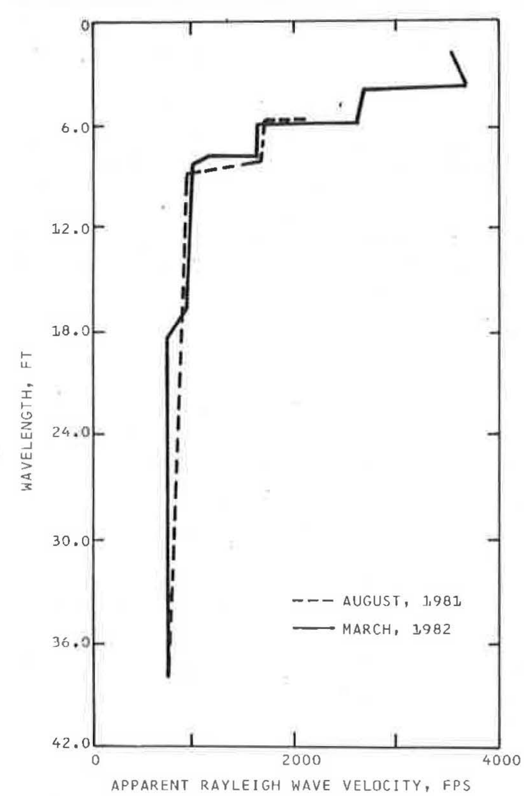


Figure 7. Dispersion curve determined in May 1982 for CRCP section.

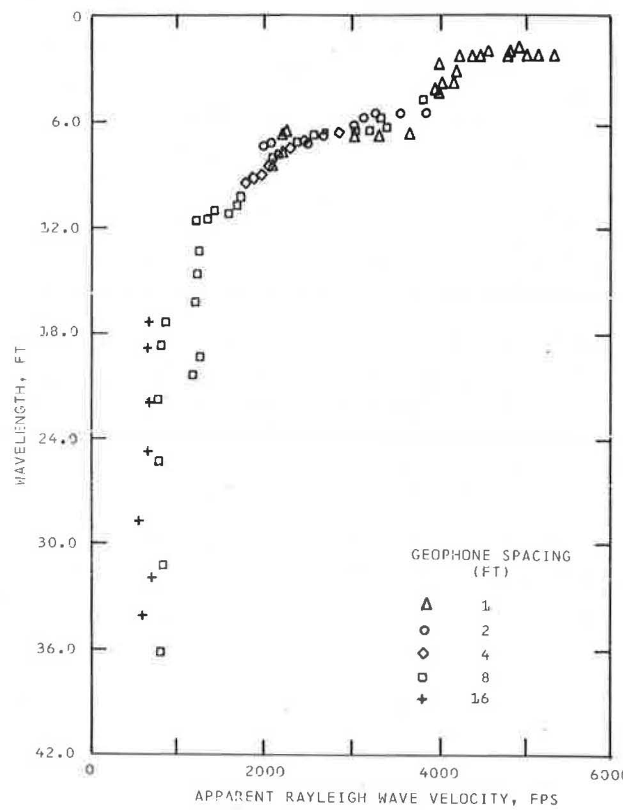
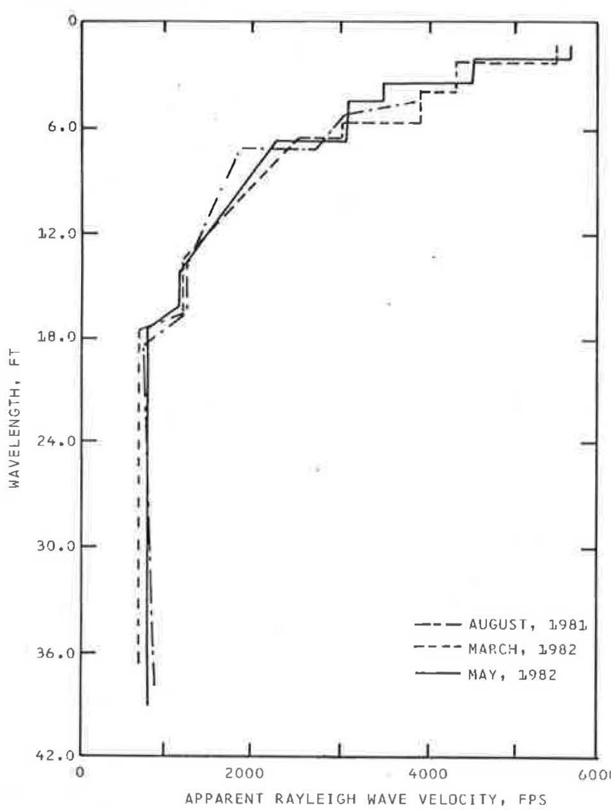


Figure 8. Average dispersion curves determined in August 1981 and March and May 1982 for CRCP.



quencies generated in the tests performed in 1981 were not high enough, no sampling of the ACP was done in that series.

CRCP Section

The most critical section studied was the CRCP section. Fine layering in the pavement system and a large contrast in the velocities for the layers in a depth of less than 3 ft required special consideration. Use of a source capable of generating high-frequency waves was essential. For spacings of 1 and 2 ft, a 2-lb sledge hammer and chisel worked well, generating frequencies as high as 3900 Hz. Good coupling between the concrete and the geophones was also necessary to monitor the high frequencies correctly. This was accomplished by epoxying the geophones to the pavement.

An example of the disperson curve for the third attempt on the CRCP section in May 1982 is shown in Figure 7. Average dispersion curves from all three attempts on this section are shown in Figure 8. Because high frequencies were not generated in August 1981, no information on the properties of the concrete and base layers could be obtained. Fewer tests were performed in March 1982 than in August 1981 due to time limitations. The shortest wavelength obtained in the second attempt was approximately 1 ft (equivalent to a sampling depth of 4 in.)

The primary concerns in the May 1982 tests were to sample even shallower depths and to check the reproducibility of the results. Several tests performed with close spacings between the geophones (spacings of 1 and 2 ft) resulted in the sampling depth being decreased to 3 in. The highest frequency in these tests was 3900 Hz whereas in the first attempt it was 3100 Hz. The 800-Hz increase in the upper bound of the frequency only decreased the depth of sampling by about 1 in.

Except for the range of wavelengths from 5 to 8 ft, in which there is some scatter, the dispersion curves in Figure 8 show less than a 9 percent difference, which demonstrates the high degree of reproducibility of the tests. The deviation for 5- to 8-ft-long wavelengths corresponds to the few inches above and below the boundary between the subbase and the compacted fill and could possibly be due to variations in the level of the subbase-fill interface along the distance covered by the geophones. However, because the emphasis in May 1982 was placed on measurement of the pavement system, the results of this series of tests seem more reliable.

Comparison of Elastic Properties

Crosshole Seismic Tests

To evaluate independently wave velocities and moduli at each site, crosshole seismic tests were performed on the ACP and soil median sections [details of the testing procedure are given by Nazarian and Stokoe (8)]. Both compression and shear wave velocities were measured. S-wave velocities determined from the crosshole tests were then compared with S-wave velocities based on the average dispersion curves for the soil median and ACP sections from March 1982 (Figures 5 and 6) and the average dispersion curve for the CRCP section from May 1982 (Figure 8). This comparison is shown in Figure 9.

S-wave velocities determined by the SASW and crosshole methods are in good agreement, especially at the median section. Deviation of the S-wave velocities under the median from these two methods is less than 7 percent except at a depth of about 5 ft, where the difference is about 14 percent. For the ACP section, there are some differences between S-wave velocities determined by the two methods, as shown in Figure 9B. The major difference occurs in the subbase and results from use of the preliminary inversion method presented in this paper. This method is unable to handle sudden changes in velocity in a thin layer. If this difference in S-wave velocities from the two methods is ignored, the remainder of the profile differs by less than 9 per-

Figure 9. Comparison of S-wave velocities from crosshole and SASW methods.

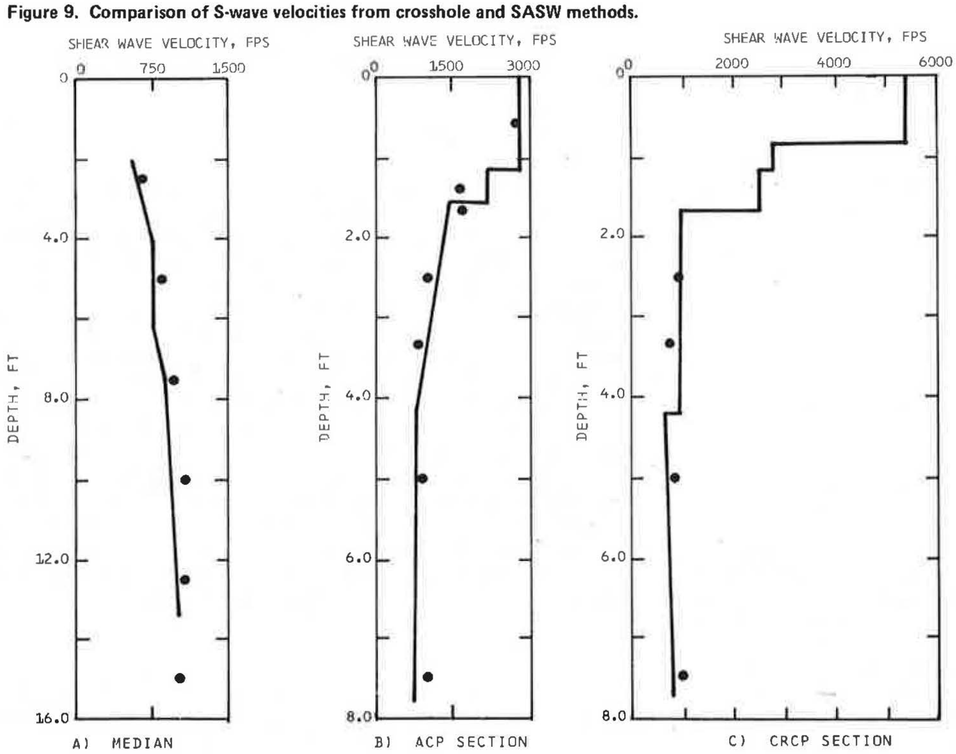


Figure 10. Comparison of Young's moduli from crosshole and SASW methods.

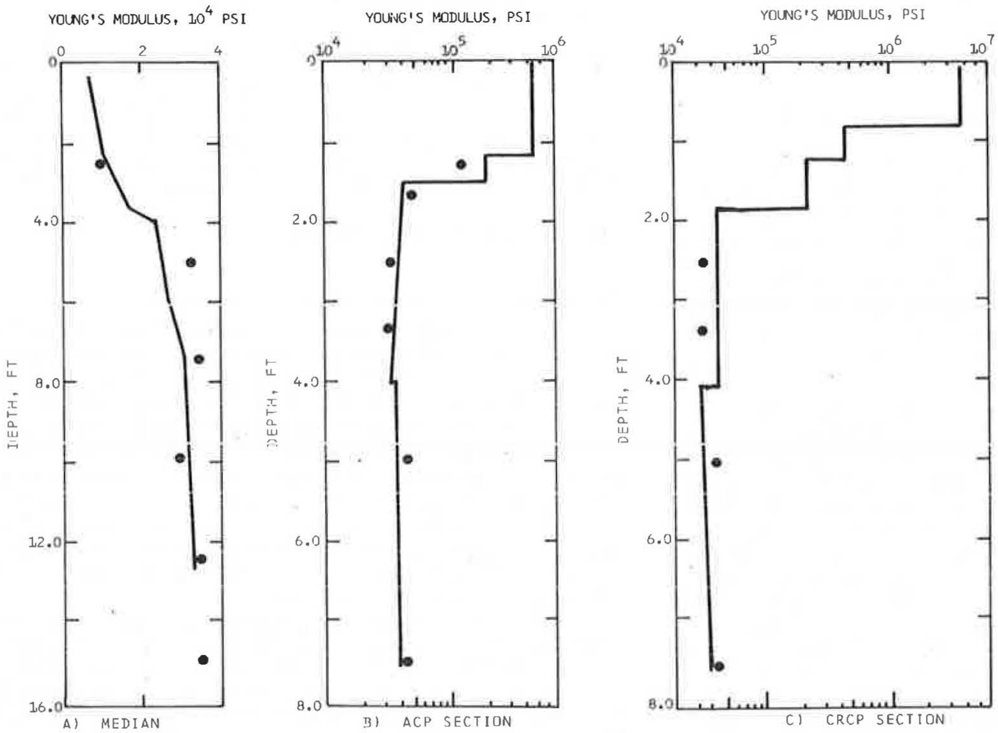


Table 1. Comparison of Young's moduli from crosshole seismic and SASW tests on soil median.

Depth (ft)	Young's Modulus (psi) Crosshole	SASW	Difference[a] (%)
2.5	10,180	11,230	+9.3
5.0	33,150	25,540	-29.8
7.5	34,810[b]	31,480	-10.5
10.0	30,230	31,880	+5.2
12.5	35,050	-	-
15.0	35,510	-	-

[a](SASW - crosshole) ÷ SASW.
[b]Evaluated from s-wave velocity.

Table 2. Comparison of Young's moduli from crosshole seismic and SASW tests on ACP section.

Layer	Depth (ft)	Young's Modulus (psi) Crosshole	SASW	Difference[a] (%)
Asphalt	0.58	467,500	453,200	-3.2
Subbase	1.38	110,000	198,310	+44.5
Compacted fill	1.67	49,500	45,610	-8.5
	2.50	32,850	37,430	+12.2
	3.33	32,350	36,900	+11.5
Sandy clay	5.0	42,050	38,820	-8.3
	7.5	40,250	39,340	-2.3

[a](SASW - crosshole) ÷ SASW.

cent for the ACP section. Because the crosshole method is well-established as an accurate method of determining in situ S-wave velocities (11,12), these close comparisons show the effectiveness of the SASW method.

Because no crosshole tests could be performed on the CRCP section, it was assumed, from crosshole tests performed under the ACP section, that the S-wave-velocity profile below the CRCP section

Table 3. Comparison of Young's moduli from crosshole seismic and SASW tests on CRCP section.

Layer	Depth (ft)	Young's Modulus (psi) Crosshole	SASW	Difference[a] (%)
CRCP	0.83	4,675,000[b]	3,928,000	+19.0
Asphalt-treated base	1.17	-	462,380	-
Lime-stabilized subbase	1.67	-	223,380	-
Compacted fill	2.50	32,850	41,450	-20.8
Sandy clay	5.00	42,050	34,740	-21.0
	7.50	40,250	37,960	-6.0

[a](SASW - crosshole) ÷ SASW.
[b]From surface refraction tests.

(i.e., below the depth of 2.5 ft) represented the material below that section. Comparison of these two S-wave-velocity profiles shows that they agree within 10 percent; hence, the SASW method can also be used effectively on concrete pavements.

Profiles of Young's moduli from the SASW and crosshole tests on the three sections are shown in Figure 10 and in Tables 1 to 3. In the crosshole tests, Young's moduli were calculated from the P-wave velocities measured in situ. In the case of the SASW tests, shear moduli were determined from the S-wave velocities, and then, with values of Poisson's ratio evaluated from the crosshole tests, Young's moduli were calculated. In general, Young's moduli from the two test methods are within about 10, 12, and 20 percent, respectively, for the soil, ACP, and CRCP sections. These close comparisons demonstrate the value of the SASW method.

Dynaflect Testing

Young's moduli were also back-calculated from deflection basins measured by Dynaflect testing on the CRCP section. These moduli are summarized in Table

Table 4. Comparison of Young's moduli calculated from wave velocities and deflection measurement on CRCP section.

Profile	Young's Modulus (psi) SASW Method	Deflection Method[a]
Continuously reinforced concrete surface layer	3,928,000	5,500,000
Asphalt concrete base layer	462,380	600,000
Lime-stabilized subgrade layer	223,380	125,000
Natural subgrade (soil layers)	37,960-41,450[b]	28,000

[a] Back-calculated from fitted deflection basins by using elastic theory (ELSYM5).
[b] Up to 7.5-ft depth.

4 along with those determined by the SASW tests at the same location. The closest comparison between moduli from the two methods occurs in the asphaltic concrete base layer, where the values are within about 13 percent. However, in the other layers the moduli differ, on the average, by about 40 percent. Based on the close comparisons of moduli measured independently by the SASW and crosshole tests, it is believed that moduli determined by the SASW tests more accurately reflect the in situ conditions than do the Dynaflect results.

SUMMARY AND CONCLUSIONS

The SASW method of determining moduli and thicknesses of pavement systems as well as soil sites can be used to solve problems in which moduli are used directly, such as in overlay designs, or indirectly, such as in controlling the quality of compaction of pavement materials during construction. The method is nondestructive, has a unique solution, and is capable of full automation.

Preliminary studies of the feasibility of the method and the testing procedure were conducted by Heisey, Stokoe, and Meyer (5). That initial work has been expanded and improved in the following areas:

1. The test setup has been modified. Instead of the CSR geometry first used, the tests are now performed by using a CRMP geometry, which significantly reduces scatter in the data. In addition, the direction of testing is reversed to eliminate the effect of possible internal phase between the receivers and to average the effect of dipping layers.
2. A simple inversion method for elimination of the effect of high- or low-velocity shallow layers has been developed so that moduli at depth can be accurately measured.

The inversion process was used to determine the elastic properties of pavements at three sites that had layerings of ACP, CRCP, and a natural soil. The elastic moduli determined by the SASW method compare favorably with those determined by crosshole seismic tests. Deviations between moduli determined by the two methods are on the average less than 10, 12, and 20 percent, respectively, in the median, ACP, and CRCP sections. Elastic moduli determined by the SASW method are also compared with those determined by Dynaflect measurements on the CRCP. The comparison is rather unfavorable: the moduli vary from 13 to 45 percent.

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