COMPREHENSIVE PAVEMENT EVALUATION USING SEISMIC PAVEMENT ANALYZER

a report submitted to
Transportation Research Council
Department of Transportation
Commonwealth of Virginia

THE UNIVERSITY OF TEXAS
AT EL PASO

June, 1994

CENTER FOR GEOTECHNICAL & HIGHWAY MATERIALS RESEARCH
THE UNIVERSITY OF TEXAS AT EL PASO
EL PASO, TEXAS 79968
(915)747-5464
COMPREHENSIVE PAVEMENT ASSESSMENT
USING
SEISMIC PAVEMENT ANALYZER

by
Soheil Nazarian, PhD, PE
Kevin Crain, MS
and
Mark Baker, DSc

for
Virginia Transportation Research Council
Department of Transportation
Box 3817 University Station
Charlottesville, VA 22903

Center for Geotechnical and Highway Materials Research
The University of Texas at El Paso
El Paso, TX 79968
(915) 747-6925

June, 1994
# TABLE OF CONTENTS

1. INTRODUCTION .................................................. 1

2. SEISMIC PAVEMENT ANALYZER ..................................... 1

3. DESCRIPTION OF MEASUREMENT TECHNOLOGIES ..................... 3
   3.1 Impulse-Response (IR) Method .................................. 3
   3.2 Ultrasonic-Surface-Wave Method ................................ 4
   3.3 Ultrasonic Compression Wave Velocity Measurement .............. 5
   3.4 Impact-Echo Method ........................................... 5

4. DATA COLLECTION AND ANALYSIS .................................. 6
   4.1 Data Collection ................................................ 6
   4.2 Data Reduction ................................................. 7

5. PRESENTATION OF RESULTS ....................................... 10
   5.1 Site 1 .......................................................... 11
   5.2 Site 2 .......................................................... 11
   5.3 Site 3 .......................................................... 12
   5.4 Site 5 .......................................................... 12
   5.5 Site 6 .......................................................... 13
   5.6 Site 7 .......................................................... 13

6. REFERENCES ...................................................... 14

APPENDIX A - RAW DATA MEASURED WITH SPA AT SITE 1
APPENDIX B - RAW DATA MEASURED WITH SPA AT SITE 2
APPENDIX C - RAW DATA MEASURED WITH SPA AT SITE 3
APPENDIX D - RAW DATA MEASURED WITH SPA AT SITE 5
APPENDIX E - RAW DATA MEASURED WITH SPA AT SITE 6
APPENDIX F - RAW DATA MEASURED WITH SPA AT SITE 7
LIST OF TABLES

Table 1  Strengths of Five Testing Techniques Used by Seismic Pavement Analyzer
Table 2  Summary of Properties Measured with SPA at Site 1
Table 3  Summary of Properties Measured with SPA at Site 2
Table 4  Summary of Properties Measured with SPA at Site 3
Table 5  Summary of Properties Measured with SPA at Site 5
Table 6  Summary of Properties Measured with SPA at Site 6
Table 7  Summary of Properties Measured with SPA at Site 7

LIST OF FIGURES

Figure 1  Schematic of Seismic Pavement Analyzer
Figure 2  Typical Time Records from Accelerometers
Figure 3  Typical Normalized Time Records Obtained with SPA
Figure 4  Typical Spectral Functions used in Impulse-Response Test
Figure 5  Typical Spectral Functions Used in Impact-Echo Test
Figure 6  Typical Spectral Functions Used in Ultrasonic-Surface-Wave Test
Figure 7  Typical Amplified Signal Used in Ultrasonic-Body-Wave Test
Figure 8  Plan View of Richmond and Site Tested
Figure 9  Typical Test Arrangement at each Test Location
COMPREHENSIVE PAVEMENT ASSESSMENT USING
SEISMIC PAVEMENT ANALYZER

Soheil Nazarian, Kevin Crain and Mark Baker
Center for Geotechnical and Highway Materials Research
The University of Texas at El Paso
El Paso, TX 79968

1. INTRODUCTION

The Seismic Pavement Analyzer (SPA) was used at six sites in Richmond, Virginia on May 16 and 17, 1994. The SPA was used to determine the variation in the shear and compression wave velocities, thickness at each site as well as to assess the existence of delamination within or lack of support under concrete slabs. Results from this study are reported herein, along with a brief explanation of the field testing procedures and data analyses.

Dr. Marg G. Lozev of the Virginia Transportation Research Council was the project manager and was present during the field testing phase. Drs. Gerry Clemena and Steve Lane also assisted us during field testing.

2. SEISMIC PAVEMENT ANALYZER

The Seismic Pavement Analyzer (SPA) is an instrument designed and constructed to monitor conditions associated with pavement deterioration. It measures such conditions as voids or loss of support under a rigid pavement, moisture infiltration in asphalt concrete pavement, fine cracking in pavements, delamination of overlays, and aging of asphalt.

The SPA detects these pavement conditions by estimating compression and/or shear wave velocities in the pavement, base, and subgrade from the following wave propagation measurements: 1. Impact Echo (IE), 2. Impulse Response (IR), 3. Spectral Analysis of Surface Waves (SASW), 4. Ultrasonic Surface Waves (USW), and 5. Ultrasonic Body Waves (UBW).

The SPA records the pavement response produced by high- and low-frequency pneumatic hammers on five accelerometers and three geophones. A computer controls data acquisition,
instrument control, and interpretation; measurements and interpretations are reported in both screen and database formats.

The equipment can perform several functions: 1. analyzing in detail pavement conditions identified in the network-level surveys; 2. diagnosing specific distress precursors to aid in selecting the maintenance treatment; and 3. monitoring pavement conditions after maintenance to determine the treatment’s effectiveness.

The operating principle of the SPA is based on generating and detecting stress waves in a layered medium. Each of the five tests and its areas of strength are summarized in Table 1. The SASW method was not utilized in this study, and therefore, not discussed any further. The design and construction of the SPA are based on two general principles. First, the strength of each method should be fully utilized; and second, testing should provide enough redundancy to identify each layer that will potentially contribute to the distress of the pavement.

The ultrasonic-body-wave method can determine the existence of cracks, even if they have not extended through the thickness of the layer. In this method, stress wave energy is generated at one point and detected at several other points. Any cracks in the material located between the source and the receiver will delay the direct propagation of waves and will reduce the amplitude associated with the arriving wave. Differentiation between a strong material containing cracks and a weak material is not possible at this time.

A void beneath or within a slab results in increased flexibility of the slab. Therefore, measuring the flexibility of the slab at different locations using the impulse-response method can pinpoint the voids or loss of support. Initial stages of debonding may not significantly affect the results from the IR method.

The impact echo method distinguishes between overlay delamination and voids beneath or within the slab. The method, a special case of ultrasonic-body-wave propagation, can determine the depth to the reflector.

The impulse response and the impact echo are the prime methods for determining the location and existence of delamination. The theoretical and experimental aspects of using these two tests for detecting overlay delamination are identical to those used for locating voids and loss of support. The only differences are the nature and location of the interface. For delamination, the void occurs at the interface of two layers and the delaminated layer is located closer to surface.

June, 1994

DRAFT

PAGE 2
3. DESCRIPTION OF MEASUREMENT TECHNOLOGIES

3.1 Impulse-Response (IR) Method

Two parameters are obtained with the IR method—the shear modulus of subgrade and the damping ratio of the system. These two parameters characterize the existence of several distress precursors. In general, the modulus of subgrade can be used to delineate between good and poor support. The damping ratio can distinguish between the loss of support or weak support. The two parameters are extracted from the flexibility spectrum measured in the field. An extensive theoretical and field study (Reddy, 1992) shows that, except for thin layers (less than 75 mm) and soft paving layers (i.e., flexible pavements), the modulus obtained by the IR method is a good representation of the shear modulus of subgrade, with little influence from the stiffness of the paving layers. In other cases, the properties of the pavement layers (AC and base) affect the outcome in such a manner that the modulus obtained from the IR test should be considered an overall modulus.

The IR tests use the low-frequency source and geophone G1 (see Figure 1). The pavement is impacted to couple stress wave energy in the surface layer. At the interface of the surface layer and the base layer, a portion of this energy is transmitted to the bottom layers, and the remainder is reflected back into the surface layer. The imparted energy is measured with a load cell. The response of the pavement, in terms of particle velocity, is monitored with the geophone and then numerically converted to displacement. The load and displacement time-histories are simultaneously recorded and are transformed to the frequency domain using a Fast-Fourier Transform algorithm. The ratio of the displacement and load (termed flexibility) at each frequency is then determined.

For analysis purposes, the pavement is modeled as a single-degree-of-freedom (SDOF) system. Three parameters are required to describe such a system—natural frequency, damping ratio, and gain factor. The last two can be replaced by the static flexibilty and the peak flexibility. These three parameters are collectively called the modal parameters of the system. The natural frequency and gain factor are used to determine the modulus of subgrade. The damping ratio is used directly.

To determine the modal parameters, a curve is fitted to the flexibility spectrum according to an elaborate curve-fitting algorithm that uses the coherence function as a weighing function (Richardson and Formenti, 1982). The poles, zeros, and gain factor obtained from the curve-fitting are easily
converted to modal parameters. From these parameters, the modulus of subgrade is determined. The shear modulus of subgrade, $G$, is calculated from (Dobry and Gazetas, 1986)

$$G = \frac{(1 - \nu)}{[2L \cdot A_s \cdot I, S_r]}$$  \hspace{1cm} (1)

where $\nu$ = Poisson’s ratio of subgrade, $L$ = length of slab, and $A_s$ = static flexibility of slab (flexibility at $f = 0$). The shape factor, $S_r$, has been developed by Dobry and Gazetas (1986). $I$, (Nazarian et al, 1994) is a parameter which considers the effect of an increase in flexibility near the edges and corners of a slab. Parameter $I$, is a function of the length and width of the slab, as well as the coordinates of the impact point relative to one corner. Depending on the size of the slab and the point of impact, the value of $I$, can be as high as 6.

The damping ratio, which typically varies between 0 to 100 percent, is an indicator of the degree of the slab’s resistance to movement. A slab that is in contact with the subgrade or contains a water-saturated void demonstrates a highly damped behavior and has a damping ratio of greater than 70 percent. A slab containing an edge void would demonstrate a damping ratio in the order of 10 to 40 percent. A loss of support located in the middle of the slab will have a damping of 30 to 60 percent.

3.2 Ultrasonic-Surface-Wave Method

The ultrasonic-surface-wave method is an offshoot of the SASW method. The major distinction between these two methods is that in the ultrasonic-surface-wave method the shear velocity of the top paving layer can be easily and directly determined without a complex inversion algorithm. To implement the method, the high-frequency source and accelerometers A2 and A3 (see Figure 1) are utilized.

At wavelengths less than or equal to the thickness of the uppermost layer, the velocity of propagation is independent of wavelength. Therefore, if one simply generates high-frequency (short-wavelength) waves, and if one assumes that the properties of the uppermost layer are uniform, the shear wave velocity of the upper layer, $V_s$, can be determined from

$$V_s = (1.13 - 0.16\nu) V_{in}$$  \hspace{1cm} (2)
The shear modulus of the top layer, $G$, can alternatively be determined from

$$G = \rho V_s^2$$

(3)

where $V_s$ = velocity of surface waves, $\rho$ = mass density, and $\nu$ = Poisson's ratio.

The methodology can be simplified even further. If one assumes that the properties of the uppermost layer are uniform, the shear wave velocity of the top layer can be determined from

$$V_s = (1.13 - 0.16\nu)(m/360D)$$

(4)

Parameter $m$ (deg/Hz) is the least-squares fit slope of the phase of the transfer function in the high-frequency range.

3.3 Ultrasonic Compression Wave Velocity Measurement.

Theoretically, all accelerometers can be used to measure compression wave velocity of the upper layer of pavement. Once the compression wave velocity of a material is known, its Young’s modulus can be readily determined.

Miller and Pursey (1955) found that when the surface of a medium is impacted, the generated stress waves propagate mostly with Rayleigh wave energy and, to a lesser extent, with shear and compression wave energy. As such, the body wave energy present in a seismic record generated using the set-up shown in Figure 1 is very small; for all practical purposes it does not contaminate the SASW results. However, compression waves travel faster that any other type of seismic wave, and are detected first on seismic records.

An automated technique for determining the arrival of compression waves has been developed. Times of first arrival of compression waves are measured by triggering on an amplitude range within a time window (Willis and Toksoz, 1983).

3.4 Impact-Echo Method

The impact-echo method can effectively locate defects, voids, cracks, and zones of deterioration within concrete. The method has been thoroughly studied and effectively used on many projects by
researchers at the National Institute of Standards and Technology. In a comprehensive theoretical and experimental study, Sansalone and Carino (1986) considered the effects of type of impact source, distance from impact point to receiver, type of receiving transducers, and depth of reflecting interfaces.

The high-frequency source and accelerometer A1, are used, and possibly A2 as well (see Figure 1). Once the compression wave velocity of concrete, \( V_p \), is known, the depth-to-reflector, \( T \), can be determined from (Sansalone and Carino, 1986)

\[
T = \frac{V_p}{2f}
\]  

(5)

where \( f \) is the resonant (return) frequency obtained by transforming the deformation record into the frequency domain.

4. DATA COLLECTION AND ANALYSIS

4.1 Data Collection

The technician initiates the testing sequence through the computer, that then lowers the sensors and impact unit onto the pavement surface. The high-frequency source is then activated. The outputs of the three accelerometers closest to the high-frequency source, as well as the load cell connected to this source, are used first. The source is fired four to seven times. For the last three impacts of the source, the output voltages of the load cell and the receivers are saved and averaged (stacked) in the frequency domain. The other (prerecording) impacts are used to adjust the gains of the pre-amplifiers. The gains are set in a manner that optimizes the dynamic range. After this step, another set of impacts are utilized to determine compression wave velocities. To perform the test, the gains of all amplifiers are set to maximum. In this manner, the arrival of compression waves can be better identified.

The same procedure is followed again, but the first three accelerometers are replaced by the last three accelerometers. A multiplexer switches the accelerometers. The middle accelerometer (third closest accelerometer to the source) is active in both sets of experiments.
Typical voltage outputs of the load cell and the three near accelerometers are shown in Figure 2. Naturally, as the distance from the source increases, the amplitude of the signal decreases.

To ensure that an adequate signal-to-noise ratio is achieved in all channels, signals similar to those shown in Figure 2 are normalized to a maximum amplitude of one, as shown in Figure 3. In this manner, the main features of the signals can be easily inspected.

In the next phase of data collection, the low-frequency load cell and the three geophones are recorded. The procedure described above for each of the accelerometer banks is utilized. A typical output of the three geophones is shown in Figure 3c in the normalized fashion. Once again, the quality of the data is adequate.

The data collected in this fashion has to be processed using signal processing and spectral analysis. These processes are described in the next section.

4.2 Data Reduction

Impulse-Response Method

This method uses the voltage output from the first geophone (the geophone closest to the source, G1) and the low-frequency load cell (see Figure 3c).

The load cell record consists of a half-sine wave approximately 2-msec long. The small reverberation past the actual impact corresponds to the reflection of the wave inside the source assembly. The amplitude of this reverberation is muted so it does not affect the results. The response of the geophone is a steady-state damped response. The slight time delay between the geophone and load cell records is the result of the separation between the source and the receiver.

A detailed description of steps necessary to complete the data reduction can be found in Nazarian et al (1994). Briefly, the output of the load cell and geophone are transformed into the frequency domain using a Fast-Fourier Transform (FFT) algorithm, obtaining the ratio of the particle velocity and the load at each frequency. This function, the mobility spectrum, is then integrated to obtain the flexibility spectrum. The flexibility spectrum is used to determine the parameters for detecting voids or loss of support.

A typical flexibility spectrum is shown in Figure 4. The response is as expected, except for frequencies below approximately 50 Hz. The erratic nature of the signal at low frequencies is probably because of the movement of the trailer.
The coherence function associated with this record is shown in Figure 4b. The coherence values are close to unity except at low frequencies. A coherence value of unity corresponds to a highly coherent signal between the load cell and receiver. In other words, there was no incoherent background noise in the signals.

In the next step, a complex-valued curve representing a single-degree-of-freedom (SDOF) dynamic system is fitted to the flexibility spectrum. A typical fitted curve is shown in Figure 4a. The agreement between the measured and the fitted data is good.

Impact-Echo Method

The impact-echo method is similar to the impulse-response method. However, the impact-echo method uses the records from the small load cell and the accelerometer closest to the high-frequency source. Typical outputs from the accelerometer and the load cell are shown in Figure 3a.

In the next step, the two signals are transformed into the frequency domain following the procedure outlined above for impulse-response testing. A typical frequency-response spectrum for a site is shown in Figure 5a.

The major peak seen in Figure 5a (at about 10 kHz) corresponds to a standing wave within the thickness of the layer and is called the resonant frequency.

The coherence function is shown in Figure 5b. In general, the data collected with the device have no incoherent noise, except at several isolated frequencies.

To calculate the thickness of the layer, the compression wave velocity of the material is determined using the ultrasonic-body-wave method. The thickness is equal to one-half of the ratio between the compression wave velocity and the return resonant frequency.

Ultrasonic-Surface-Wave Method

This method determines the shear wave velocity or shear modulus of the top layer, using the time records of two accelerometers, accelerometer A2 (150 mm away from the source) and accelerometer A3 (300 mm away from the source) (see Figure 3a). These two signals are Fourier-transformed and the ratio of the two signals is calculated in the form of the transfer function. However, unlike the previous two methods, the ultrasonic-surface-wave method uses only the phase of the transfer function.

A phase spectrum for time records similar to those shown in Figure 3a is shown in Figure 6a.
The phase oscillates on a radius between $\pi$ and $-\pi$ radians (180 and -180 degrees). This is the standard method of presenting phase data, because the detailed variation in the data can be observed in a small space.

The data shown in Figure 6a are smooth and do not exhibit much scatter in phase with the frequency, up to a frequency of 35 or 40 kHz. However, the data are rather noisy above a frequency of 35 or 40 kHz.

The coherence function associated with this record is shown in Figure 6b. The coherence is almost equal to one, up to a frequency of 35 or 40 kHz. Above the frequency of 35 kHz, the data are of low quality and are not usable.

The frequency of 35 kHz for this experiment corresponds to a wavelength of less than 38 mm. Shorter wavelengths can be investigated using accelerometer A1 and accelerometer A2 (which are spaced 75 mm apart). One physical limitation is the aggregate size. Wavelengths shorter than the maximum aggregate size probably do not follow the laws of wave propagation in a homogeneous medium.

The shear wave velocity of the top layer was obtained using a complex-valued curve-fitting process with the coherence as the weighing function (Nazarian and Desai, 1993). The results are shown in Figure 6a. The actual and fitted curves compare quite favorably up to a frequency of 30 kHz.

In the next step, the phase is "unwrapped"; that is, the appropriate number of cycles is added to each phase. The unwrapped phase for the "wrapped" phase shown in Figure 6a is shown in Figure 6c. The slope of the line is basically constant with frequency.

Finally, a line is fitted to the curve in the range of frequencies corresponding to wavelengths shorter than the thickness of the top layer. The slope of the line can be used to determine the shear wave velocity (see previous section).

**Ultrasonic-Body-Wave Method**

The ultrasonic-body-wave method uses the same records as in the ultrasonic-surface-wave method. In Figure 3, the arrival of the compression waves (P-waves) cannot be identified in part because the surface wave energy dominates all signals. To determine the arrival of the P-waves, the gain of all amplifiers is set at the maximum possible range to collect data for determining compression.
wave velocities. Such a record is shown in Figure 7. Accelerometers A1 and A2 cannot identify the energy associated with the compression waves, because the seismic energy has not traveled over enough distance to separate into distinct compressional and shear waves. However, the other accelerometers, can identify the arrival of the P-waves. In Figure 7, the arrows in each record correspond to the arrival of these waves; typically, accelerometers A3 and A4 record the arrival of energy most consistently. The compression wave velocity is calculated from the distance between the receivers and the difference in the travel time. The compression wave velocity can then be converted to Young’s modulus.

5. PRESENTATION OF RESULTS

Six sites in the Richmond area were tested during two days of field testing. As shown in Figure 8, the sites were either located on I-295 or Route 60. The typical cross-sections of the six sites were similar and consisted of about 200 mm of CRCP with reinforcement placed at a depth of about 130 mm, over a 150-mm thick layer of stabilized base (stabilized with either asphalt or cement), over subgrade.

Five different nondestructive testing devices were almost concurrently utilized at each site. These devices were: a digital-imaging camera, an impact-echo device, an ultrasonic device (V-meter), a falling weight deflectometer and the Seismic Pavement Analyzer. The results from the Seismic Pavement Analyzer are discussed below.

All test locations had been pre-selected and marked by the staff of Virginia Transportation Research Council prior to field testing. A schematic of marks (circles and pluses) for one test point is shown in Figure 9 along with the relative position of the SPA sensors. The lateral position of the SPA sensors varied between zero to 30 cm from the longitudinal centerline of the marked area. This was necessary so that the trailer can be accommodated on the pavement.

The results from the tests at the six sites are summarized in Tables 2 through 6. The raw data for the sites are included in Appendices A through F. Based upon the experience of the authors except for a few isolated points the quality of the data collected was high.

In the remainder of this report the results are briefly analyzed. It should be mentioned that the sites were numbered as 1 through 3 and 5 through 7, with no results available for Site 4.
5.1 Site 1

The variations in compression wave velocities with test location for Accelerometer 3 (30 cm from the source) and Accelerometer 4 (60 cm from the source) are shown in Table 2. The velocities from Accelerometer 4, rounded to the closest 100 m/sec, are more or less constant and about 3,800 m/sec. For Accelerometer 3, compression wave velocities vary between 3,500 m/s to 3,800 m/s.

The shear wave velocities obtained from the ultrasonic surface waves are also consistent and are about 2500 m/sec. The lower values correspond well with the existing cracks at the site.

Using a compression wave velocity of 3,800 m/sec, the thickness at each point were calculated as reported in Table 2. The thickness of the concrete layer is about 205 mm except for Location 3 where it is determined as about 188 mm. Investigation of the raw data from the impact-echo tests (see Appendix A) reveals two frequency ranges with significant energy. The first one, about 9 kHz corresponds to the slab return frequency, and was used to calculate the thickness. The second one, which occurs about a frequency of 13 to 14 kHz in some of the records, may be an indicator of possible delamination or debonding at the reinforcement level.

The subgrade moduli measured with the IR tests (see Table 2) indicate that Locations 5 and 7 are much weaker than the others. As the IR tests indicate a fully-damped system, it may be assumed that the problem can be in the concrete and not the subgrade.

5.2 Site 2

In general, the concrete at Site 2 exhibited a pattern of surface cracking. This cracking is consistent with the corresponding compression wave velocities measured with both accelerometers (see Table 3) as compared to those of Site 1. The cracks being typically "tight", the shear wave velocities measured with the ultrasonic surface waves are not as much affected. Location 1 exhibits low shear and compression wave velocities.

The thicknesses measured at Site 2, as reflected in Table 3, are more or less constant and about 207 mm. However, once again the raw data from the impact-echo tests presented in Appendix B, indicates that one might possibly expect some debonding at the reinforcement level.

Generally low subgrade modulus for a stabilized subgrade along with damping ratio on the order of 50 percent may be an indication of potential problems at this site. Two potential problems to look for are the debonding within the concrete and loss of support underneath the slab.

June, 1994

DRAFT
5.3 Site 3

The compression wave velocities measured with Accelerometer 4 are quite consistent and about 3800 m/sec for all locations tested (see Table 4). Accelerometer 3 measured lower velocities and are lower than those of Accelerometer 4. The reasons for this matter, except from either inconsistencies in determining the arrival of the waves or the existence of tight cracks near the surface on the concrete surface, is not known at this time. The shear wave velocities are typically about 2600 m/sec with a range of values of 2,500 m/sec to 3,100 m/sec.

The thickness of the layer is more or less constant, and as reflected in Table 4, about 210 mm. The raw data from the impact-echo tests are included in Appendix C. Besides the energy related to thickness (around a frequency of 9 kHz), some energy can be detected around a frequency of 13 kHz to 14 kHz. This can be interpreted as the possibility for the initiation of debonding of the concrete at the reinforcement level.

The subgrade moduli determined from the impulse-response tests are more or less constant and the values are indicative of an average-quality stabilized subgrade.

5.4 Site 5

The compression wave velocities measured with both Receivers 3 and 4 at this site vary with test locations. Typically, one can find a reasonable correlation between the level of cracking at a given location and its compression wave velocity (see Table 5). The shear wave velocities more or less follow a similar pattern; that is, along the site, the lower compression wave velocities correspond to lower shear wave velocities. Unfortunately, part of the data at Location 4 was corrupt and therefore, no values for the shear wave velocity or the thickness of this point is reported.

The thickness of the CRC at this site is relatively constant and about 205 mm. Once again, based upon the raw IE data presented in Appendix D, some possibility of delamination can be detected at some of the test locations.

The moduli of subgrade from the IR tests are quite low and are about 0.3 GPa to 0.9 GPa. This is an indication of potential problems at the site is the subgrade. Not knowing the nature of the base and subgrade at the time of preparing this report, it is difficult to make any conclusive remarks. The worst points are Locations 2 and 5. As the damping ratio is quite high, the possibility of foundation softening due to saturation should be investigated.

June, 1994
5.5 Site 6

Table 6 contains the summary of properties measured at Site 6. The compression wave velocities measured with Receiver 4 are constant and about 3800 m/sec. This is expected because the cracks at the site were oriented in the longitudinal direction and were probably shallow. The velocities measured with Receiver 3 vary between different points, and reasonably correlate with the degree of cracking at the site. It would have been interesting (and probably desirable) to test this site at an angle to the direction of cracks.

The shear wave velocities measured with the ultrasonic surface wave method are more or less constant and about 2500 m/sec to 2600 m/sec. Once again, as the direction of propagation of surface waves and the crack pattern were parallel this should be expected.

The raw data from the IE tests at this site are shown in Appendix E. At this site "obvious" return frequencies relating to the thickness of the concrete can only be observed at a few points (i.e., Locations 2, 3, 6 and 8). For the remainder of the locations the seismic energy is distributed over a much wider range of frequencies, and in many points the existence of delamination is strongly indicated.

The subgrade moduli are relatively low except for Locations 5 and 8. An investigation into the situation of the base and subgrade at this site is also advisable.

5.6 Site 7

As reflected in Table 7, the shear and compression wave velocities measured at this site are more or less constant. The shear wave velocity is about 2600 m/sec and the compression wave velocity is 3800 m/sec.

Once again, by inspecting the raw IE data in Appendix F, one can detect a strong possibility of delamination at many locations (such as 3, 4, 5 and 6). Based upon the predominant frequency from each record, the thickness was calculated and reported in Table 7.

The moduli of subgrade from IR tests are about average at the start of the section and become much higher towards the end. Two points of concern are Locations 2 and 5 where the damping ratios are about 50 percent.
6. REFERENCES


### Table 1 - Strengths of Five Testing Techniques Used by Seismic Pavement Analyzer

<table>
<thead>
<tr>
<th>Testing Technique</th>
<th>Strengths</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultrasonic Body Wave</td>
<td>Young's Modulus of top paving layer</td>
</tr>
<tr>
<td>Ultrasonic Surface Wave</td>
<td>Shear modulus of top paving layer</td>
</tr>
<tr>
<td>Impulse Response</td>
<td>Modulus of subgrade reaction of foundation layers</td>
</tr>
<tr>
<td>Spectral Analysis of Surface Waves</td>
<td>Modulus of each layer&lt;br&gt;Thickness of each layer&lt;br&gt;Variation in modulus within each layer</td>
</tr>
<tr>
<td>Impact Echo</td>
<td>Thickness of paving, i.e. layer or depth to delaminated layer</td>
</tr>
<tr>
<td>Location</td>
<td>Compression Wave Velocity, m/sec</td>
</tr>
<tr>
<td>----------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td></td>
<td>Rec. 3</td>
</tr>
<tr>
<td>1</td>
<td>3,800</td>
</tr>
<tr>
<td>2</td>
<td>3,500</td>
</tr>
<tr>
<td>3</td>
<td>3,800</td>
</tr>
<tr>
<td>4</td>
<td>3,500</td>
</tr>
<tr>
<td>5</td>
<td>3,500</td>
</tr>
<tr>
<td>6</td>
<td>3,500</td>
</tr>
<tr>
<td>7</td>
<td>3,500</td>
</tr>
<tr>
<td>8</td>
<td>3,500</td>
</tr>
<tr>
<td>Location</td>
<td>Compression Wave Velocity, m/sec</td>
</tr>
<tr>
<td>----------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td></td>
<td>Rec. 3</td>
</tr>
<tr>
<td>1</td>
<td>2,700</td>
</tr>
<tr>
<td>2</td>
<td>3,000</td>
</tr>
<tr>
<td>3</td>
<td>3,200</td>
</tr>
<tr>
<td>4</td>
<td>3,300</td>
</tr>
<tr>
<td>5</td>
<td>3,200</td>
</tr>
<tr>
<td>6</td>
<td>3,500</td>
</tr>
<tr>
<td>7</td>
<td>3,500</td>
</tr>
<tr>
<td>8</td>
<td>3,300</td>
</tr>
<tr>
<td>9</td>
<td>3,600</td>
</tr>
<tr>
<td>10</td>
<td>2,900</td>
</tr>
<tr>
<td>Location</td>
<td>Compression Wave Velocity, m/sec</td>
</tr>
<tr>
<td>----------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td>1</td>
<td>2,800</td>
</tr>
<tr>
<td>2</td>
<td>3,300</td>
</tr>
<tr>
<td>3</td>
<td>3,300</td>
</tr>
<tr>
<td>4</td>
<td>3,200</td>
</tr>
<tr>
<td>5</td>
<td>3,600</td>
</tr>
<tr>
<td>6</td>
<td>3,500</td>
</tr>
</tbody>
</table>
Table 5 - Summary of Properties Measured with SPA at Site 5

<table>
<thead>
<tr>
<th>Location</th>
<th>Compression Wave Velocity, m/sec</th>
<th>Shear Wave Velocity, m/sec</th>
<th>Thickness, mm</th>
<th>Subgrade Modulus, GPa</th>
<th>Damping Ratio, percent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rec. 3</td>
<td>Rec. 4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2,900</td>
<td>2,500</td>
<td>2,200</td>
<td>207</td>
<td>0.6</td>
</tr>
<tr>
<td>2</td>
<td>3,300</td>
<td>2,800</td>
<td>2,400</td>
<td>213</td>
<td>0.3</td>
</tr>
<tr>
<td>3</td>
<td>4,000</td>
<td>3,400</td>
<td>2,700</td>
<td>207</td>
<td>0.5</td>
</tr>
<tr>
<td>4</td>
<td>3,200</td>
<td>3,000</td>
<td>--</td>
<td>--</td>
<td>0.3</td>
</tr>
<tr>
<td>5</td>
<td>3,800</td>
<td>3,800</td>
<td>2,800</td>
<td>200</td>
<td>0.8</td>
</tr>
<tr>
<td>6</td>
<td>3,200</td>
<td>3,800</td>
<td>2,400</td>
<td>207</td>
<td>0.9</td>
</tr>
<tr>
<td>7</td>
<td>3,300</td>
<td>3,400</td>
<td>2,700</td>
<td>211</td>
<td>0.5</td>
</tr>
<tr>
<td>8</td>
<td>3,300</td>
<td>3,400</td>
<td>2,700</td>
<td>207</td>
<td>0.6</td>
</tr>
<tr>
<td>Location</td>
<td>Compression Wave Velocity, m/sec</td>
<td>Shear Wave Velocity, m/sec</td>
<td>Thickness, mm</td>
<td>Subgrade Modulus, GPa</td>
<td>Damping Ratio, percent</td>
</tr>
<tr>
<td>----------</td>
<td>---------------------------------</td>
<td>---------------------------</td>
<td>--------------</td>
<td>----------------------</td>
<td>-----------------------</td>
</tr>
<tr>
<td></td>
<td>Rec. 3</td>
<td>Rec. 4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>3,600</td>
<td>3,800</td>
<td>2,500</td>
<td>--</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>2,900</td>
<td>3,800</td>
<td>2,500</td>
<td>213</td>
<td>0.6</td>
</tr>
<tr>
<td>3</td>
<td>2,900</td>
<td>3,800</td>
<td>2,500</td>
<td>207</td>
<td>0.6</td>
</tr>
<tr>
<td>4</td>
<td>3,600</td>
<td>3,800</td>
<td>2,600</td>
<td>179</td>
<td>0.2</td>
</tr>
<tr>
<td>5</td>
<td>3,200</td>
<td>3,800</td>
<td>2,300</td>
<td>181</td>
<td>1.7</td>
</tr>
<tr>
<td>6</td>
<td>3,600</td>
<td>3,800</td>
<td>2,600</td>
<td>207</td>
<td>--</td>
</tr>
<tr>
<td>7</td>
<td>3,000</td>
<td>3,800</td>
<td>2,700</td>
<td>198</td>
<td>0.8</td>
</tr>
<tr>
<td>8</td>
<td>2,900</td>
<td>3,800</td>
<td>2,600</td>
<td>207</td>
<td>1.7</td>
</tr>
<tr>
<td>Location</td>
<td>Compression Wave Velocity, m/sec</td>
<td>Shear Wave Velocity, m/sec</td>
<td>Thickness, mm</td>
<td>Subgrade Modulus, GPa</td>
<td>Damping Ratio, percent</td>
</tr>
<tr>
<td>----------</td>
<td>----------------------------------</td>
<td>---------------------------</td>
<td>--------------</td>
<td>----------------------</td>
<td>-----------------------</td>
</tr>
<tr>
<td></td>
<td>Rec. 3</td>
<td>Rec. 4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>3,600</td>
<td>3,800</td>
<td>2,600</td>
<td>--</td>
<td>0.8</td>
</tr>
<tr>
<td>2</td>
<td>3,600</td>
<td>3,800</td>
<td>2,600</td>
<td>200</td>
<td>1.1</td>
</tr>
<tr>
<td>3</td>
<td>3,500</td>
<td>3,800</td>
<td>2,700</td>
<td>194</td>
<td>1.1</td>
</tr>
<tr>
<td>4</td>
<td>3,200</td>
<td>3,800</td>
<td>2,500</td>
<td>198</td>
<td>1.6</td>
</tr>
<tr>
<td>5</td>
<td>3,600</td>
<td>3,800</td>
<td>2,600</td>
<td>141</td>
<td>2.4</td>
</tr>
<tr>
<td>6</td>
<td>3,000</td>
<td>3,800</td>
<td>2,500</td>
<td>143</td>
<td>2.5</td>
</tr>
<tr>
<td>7</td>
<td>3,600</td>
<td>3,800</td>
<td>2,700</td>
<td>190</td>
<td>2.6</td>
</tr>
</tbody>
</table>
Figure 1 - Schematic of Seismic Pavement Analyzer
Figure 2 - Typical Time Records from Accelerometers
Figure 3 - Typical Normalized Time Records Obtained with SPA
Figure 4 - Typical Spectral Functions used in Impulse-Response Test
Figure 5: Typical Spectral Functions Used in Impact-Echo Test
Figure 6 - Typical Spectral Functions Used in Ultrasonic-Surface-Wave Test
Figure 7 - Typical Amplified Signal Used in Ultrasonic-Body-Waves Test
Figure 8 - Plan View of Richmond and Site Tested
Figure 9 - Typical Test Arrangement at each Test Location
APPENDIX A

RAW DATA MEASURED WITH SPA AT SITE 1
Site 1
Impact Echo (Individually Normalized)

Normalized Intensity

Frequency, kHz

Location

1 2 3 4 5 6 7 8
Site 1
Impulse Response (indiv. Normalized)
Site 1
Impact Echo (Globally Normalized)

Normalized Inheritance

Location

Frequency, kHz

0 2 4 6 8 10 12 14 16 18 20
APPENDIX B

RAW DATA MEASURED WITH SPA AT SITE 2
Site 2
High Frequency Load Cell (1)

Normalized Amplitude

Time, msec

Location
Site 2
accelerometer 3

Normalized Amplitude

Location

Time, msec

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
Site 2
accelerometer 3

Normalized Amplitude

Location

Time, msec
Site 2
Low Frequency Load Cell

Normalized Amplitude

Location

Time, msec
APPENDIX C

RAW DATA MEASURED WITH SPA AT SITE 3
Site 3
Impulse Response (indiv. Normalized)
APPENDIX D

RAW DATA MEASURED WITH SPA AT SITE 5
Site 5
High Frequency Load Cell (1)

Normalized Amplitude

Location

Time, msec
Site 5
accelerometer 2

Normalized Amplitude

Location

Time, msec

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
Site 5
accelerometer 3

Normalized Amplitude

Time, msec

Location
Site 5
accelerometer 4

Normalized Amplitude

Time, msec

Location
Site 5
accelerometer 5

Normalized Amplitude

Location 1, 2, 3, 4, 5, 6, 7, 8

Time, msec
APPENDIX E

RAW DATA MEASURED WITH SPA AT SITE 6
APPENDIX E

RAW DATA MEASURED WITH SPA AT SITE 6
Site 6
accelerometer 3

Normalized Amplitude

Time, msec

Location

1
2
3
4
5
6
7
8
Site 6
accelerometer 3

Normalized Amplitude

Time, msec
APPENDIX F

RAW DATA MEASURED WITH SPA AT SITE 7
APPENDIX F

RAW DATA MEASURED WITH SPA AT SITE 7
Site 7
accelerometer 3

Normalized Amplitude vs. Time, msec

Location

0 0.5 1 1.5 2 2.5 3 3.5 4
COMPREHENSIVE PAVEMENT EVALUATION USING SEISMIC PAVEMENT ANALYZER

a report submitted to

Transportation Research Council
Department of Transportation
Commonwealth of Virginia

June, 1994

CENTER FOR GEOTECHNICAL & HIGHWAY MATERIALS RESEARCH
THE UNIVERSITY OF TEXAS AT EL PASO
EL PASO, TEXAS 79968
(915)747-5464
COMPREHENSIVE PAVEMENT ASSESSMENT USING SEISMIC PAVEMENT ANALYZER

by

Soheil Nazarian, PhD, PE
Kevin Crain, MS
and
Mark Baker, DSc

for
Virginia Transportation Research Council
Department of Transportation
Box 3817 University Station
Charlottesville, VA 22903

Center for Geotechnical and Highway Materials Research
The University of Texas at El Paso
El Paso, TX 79968
(915) 747-6925

June, 1994
# TABLE OF CONTENTS

1. INTRODUCTION ........................................... 1

2. SEISMIC PAVEMENT ANALYZER .......................... 1

3. DESCRIPTION OF MEASUREMENT TECHNOLOGIES ........... 3
   3.1 Impulse-Response (IR) Method ........................... 3
   3.2 Ultrasonic-Surface-Wave Method ......................... 4
   3.3 Ultrasonic Compression Wave Velocity Measurement ....... 5
   3.4 Impact-Echo Method .................................... 5

4. DATA COLLECTION AND ANALYSIS .......................... 6
   4.1 Data Collection ....................................... 6
   4.2 Data Reduction ........................................ 7

5. PRESENTATION OF RESULTS ............................... 10
   5.1 Site 1 .................................................. 11
   5.2 Site 2 .................................................. 11
   5.3 Site 3 .................................................. 12
   5.4 Site 5 .................................................. 12
   5.5 Site 6 .................................................. 13
   5.6 Site 7 .................................................. 13

6. REFERENCES .............................................. 14

APPENDIX A - RAW DATA MEASURED WITH SPA AT SITE 1

APPENDIX B - RAW DATA MEASURED WITH SPA AT SITE 2

APPENDIX C - RAW DATA MEASURED WITH SPA AT SITE 3

APPENDIX D - RAW DATA MEASURED WITH SPA AT SITE 5

APPENDIX E - RAW DATA MEASURED WITH SPA AT SITE 6

APPENDIX F - RAW DATA MEASURED WITH SPA AT SITE 7
LIST OF TABLES

Table 1  Strengths of Five Testing Techniques Used by Seismic Pavement Analyzer
Table 2  Summary of Properties Measured with SPA at Site 1
Table 3  Summary of Properties Measured with SPA at Site 2
Table 4  Summary of Properties Measured with SPA at Site 3
Table 5  Summary of Properties Measured with SPA at Site 5
Table 6  Summary of Properties Measured with SPA at Site 6
Table 7  Summary of Properties Measured with SPA at Site 7

LIST OF FIGURES

Figure 1  Schematic of Seismic Pavement Analyzer
Figure 2  Typical Time Records from Accelerometers
Figure 3  Typical Normalized Time Records Obtained with SPA
Figure 4  Typical Spectral Functions used in Impulse-Response Test
Figure 5  Typical Spectral Functions Used in Impact-Echo Test
Figure 6  Typical Spectral Functions Used in Ultrasonic-Surface-Wave Test
Figure 7  Typical Amplified Signal Used in Ultrasonic-Body-Wave Test
Figure 8  Plan View of Richmond and Site Tested
Figure 9  Typical Test Arrangement at each Test Location
COMPREHENSIVE PAVEMENT ASSESSMENT USING 
SEISMIC PAVEMENT ANALYZER 

Soheil Nazarian, Kevin Crain and Mark Baker 
Center for Geotechnical and Highway Materials Research 
The University of Texas at El Paso 
El Paso, TX 79968 

1. INTRODUCTION

The Seismic Pavement Analyzer (SPA) was used at six sites in Richmond, Virginia on May 16 and 17, 1994. The SPA was used to determine the variation in the shear and compression wave velocities, thickness at each site as well as to assess the existence of delamination within or lack of support under concrete slabs. Results from this study are reported herein, along with a brief explanation of the field testing procedures and data analyses.

Dr. Marg G. Lozev of the Virginia Transportation Research Council was the project manager and was present during the field testing phase. Drs. Gerry Clemena and Steve Lane also assisted us during field testing.

2. SEISMIC PAVEMENT ANALYZER

The Seismic Pavement Analyzer (SPA) is an instrument designed and constructed to monitor conditions associated with pavement deterioration. It measures such conditions as voids or loss of support under a rigid pavement, moisture infiltration in asphalt concrete pavement, fine cracking in pavements, delamination of overlays, and aging of asphalt.

The SPA detects these pavement conditions by estimating compression and/or shear wave velocities in the pavement, base, and subgrade from the following wave propagation measurements: 1. Impact Echo (IE), 2. Impulse Response (IR), 3. Spectral Analysis of Surface Waves (SASW), 4. Ultrasonic Surface Waves (USW), and 5. Ultrasonic Body Waves (UBW).

The SPA records the pavement response produced by high- and low-frequency pneumatic hammers on five accelerometers and three geophones. A computer controls data acquisition,
instrument control, and interpretation; measurements and interpretations are reported in both screen and database formats.

The equipment can perform several functions: 1. analyzing in detail pavement conditions identified in the network-level surveys; 2. diagnosing specific distress precursors to aid in selecting the maintenance treatment; and 3. monitoring pavement conditions after maintenance to determine the treatment’s effectiveness.

The operating principle of the SPA is based on generating and detecting stress waves in a layered medium. Each of the five tests and its areas of strength are summarized in Table 1. The SASW method was not utilized in this study, and therefore, not discussed any further. The design and construction of the SPA are based on two general principles. First, the strength of each method should be fully utilized; and second, testing should provide enough redundancy to identify each layer that will potentially contribute to the distress of the pavement.

The ultrasonic-body-wave method can determine the existence of cracks, even if they have not extended through the thickness of the layer. In this method, stress wave energy is generated at one point and detected at several other points. Any cracks in the material located between the source and the receiver will delay the direct propagation of waves and will reduce the amplitude associated with the arriving wave. Differentiation between a strong material containing cracks and a weak material is not possible at this time.

A void beneath or within a slab results in increased flexibility of the slab. Therefore, measuring the flexibility of the slab at different locations using the impulse-response method can pinpoint the voids or loss of support. Initial stages of debonding may not significantly affect the results from the IR method.

The impact echo method distinguishes between overlay delamination and voids beneath or within the slab. The method, a special case of ultrasonic-body-wave propagation, can determine the depth to the reflector.

The impulse response and the impact echo are the prime methods for determining the location and existence of delamination. The theoretical and experimental aspects of using these two tests for detecting overlay delamination are identical to those used for locating voids and loss of support. The only differences are the nature and location of the interface. For delamination, the void occurs at the interface of two layers and the delaminated layer is located closer to surface.

June, 1994
3. DESCRIPTION OF MEASUREMENT TECHNOLOGIES

3.1 Impulse-Response (IR) Method

Two parameters are obtained with the IR method—the shear modulus of subgrade and the damping ratio of the system. These two parameters characterize the existence of several distress precursors. In general, the modulus of subgrade can be used to delineate between good and poor support. The damping ratio can distinguish between the loss of support or weak support. The two parameters are extracted from the flexibility spectrum measured in the field. An extensive theoretical and field study (Reddy, 1992) shows that, except for thin layers (less than 75 mm) and soft paving layers (i.e., flexible pavements), the modulus obtained by the IR method is a good representation of the shear modulus of subgrade, with little influence from the stiffness of the paving layers. In other cases, the properties of the pavement layers (AC and base) affect the outcome in such a manner that the modulus obtained from the IR test should be considered as overall modulus.

The IR tests use the low-frequency source and geophone G1 (see Figure 1). The pavement is impacted to couple stress wave energy in the surface layer. At the interface of the surface layer and the base layer, a portion of this energy is transmitted to the bottom layers, and the remainder is reflected back into the surface layer. The imparted energy is measured with a load cell. The response of the pavement, in terms of particle velocity, is monitored with the geophone and then numerically converted to displacement. The load and displacement time-histories are simultaneously recorded and are transformed to the frequency domain using a Fast-Fourier Transform algorithm. The ratio of the displacement and load (termed flexibility) at each frequency is then determined.

For analysis purposes, the pavement is modeled as a single-degree-of-freedom (SDOF) system. Three parameters are required to describe such a system—natural frequency, damping ratio, and gain factor. The last two can be replaced by the static flexibility and the peak flexibility. These three parameters are collectively called the modal parameters of the system. The natural frequency and gain factor are used to determine the modulus of subgrade. The damping ratio is used directly.

To determine the modal parameters, a curve is fitted to the flexibility spectrum according to an elaborate curve-fitting algorithm that uses the coherence function as a weighting function (Richardson and Formenti, 1982). The poles, zeros, and gain factor obtained from the curve-fitting are easily
converted to modal parameters. From these parameters, the modulus of subgrade is determined. The shear modulus of subgrade, $G$, is calculated from (Dobry and Gazetas, 1986)

$$G = \frac{(1 - \nu^2)}{[2L, A_o, I_s, S_o]}$$

(1)

where $\nu$ = Poisson's ratio of subgrade, $L$ = length of slab, and $A_o$ = static flexibility of slab (flexibility at $f = 0$). The shape factor, $S_o$, has been developed by Dobry and Gazetas (1986). $I_s$ (Nazarian et al, 1994) is a parameter which considers the effect of an increase in flexibility near the edges and corners of a slab. Parameter $I_s$ is a function of the length and width of the slab, as well as the coordinates of the impact point relative to one corner. Depending on the size of the slab and the point of impact, the value of $I_s$ can be as high as 6.

The damping ratio, which typically varies between 0 to 100 percent, is an indicator of the degree of the slab's resistance to movement. A slab that is in contact with the subgrade or contains a water-saturated void demonstrates a highly damped behavior and has a damping ratio of greater than 70 percent. A slab containing an edge void would demonstrate a damping ratio in the order of 10 to 40 percent. A loss of support located in the middle of the slab will have a damping of 30 to 60 percent.

3.2 Ultrasonic-Surface-Wave Method

The ultrasonic-surface-wave method is an offshoot of the SASW method. The major distinction between these two methods is that in the ultrasonic-surface-wave method the shear velocity of the top paving layer can be easily and directly determined without a complex inversion algorithm. To implement the method, the high-frequency source and accelerometers A2 and A3 (see Figure 1) are utilized.

At wavelengths less than or equal to the thickness of the uppermost layer, the velocity of propagation is independent of wavelength. Therefore, if one simply generates high-frequency (short-wavelength) waves, and if one assumes that the properties of the uppermost layer are uniform, the shear wave velocity of the upper layer, $V_s$, can be determined from

$$V_s = (1.13 - 0.16\nu) V_p$$

(2)
The shear modulus of the top layer, $G$, can alternatively be determined from

$$G = \rho \nu^2$$

(3)

where $\nu_p$ = velocity of surface waves, $\rho$ = mass density, and $\nu$ = Poisson’s ratio.

The methodology can be simplified even further. If one assumes that the properties of the uppermost layer are uniform, the shear wave velocity of the top layer can be determined from

$$V_s = (1.13 - 0.16\omega)(\text{m}/360\text{D})$$

(4)

Parameter $m$ (deg/Hz) is the least-squares fit slope of the phase of the transfer function in the high-frequency range.

3.3 Ultrasonic Compression Wave Velocity Measurement.

Theoretically, all accelerometers can be used to measure compressione wave velocity of the upper layer of pavement. Once the compression wave velocity of a material is known, its Young’s modulus can be readily determined.

Miller and Pursey (1955) found that when the surface of a medium is impacted, the generated stress waves propagate mostly with Rayleigh wave energy and, to a lesser extent, with shear and compression wave energy. As such, the body wave energy present in a seismic record generated using the set-up shown in Figure 1 is very small; for all practical purposes it does not contaminate the SASW results. However, compression waves travel faster than any other type of seismic wave, and are detected first on seismic records.

An automated technique for determining the arrival of compression waves has been developed. Times of first arrival of compression waves are measured by triggering on an amplitude range within a time window (Willis and Toksoz, 1983).

3.4 Impact-Echo Method

The impact-echo method can effectively locate defects, voids, cracks, and zones of deterioration within concrete. The method has been thoroughly studied and effectively used on many projects by
researchers at the National Institute of Standards and Technology. In a comprehensive theoretical and experimental study, Sansalone and Carino (1986) considered the effects of type of impact source, distance from impact point to receiver, type of receiving transducers, and depth of reflecting interfaces.

The high-frequency source and accelerometer A1, are used, and possibly A2 as well (see Figure 1). Once the compression wave velocity of concrete, $v_p$, is known, the depth-to-reflector, $T$, can be determined from (Sansalone and Carino, 1986)

$$T = \frac{v_p}{2f}$$

(5)

where $f$ is the resonant (return) frequency obtained by transforming the deformation record into the frequency domain.

4. DATA COLLECTION AND ANALYSIS

4.1 Data Collection

The technician initiates the testing sequence through the computer, that then lowers the sensors and impact unit onto the pavement surface. The high-frequency source is then activated. The outputs of the three accelerometers closest to the high-frequency source, as well as the load cell connected to this source, are used first. The source is fired four to seven times. For the last three impacts of the source, the output voltages of the load cell and the receivers are saved and averaged (stacked) in the frequency domain. The other (prerecording) impacts are used to adjust the gains of the pre-amplifiers. The gains are set in a manner that optimizes the dynamic range. After this step, another set of impacts are utilized to determine compression wave velocities. To perform the test, the gains of all amplifiers are set to maximum. In this manner, the arrival of compression waves can be better identified.

The same procedure is followed again, but the first three accelerometers are replaced by the last three accelerometers. A multiplexer switches the accelerometers. The middle accelerometer (third closest accelerometer to the source) is active in both sets of experiments.
Typical voltage outputs of the load cell and the three near accelerometers are shown in Figure 2. Naturally, as the distance from the source increases, the amplitude of the signal decreases.

To ensure that an adequate signal-to-noise ratio is achieved in all channels, signals similar to those shown in Figure 2 are normalized to a maximum amplitude of one, as shown in Figure 3. In this manner, the main features of the signals can be easily inspected.

In the next phase of data collection, the low-frequency load cell and the three geophones are recorded. The procedure described above for each of the accelerometer banks is utilized. A typical output of the three geophones is shown in Figure 3c in the normalized fashion. Once again, the quality of the data is adequate.

The data collected in this fashion has to be processed using signal processing and spectral analysis. These processes are described in the next section.

4.2 Data Reduction

*Impulse-Response Method*

This method uses the voltage output from the first geophone (the geophone closest to the source, G1) and the low-frequency load cell (see Figure 3c).

The load cell record consists of a half-sine wave approximately 2-msec long. The small reverberation past the actual impact corresponds to the reflection of the wave inside the source assembly. The amplitude of this reverberation is muted so it does not affect the results. The response of the geophone is a steady-state damped response. The slight time delay between the geophone and load cell records is the result of the separation between the source and the receiver.

A detailed description of steps necessary to complete the data reduction can be found in Nazarian et al (1994). Briefly, the output of the load cell and geophone are transformed into the frequency domain using a Fast-Fourier Transform (FFT) algorithm, obtaining the ratio of the particle velocity and the load at each frequency. This function, the mobility spectrum, is then integrated to obtain the flexibility spectrum. The flexibility spectrum is used to determine the parameters for detecting voids or loss of support.

A typical flexibility spectrum is shown in Figure 4. The response is as expected, except for frequencies below approximately 50 Hz. The erratic nature of the signal at low frequencies is probably because of the movement of the trailer.
The coherence function associated with this record is shown in Figure 4b. The coherence values are close to unity except at low frequencies. A coherence value of unity corresponds to a highly coherent signal between the load cell and receiver. In other words, there was no incoherent background noise in the signals.

In the next step, a complex-valued curve representing a single-degree-of-freedom (SDOF) dynamic system is fitted to the flexibility spectrum. A typical fitted curve is shown in Figure 4a. The agreement between the measured and the fitted data is good.

**Impact-Echo Method**

The impact-echo method is similar to the impulse-response method. However, the impact-echo method uses the records from the small load cell and the accelerometer closest to the high-frequency source. Typical outputs from the accelerometer and the load cell are shown in Figure 3a.

In the next step, the two signals are transformed into the frequency domain following the procedure outlined above for impulse-response testing. A typical frequency-response spectrum for a site is shown in Figure 5a.

The major peak seen in Figure 5a (at about 10 kHz) corresponds to a standing wave within the thickness of the layer and is called the return (resonant) frequency.

The coherence function is shown in Figure 5b. In general, the data collected with the device have no incoherent noise, except at several isolated frequencies.

To calculate the thickness of the layer, the compression wave velocity of the material is determined using the ultrasonic-body-wave method. The thickness is equal to one-half of the ratio between the compression wave velocity and the return resonant frequency.

**Ultrasonic-Surface-Wave Method**

This method determines the shear wave velocity or shear modulus of the top layer, using the time records of two accelerometers, accelerometer A2 (150 mm away from the source) and accelerometer A3 (300 mm away from the source) (see Figure 3a). These two signals are Fourier-transformed and the ratio of the two signals is calculated in the form of the transfer function. However, unlike the previous two methods, the ultrasonic-surface-wave method uses only the phase of the transfer function.

A phase spectrum for time records similar to those shown in Figure 3a is shown in Figure 6a.
The phase oscillates on a radius between \( \pi \) and \(-\pi\) radians (180 and -180 degrees). This is the standard method of presenting phase data, because the detailed variation in the data can be observed in a small space.

The data shown in Figure 6A are smooth and do not exhibit much scatter in phase with the frequency, up to a frequency of 35 or 40 kHz. However, the data are rather noisy above a frequency of 35 or 40 kHz.

The coherence function associated with this record is shown in Figure 6B. The coherence is almost equal to one, up to a frequency of 35 or 40 kHz. Above the frequency of 35 kHz, the data are of low quality and are not usable.

The frequency of 35 kHz for this experiment corresponds to a wavelength of less than 38 mm. Shorter wavelengths can be investigated using accelerometer A1 and accelerometer A2 (which are spaced 75 mm apart). One physical limitation is the aggregate size. Wavelengths shorter than the maximum aggregate size probably do not follow the laws of wave propagation in a homogeneous medium.

The shear wave velocity of the top layer was obtained using a complex-valued curve-fitting process with the coherence as the weighting function (Navarrian and Desai, 1993). The results are shown in Figure 6A. The actual and fitted curves compare quite favorably up to a frequency of 30 kHz.

In the next step, the phase is "unwrapped"; that is, the appropriate number of cycles is added to each phase. The unwrapped phase for the "wrapped" phase shown in Figure 6A is shown in Figure 6C. The slope of the line is basically constant with frequency.

Finally, a line is fitted to the curve in the range of frequencies corresponding to wavelengths shorter than the thickness of the top layer. The slope of the line can be used to determine the shear wave velocity (see previous section).

**Ultrasonic-Body-Wave Method**

The ultrasonic-body-wave method uses the same records as in the ultrasonic-surface-wave method. In Figure 3, the arrival of the compression waves (P-waves) cannot be identified in part because the surface wave energy dominates all signals. To determine the arrival of the P-waves, the gain of all amplifiers is set at the maximum possible range to collect data for determining compression...
wave velocities. Such a record is shown in Figure 7. Accelerometers A1 and A2 cannot identify the energy associated with the compression waves, because the seismic energy has not traveled over enough distance to separate into distinct compressional and shear waves. However, the other accelerometers, can identify the arrival of the P-waves. In Figure 7, the arrows in each record correspond to the arrival of these waves; typically, accelerometers A3 and A4 record the arrival of energy most consistently. The compression wave velocity is calculated from the distance between the receivers and the difference in the travel time. The compression wave velocity can then be converted to Young’s modulus.

5. PRESENTATION OF RESULTS

Six sites in the Richmond area were tested during two days of field testing. As shown in Figure 8, the sites were either located on I-295 or Route 60. The typical cross-sections of the six sites were similar and consisted of about 200 mm of CRCP with reinforcement placed at a depth of about 130 mm, over a 150-mm thick layer of stabilized base (stabilized with either asphalt or cement), over subgrade.

Five different nondestructive testing devices were almost concurrently utilized at each site. These devices were: a digital-imaging camera, an impact-echo device, an ultrasonic device (V-meter), a falling weight deflectometer and the Seismic Pavement Analyzer. The results from the Seismic Pavement Analyzer are discussed below.

All test locations had been pre-selected and marked by the staff of Virginia Transportation Research Council prior to field testing. A schematic of marks (circles and pluses) for one test point is shown in Figure 9 along with the relative position of the SPA sensors. The lateral position of the SPA sensors varied between zero to 30 cm from the longitudinal centerline of the marked area. This was necessary so that the trailer can be accommodated on the pavement.

The results from the tests at the six sites are summarized in Tables 2 through 6. The raw data for the sites are included in Appendices A through F. Based upon the experience of the authors except for a few isolated points the quality of the data collected was high.

In the remainder of this report the results are briefly analyzed. It should be mentioned that the sites were numbered as 1 through 3 and 5 through 7, with no results available for Site 4.
5.1 Site 1

The variations in compression wave velocities with test location for Accelerometer 3 (30 cm from the source) and Accelerometer 4 (60 cm from the source) are shown in Table 2. The velocities from Accelerometer 4, rounded to the closest 100 m/sec, are more or less constant and about 3,800 m/sec. For Accelerometer 3, compression wave velocities vary between 3,500 m/s to 3,800 m/s.

The shear wave velocities obtained from the ultrasonic surface waves are also consistent and are about 2500 m/sec. The lower values correspond well with the existing cracks at the site.

Using a compression wave velocity of 3,800 m/sec, the thickness at each point were calculated as reported in Table 2. The thickness of the concrete layer is about 205 mm except for Location 3 where it is determined as about 188 mm. Investigation of the raw data from the impact-echo tests (see Appendix A) reveals two frequency ranges with significant energy. The first one, about 9 kHz corresponds to the slab return frequency, and was used to calculate the thickness. The second one, which occurs about a frequency of 13 to 14 kHz in some of the records, may be an indicator of possible delamination or debonding at the reinforcement level.

The subgrade moduli measured with the IR tests (see Table 2) indicate that Locations 5 and 7 are much weaker than the others. As the IR tests indicate a fully-damped system, it may be assumed that the problem can be in the concrete and not the subgrade.

5.2 Site 2

In general, the concrete at Site 2 exhibited a pattern of surface cracking. This cracking is consistent with the corresponding compression wave velocities measured with both accelerometers (see Table 3) as compared to those of Site 1. The cracks being typically "tight", the shear wave velocities measured with the ultrasonic surface waves are not as much affected. Location 1 exhibits low shear and compression wave velocities.

The thicknesses measured at Site 2, as reflected in Table 3, are more or less constant and about 207 mm. However, once again the raw data from the impact-echo tests presented in Appendix B, indicates that one might possibly expect some debonding at the reinforcement level.

Generally low subgrade modulus for a stabilized subgrade along with damping ratio on the order of 50 percent may be an indication of potential problems at this site. Two potential problems to look for are the debonding within the concrete and loss of support underneath the slab.
5.3 Site 3

The compression wave velocities measured with Accelerometer 4 are quite consistent and about 3800 m/sec for all locations tested (see Table 4). Accelerometer 3 measured lower velocities and are lower than those of Accelerometer 4. The reasons for this matter, except from either inconsistencies in determining the arrival of the waves or the existence of tight cracks near the surface on the concrete surface, is not known at this time. The shear wave velocities are typically about 2600 m/sec with a range of values of 2,500 m/sec to 3,100 m/sec.

The thickness of the layer is more or less constant, and as reflected in Table 4, about 210 mm. The raw data from the impact-echo tests are included in Appendix C. Besides the energy related to thickness (around a frequency of 9 kHz), some energy can be detected around a frequency of 13 kHz to 14 kHz. This can be interpreted as the possibility for the initiation of debonding of the concrete at the reinforcement level.

The subgrade moduli determined from the impulse-response tests are more or less constant and the values are indicative of an average-quality stabilized subgrade.

5.4 Site 5

The compression wave velocities measured with both Receivers 3 and 4 at this site vary with test locations. Typically, one can find a reasonable correlation between the level of cracking at a given location and its compression wave velocity (see Table 5). The shear and compression wave velocities more or less follow a similar pattern; that is, along the site, the lower compression wave velocities correspond to lower shear wave velocities. Unfortunately, part of the data at Location 4 was corrupt and therefore, no values for the shear wave velocity or the thickness of this point is reported.

The thickness of the CRC at this site is relatively constant and about 205 mm. Once again, based upon the raw IE data presented in Appendix D, some possibility of delamination can be detected at some of the test locations.

The moduli of subgrade from the IR tests are quite low and are about 0.3 GPa to 0.9 GPa. This is an indication of potential problems at the site in the subgrade. Not knowing the nature of the base and subgrade at the time of preparing this report, it is difficult to make any conclusive remarks. The worst points are Locations 2 and 5. As the damping ratio is quite high, the possibility of foundation softening due to saturation should be investigated.
5.5 Site 6

Table 6 contains the summary of properties measured at Site 6. The compression wave velocities measured with Receiver 4 are constant and about 3800 m/sec. This is expected because the cracks at the site were oriented in the longitudinal direction and were probably shallow. The velocities measured with Receiver 3 vary between different points, and reasonably correlate with the degree of cracking at the site. It would have been interesting (and probably desirable) to test this site at an angle to the direction of cracks.

The shear wave velocities measured with the ultrasonic surface wave method are more or less constant and about 2500 m/sec to 2600 m/sec. Once again, as the direction of propagation of surface waves and the crack pattern were parallel this should be expected.

The raw data from the IE tests at this site are shown in Appendix E. At this site "obvious" return frequencies relating to the thickness of the concrete can only be observed at a few points (i.e. Locations 2, 3, 6 and 8). For the remainder of the locations the seismic energy is distributed over a much wider range of frequencies, and in many points the existence of delamination is strongly indicated.

The subgrade moduli are relatively low except for Locations 5 and 8. An investigation into the situation of the base and subgrade at this site is also advisable.

5.6 Site 7

As reflected in Table 7, the shear and compression wave velocities measured at this site are more or less constant. The shear wave velocity is about 2600 m/sec and the compression wave velocity is 3800 m/sec.

Once again, by inspecting the raw IE data in Appendix F, one can detect a strong possibility of delamination at many locations (such as 3, 4, 5 and 6). Based upon the predominant frequency from each record, the thickness was calculated and reported in Table 7.

The moduli of subgrade from IR tests are about average at the start of the section and become much higher towards the end. Two points of concern are Locations 2 and 5 where the damping ratios are about 50 percent.
6. REFERENCES


<table>
<thead>
<tr>
<th>Testing Technique</th>
<th>Strengths</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultrasonic Body Wave</td>
<td>Young's Modulus of top paving layer</td>
</tr>
<tr>
<td>Ultrasonic Surface Wave</td>
<td>Shear modulus of top paving layer</td>
</tr>
<tr>
<td>Impulse Response</td>
<td>Modulus of subgrade reaction of foundation layers</td>
</tr>
</tbody>
</table>
| Spectral Analysis of Surface Waves | Modulus of each layer  
|                               | Thickness of each layer  
|                               | Variation in modulus within each layer                                   |
| Impact Echo                  | Thickness of paving layer or depth to delaminated layer                    |
Table 2 - Summary of Properties Measured with SPA at Site 1

<table>
<thead>
<tr>
<th>Location</th>
<th>Compression Wave Velocity, m/sec</th>
<th>Shear Wave Velocity, m/sec</th>
<th>Thickness, mm</th>
<th>Subgrade Modulus, GPa</th>
<th>Damping Ratio, percent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rec. 3</td>
<td>Rec. 4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>3,800</td>
<td>3,800</td>
<td>2,500</td>
<td>211</td>
<td>1.3</td>
</tr>
<tr>
<td>2</td>
<td>3,500</td>
<td>3,800</td>
<td>2,400</td>
<td>207</td>
<td>1.4</td>
</tr>
<tr>
<td>3</td>
<td>3,800</td>
<td>3,800</td>
<td>2,200</td>
<td>188</td>
<td>1.4</td>
</tr>
<tr>
<td>4</td>
<td>3,500</td>
<td>3,400</td>
<td>2,400</td>
<td>207</td>
<td>1.1</td>
</tr>
<tr>
<td>5</td>
<td>3,500</td>
<td>3,800</td>
<td>2,600</td>
<td>207</td>
<td>0.7</td>
</tr>
<tr>
<td>6</td>
<td>3,500</td>
<td>3,800</td>
<td>2,500</td>
<td>207</td>
<td>1.0</td>
</tr>
<tr>
<td>7</td>
<td>3,500</td>
<td>3,400</td>
<td>2,500</td>
<td>204</td>
<td>0.4</td>
</tr>
<tr>
<td>8</td>
<td>3,500</td>
<td>3,800</td>
<td>2,600</td>
<td>207</td>
<td>1.1</td>
</tr>
<tr>
<td>Location</td>
<td>Compression Wave Velocity, m/sec</td>
<td>Shear Wave Velocity, m/sec</td>
<td>Thickness, mm</td>
<td>Subgrade Modulus, GPa</td>
<td>Damping Ratio, percent</td>
</tr>
<tr>
<td>----------</td>
<td>---------------------------------</td>
<td>---------------------------</td>
<td>---------------</td>
<td>----------------------</td>
<td>-----------------------</td>
</tr>
<tr>
<td></td>
<td>Rec. 3</td>
<td>Rec. 4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2,700</td>
<td>2,300</td>
<td>2,200</td>
<td>207</td>
<td>0.6</td>
</tr>
<tr>
<td>2</td>
<td>3,000</td>
<td>3,400</td>
<td>2,500</td>
<td>207</td>
<td>0.8</td>
</tr>
<tr>
<td>3</td>
<td>3,200</td>
<td>2,500</td>
<td>2,500</td>
<td>207</td>
<td>1.0</td>
</tr>
<tr>
<td>4</td>
<td>3,300</td>
<td>3,400</td>
<td>2,500</td>
<td>207</td>
<td>0.9</td>
</tr>
<tr>
<td>5</td>
<td>3,200</td>
<td>3,400</td>
<td>2,600</td>
<td>204</td>
<td>1.0</td>
</tr>
<tr>
<td>6</td>
<td>3,500</td>
<td>3,400</td>
<td>2,700</td>
<td>207</td>
<td>1.2</td>
</tr>
<tr>
<td>7</td>
<td>3,500</td>
<td>3,409</td>
<td>2,400</td>
<td>211</td>
<td>0.5</td>
</tr>
<tr>
<td>8</td>
<td>3,300</td>
<td>3,800</td>
<td>2,300</td>
<td>213</td>
<td>0.9</td>
</tr>
<tr>
<td>9</td>
<td>3,600</td>
<td>3,800</td>
<td>2,400</td>
<td>207</td>
<td>0.9</td>
</tr>
<tr>
<td>10</td>
<td>2,900</td>
<td>3,800</td>
<td>2,500</td>
<td>202</td>
<td>1.1</td>
</tr>
</tbody>
</table>
**Table 4 - Summary of Properties Measured with SPA at Site 3**

<table>
<thead>
<tr>
<th>Location</th>
<th>Compression Wave Velocity, m/sec</th>
<th>Shear Wave Velocity, m/sec</th>
<th>Thickness, mm</th>
<th>Subgrade Modulus, G</th>
<th>Damping Ratio, percent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rec. 3</td>
<td>Rec. 4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2,800</td>
<td>3,800</td>
<td>2,600</td>
<td>207</td>
<td>0.9</td>
</tr>
<tr>
<td>2</td>
<td>3,300</td>
<td>3,800</td>
<td>2,600</td>
<td>211</td>
<td>1.3</td>
</tr>
<tr>
<td>3</td>
<td>3,300</td>
<td>3,800</td>
<td>2,800</td>
<td>211</td>
<td>1.2</td>
</tr>
<tr>
<td>4</td>
<td>3,200</td>
<td>3,800</td>
<td>2,600</td>
<td>211</td>
<td>1.2</td>
</tr>
<tr>
<td>5</td>
<td>3,600</td>
<td>3,800</td>
<td>2,500</td>
<td>207</td>
<td>1.1</td>
</tr>
<tr>
<td>6</td>
<td>3,500</td>
<td>3,800</td>
<td>3,100</td>
<td>202</td>
<td>0.8</td>
</tr>
<tr>
<td>Location</td>
<td>Compression Wave Velocity, m/sec</td>
<td>Shear Wave Velocity, m/sec</td>
<td>Thickness, mm</td>
<td>Subgrade Modulus, GPa</td>
<td>Damping Ratio, percent</td>
</tr>
<tr>
<td>----------</td>
<td>---------------------------------</td>
<td>---------------------------</td>
<td>---------------</td>
<td>----------------------</td>
<td>-----------------------</td>
</tr>
<tr>
<td></td>
<td>Rec. 3</td>
<td>Rec. 4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2,900</td>
<td>2,500</td>
<td>2,200</td>
<td>307</td>
<td>0.6</td>
</tr>
<tr>
<td>2</td>
<td>3,300</td>
<td>2,800</td>
<td>2,400</td>
<td>213</td>
<td>0.3</td>
</tr>
<tr>
<td>3</td>
<td>4,000</td>
<td>3,400</td>
<td>2,700</td>
<td>207</td>
<td>0.5</td>
</tr>
<tr>
<td>4</td>
<td>3,200</td>
<td>3,000</td>
<td>--</td>
<td>--</td>
<td>0.3</td>
</tr>
<tr>
<td>5</td>
<td>3,800</td>
<td>3,800</td>
<td>2,800</td>
<td>200</td>
<td>0.8</td>
</tr>
<tr>
<td>6</td>
<td>3,200</td>
<td>3,800</td>
<td>2,400</td>
<td>207</td>
<td>0.9</td>
</tr>
<tr>
<td>7</td>
<td>3,300</td>
<td>3,400</td>
<td>2,700</td>
<td>211</td>
<td>0.5</td>
</tr>
<tr>
<td>8</td>
<td>3,300</td>
<td>3,400</td>
<td>2,700</td>
<td>207</td>
<td>0.6</td>
</tr>
</tbody>
</table>
Table 6 - Summary of Properties Measured with SPA at Site 6

<table>
<thead>
<tr>
<th>Location</th>
<th>Compression Wave Velocity, m/sec</th>
<th>Shear Wave Velocity, m/sec</th>
<th>Thickness, mm</th>
<th>Subgrade Modulus, GPa</th>
<th>Damping Ratio, percent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rec. 3</td>
<td>Rec. 4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>3,600</td>
<td>3,800</td>
<td>2,500</td>
<td>--</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>2,900</td>
<td>3,800</td>
<td>2,500</td>
<td>213</td>
<td>0.6</td>
</tr>
<tr>
<td>3</td>
<td>2,900</td>
<td>3,800</td>
<td>2,500</td>
<td>207</td>
<td>0.6</td>
</tr>
<tr>
<td>4</td>
<td>3,600</td>
<td>3,800</td>
<td>2,600</td>
<td>179</td>
<td>0.2</td>
</tr>
<tr>
<td>5</td>
<td>3,200</td>
<td>3,800</td>
<td>2,300</td>
<td>181</td>
<td>1.7</td>
</tr>
<tr>
<td>6</td>
<td>3,600</td>
<td>3,800</td>
<td>2,600</td>
<td>207</td>
<td>--</td>
</tr>
<tr>
<td>7</td>
<td>3,000</td>
<td>3,800</td>
<td>2,700</td>
<td>198</td>
<td>0.8</td>
</tr>
<tr>
<td>8</td>
<td>2,900</td>
<td>3,800</td>
<td>2,600</td>
<td>207</td>
<td>1.7</td>
</tr>
</tbody>
</table>
Table 7 - Summary of Properties Measured with SPA at Site 7

<table>
<thead>
<tr>
<th>Location</th>
<th>Compression Wave Velocity, m/sec</th>
<th>Shear Wave Velocity, m/sec</th>
<th>Thickness, mm</th>
<th>Subgrade Modulus, GPa</th>
<th>Damping Ratio, percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3,600</td>
<td>3,800</td>
<td>2,600</td>
<td>1.1</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>3,600</td>
<td>3,800</td>
<td>2,600</td>
<td>1.1</td>
<td>46</td>
</tr>
<tr>
<td>3</td>
<td>3,500</td>
<td>3,800</td>
<td>2,700</td>
<td>1.1</td>
<td>78</td>
</tr>
<tr>
<td>4</td>
<td>3,200</td>
<td>3,800</td>
<td>2,500</td>
<td>1.6</td>
<td>78</td>
</tr>
<tr>
<td>5</td>
<td>3,600</td>
<td>3,800</td>
<td>2,600</td>
<td>2.4</td>
<td>57</td>
</tr>
<tr>
<td>6</td>
<td>3,000</td>
<td>3,800</td>
<td>2,500</td>
<td>2.5</td>
<td>82</td>
</tr>
<tr>
<td>7</td>
<td>3,600</td>
<td>3,800</td>
<td>2,700</td>
<td>2.6</td>
<td>84</td>
</tr>
</tbody>
</table>
Figure 1 - Schematic of Seismic Pavement Analyzer
Figure 2 - Typical Time Records from Accelerometers
Figure 3 - Typical Normalized Time Records Obtained with SPA
Figure 4 - Typical Spectral Functions used in Impulse-Response Test
Figure 5 - Typical Spectral Functions Used in Impact-Echo Test
Figure 6 - Typical Spectral Functions Used in Ultrasonic-Surface-Wave Test
Figure 7 - Typical Amplified Signal Used in Ultrasonic-Body-Waves Test
Figure 8 - Plan View of Richmond and Site Tested
Figure 9 - Typical Test Arrangement at each Test Location
APPENDIX A

RAW DATA MEASURED WITH SPA AT SITE 1
Site 1
High Frequency Load Cell (1)

Normalized Amplitude

Time, msec

Location

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8

8
7
6
5
4
3
2
1
APPENDIX B

RAW DATA MEASURED WITH SPA AT SITE 2
Site 2
High Frequency Load Cell (1)

Normalized Amplitude

Location

Time, msec
Site 2
Low Frequency Load Cell

Normalized Amplitude

Location

Time, msec
Site 2
Surface Waves (150-mm Rec. Spacing)

Phase of Transfer Function

Location

Frequency, kHz
APPENDIX C

RAW DATA MEASURED WITH SPA AT SITE 3
Site 3
Accelerometer 2

Normalized Amplitude

Location
1 2 3 4 5 6

Time, msec
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
Site 3
Impact Echo (Individually Normalized)

Normalized Inertia

Location

Frequency, kHz
Site 3
Surface Waves (150-mm Rec. Spacing)
APPENDIX D

RAW DATA MEASURED WITH SPA AT SITE 5
Site 5
accelerometer 2

Normalized Amplitude

Location

Time, msec
Site 5
accelerometer 3

Normalized Amplitude

Time, msec

Location

0 0.5 1 1.5 2 2.5 3 3.5 4
Site 5
accelerometer 5

Normalized Amplitude

Location

Time, msec

0 0.5 1 1.5 2 2.5 3 3.5 4
Site 5
accelerometer 5

Normalized Amplitude

Time, msec

Location

1 2 3 4 5 6 7 8
Site 5
Geophone 1

Normalized Amplitude

Time, msec

Location
Site 5
Impulse Response (indiv. Normalized)
APPENDIX E

RAW DATA MEASURED WITH SPA AT SITE 6
APPENDIX E

RAW DATA MEASURED WITH SPA AT SITE 6
Site 6
accelerometer 1

Normalized Amplitude vs. Time, msec
Site 6
accelerometer 3

Normalized Amplitude

Time, msec

Location

1 2 3 4 5 6 7 8
APPENDIX F

RAW DATA MEASURED WITH SPA AT SITE 7
APPENDIX F

RAW DATA MEASURED WITH SPA AT SITE 7
Site 7
accelerometer 3

Normalized Amplitude

Location

Time, msec

0 0.5 1 1.5 2 2.5 3 3.5 4
Site 7
Geophone 1

Normalized Amplitude

Location

Time, msec
Site 7
Impulse Response (indiv. Normalized)