

Design Moduli for Flexible Pavements Using Seismic Tests

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The pavement community around the country has realized the importance of designing pavements based on mechanistic-empirical (M-E) principles. The new design guide developed under NCHRP 1-37A, if approved by the States, will encourage the broader use of M-E pavement design approaches.

In mechanistic structural design of pavements, the layer moduli are the main parameters that need to be accurately measured. A nondestructive testing device, the Seismic Pavement Analyzer (SPA), whose operating principle is based on generating and detecting seismic waves in a layered medium, can be used for this purpose. Seismic methods provide fundamentally-correct linear-elastic moduli of different layers. To incorporate in pavement design and analysis, seismic moduli of different layers have to be adjusted to represent moduli at strain and stress levels that are close to those applied by truck traffic. To do so, the nonlinear and visco-elastic behaviors of different layers should be accurately determined. The algorithm developed has been incorporated in a software package called SMART (Seismic Modulus Analysis and Reduction Tool). The procedure is particularly attractive in the situations where pavement layers are thin, depth to bedrock is shallow or when the water table is close to the pavement surface.

In this paper the process of using seismic data and laboratory tests to determine design modulus values are presented. A case study is included to demonstrate the use of SMART a tool for estimating the design modulus based on seismic testing.

INTRODUCTION

The pavement community around the country has realized the importance of designing pavements based on mechanistic-empirical (M-E) principles. The new design guide developed under NCHRP 1-37A, if approved by the States, will encourage the broader use of M-E pavement design approaches. A number of economical reasons exist to support the move towards mechanistic design methods. Pavement rehabilitation requires a major commitment of resources by the nation's highway agencies. The sheer magnitude of annual expenditures on pavements justifies the application of the best available design procedures to optimize the use of highway funds.

The consensus of the pavement agencies is that further work needs to be carried out to incorporate the M-E design guide in the state-of-practice. One of the main concerns is the calibration and validation of the models for local conditions. Another concern with the guide is the large amount of information that it requires to carry out a design. It is foreseen that it will take close to a decade to fully implement the new mechanistic-empirical design guide. To aide in the evaluation and or implementation of the guide research projects across the nation have been initiated. One area that is an essential part of the mechanistic design process and which has made substantial progress in the last two decades is NDT technology.

NDT methods measure properties of the pavements such as thickness and modulus of the different pavement layers. Currently, NDT devices such as, the Falling Weight Deflectometer (FWD), the Ground Penetrating Radar (GPR), the Seismic Pavement Analyzer (SPA), and the Portable Seismic Pavement Analyzer (PSPA), are available for collecting field data. Each of these technologies provides support to the design process.

The study discussed in this paper focuses on seismic technology, specifically the use of SPA to determine design modulus values that can be used in pavement design programs. Data collected from SPA is analyzed based on seismic analysis routines and mechanistic algorithms to determine design moduli values.

The Seismic Pavement Analyzer detects stress waves in a layered system based on small impulse loads. The test is based on the concept that waves with different frequencies travel through the pavement layers with different velocities. The results of this NDT test are then used to obtain elastic

moduli of different layers. The beauty of seismic technology such as the SPA compared to other NDT devices is that it measures the elastic modulus or “seismic modulus” of pavement layers which is an in-situ property that can also be measured in laboratories.

In this paper a software package that reduces SPA test results to determine design modulus values of pavement layer system is demonstrated. The results using actual field data are presented. Finally a validation of the algorithm used in SMART is provided.

SPECTRAL-ANALYSIS-OF-SURFACE-WAVES (SASW) METHOD

The spectral-analysis-of-surface-waves (SASW) method is introduced as a nondestructive pavement testing method that uses the field data from SPA to analyze the pavement. The SASW method determines the elastic modulus profiles of pavement layers (Nazarian and Stokoe, 1986; Nazarian and Stokoe, 1987). The process involves determining the dispersive characteristic of seismic surface waves in a layered system. It is based on the concept that waves with different frequencies (or wavelengths) travel through the pavement layers with different velocities.

Figure 1 shows the process involved in the SASW method. The SASW test is performed in three stages: (1) in situ testing, (2) determination of experimental dispersion curve, and (3) determination of stiffness profile.

The field testing consists of generating and detecting surface waves by impacting the surface of a pavement. The captured signals are manipulated using the Fourier and spectral analyses to determine the cross-power spectra and coherence functions. By processing the cross-power spectra and the coherence functions, an experimental dispersion curve is constructed. This curve represents the dependence of phase velocity on frequency or wavelength. The final step is determining the elastic modulus profile from the experimental dispersion curves. The process is known as inversion or backcalculation (Nazarian and Desai, 1993).

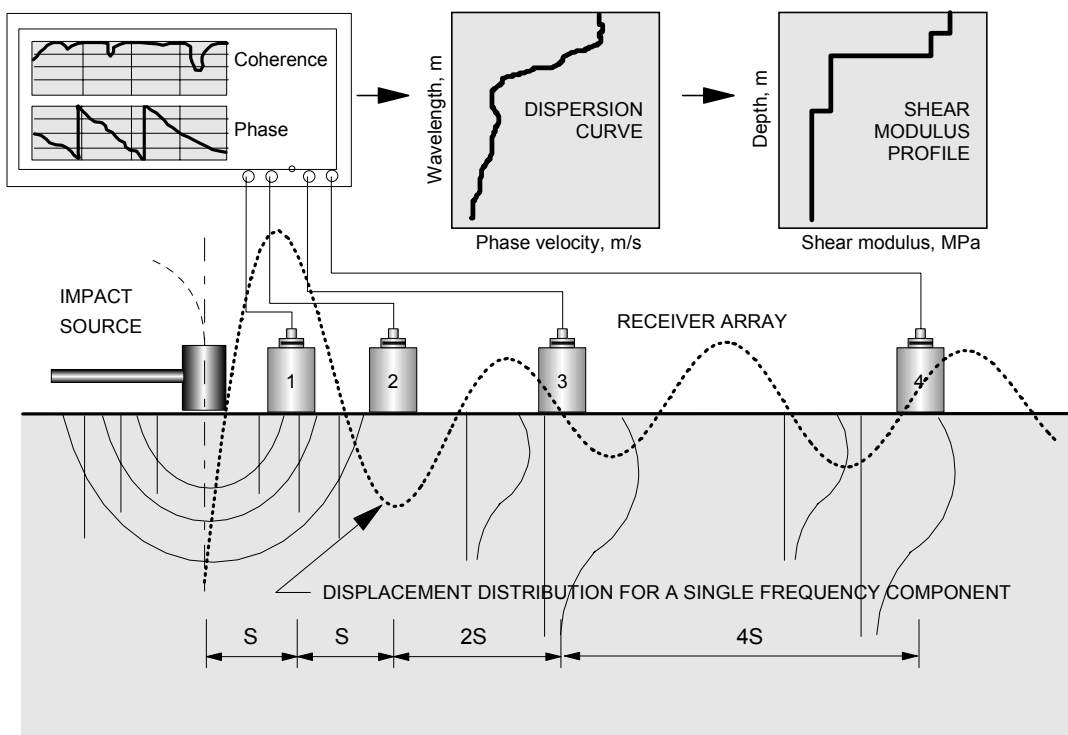


Figure 1- Schematic of SASW Test Procedures.

SEISMIC PAVEMENT ANALYZER (SPA)

Under funding from the Strategic Highway Research Program (SHRP), a rapid nondestructive testing device named the Seismic Pavement Analyzer (SPA) was developed (Nazarian et al., 1995).

A detailed discussion on the conceptual background of SPA can be found in Nazarian et al. (1995). The operating principle of SPA is based on generating and detecting stress waves in a layered medium. The equipment has been used in several applications such as analyzing pavement conditions in project-level surveys, diagnosing specific distress precursors to aid in selecting a maintenance treatment, and monitoring pavement conditions after construction as a quality control tool. The SPA can perform four different nondestructive seismic tests; which are impulse-response (IR) test, ultrasonic surface wave velocity measurement test, impact-echo test, and SASW test.

The SPA, as shown in Figure 2, is mainly designed to determine the variation in modulus with depth. It has a source transducer frame which is built up on a trailer that can be towed behind a vehicle. The device is controlled by an operator at a computer connected to the trailer. To start the test the machine lowers its transducers and sources to the surface of the pavement. As the goal in the SASW test method is to generate and detect surface waves over a wide range of wavelengths, first a high frequency pneumatic hammer generates waves that primarily propagate through the ACP and base layers. Then a low frequency pneumatic hammer generates waves traveling down to the subgrade layer. The pavement response produced by the hammers is monitored, captured and stored using five accelerometers and three geophones. The data collected with the above setup is then transformed into a dispersion curve called hereafter the experimental dispersion curve.

Measurements are discrete, that is the device has to be situated at a desired point for measurements. A complete testing cycle at one point may take up to one minute. Most of data reduction is also executed during this one minute by the computer. Based on the SPA setup, moduli down to a depth of about two meter can be measured.



Figure 2 - Seismic Pavement Analyzer (SPA)

SEISMIC MODULUS ANALYSIS AND REDCTION TOOL (SMART)

The successful use of pavement analysis algorithms requires a balance between the input parameters, the structural models, and the transfer functions. Striking such balance depends on the different levels of sophistication associated with different types of roads. For example, using simplified empirical models may be adequate for many tertiary roads in the network. Secondary roads can be simply designed using criteria developed based on FWD results and linear-elastic models. However, major highways should take advantage of thorough laboratory and field tests, with a reasonably sophisticated nonlinear elastic algorithm.

In a mechanistic pavement analysis process it becomes crucial to determine (1) pavement-related physical constants, (2) the strength and stiffness parameters and constitutive model of each layer from laboratory and field testing. Pavement evaluation algorithms range from one of many layer theory or finite element programs. The materials can be modeled as linear or nonlinear and elastic or viscoelastic. The applied load can range from dynamic to static. The reliability level of any process depends highly on the compatibility of the level of inputs and outputs used in contrast to the analytical algorithm.

SMART was designed for a flexible pavement system based on the classical layered elastic theory with a modification on the analysis of the structural response of the pavement system. The algorithm integrated in this program is a compromise between the simple linear model and comprehensive nonlinear model. This algorithm takes advantage of the speed of the linear analysis while incorporating the nonlinear behavior of the pavement layers. Although the algorithm is not strictly a nonlinear algorithm, it accounts for the nonlinear behavior of the pavement materials under actual truck traffic. The algorithm is referred to as an equivalent-linear analysis method.

Even though the primary input to SMART is seismic modulus for each layer, other inputs to describe each layer of the pavement system are also required. The level of inputs required in the program depends on the type of material models selected for each layer. The remaining inputs and material models used by the program are described in the following sections.

Material Models

Asphalt-Concrete Pavement Layer (ACP): The material models for the ACP layer used in SMART are summarized Table 1. The modified linear-elastic model is rather simple since the modulus is considered as a constant value. To incorporate the viscoelastic model, the recommendations by Aouad et al. (1993), Li and Nazarian (1994) are incorporated in this model in an approximate fashion. The advantage of these models is that they can rapidly yield results. Their main limitation is that the results are rather approximate if the loads are large enough for the material to exhibit a nonlinear behavior.

The second and third options used in SMART to adjust for viscoelasticity are based on the master curve concept. This curve uses the principals of viscoelastic and time-temperature superposition. This curve can be used to adjust the moduli for frequency and temperature. The new M-E Design Guide has adopted such curve. Witczak et al. (1999) describe the newer methodology proposed in the development of the master curve. The general practice has been that the complex modulus testing is performed at various temperatures at similar loading times. The master curve is then constructed based on a reference temperature using a time-temperature shift factor. As Table 1 illustrates, a sigmoidal function proposed by Ferry (1970) can be used to generate a master curve.

The sigmoidal parameters α , β , γ and δ should be preferably obtained from laboratory testing. The other option in determining the curve parameters, in the absence of lab testing, is through the mix properties as suggested by Mirza and Witczak (1995). Regression equations were developed to determine the curve parameters. Abdallah et al. (2003) provide detail on each of the equations used to adjust the ACP modulus due to temperature and frequency that is used in SMART.

Table 1 – Material Models for Asphalt Concrete Layer

<p>Linear-Elastic Model</p>	$E = E_{seis} = \frac{\sigma}{\epsilon},$ <p>where E is the modulus at a given depth, E_{seis} is the seismic modulus of the layer σ is the related stress and ϵ is the corresponding strain.</p>
<p>Viscoelastic Model</p>	<p>(1) Based on temperature correction (Li and Nazarian, 1994),</p> $E_{77^{\circ}F} = \frac{E_t}{1.35 - 0.0078(t - 32)},$ <p>where E_{75} and E_t are the moduli at 77° F and temperature t (in Fahrenheit)</p> <p>(2) Based on mater curve (Ferry, 1970),</p> $\log(E^*) = \delta + \frac{\alpha}{1 + e^{\beta + \gamma \log t_r}},$ <p>where E^* = dynamic modulus, t_r = loading period, δ = Minimum value of dynamic modulus, $\delta + \alpha$ = Maximum value of dynamic modulus and β, γ = sigmoidal function shape parameter. Mirza and Witczak (1995) have proposed the following relationships for obtaining values of the sigmoid parameters in the absence of lab tests:</p> $\delta = -1.249937 + 0.02932\rho_{200} - 0.001767\rho_{200}^2 - 0.002841\rho_4 - 0.058097V_a - \frac{0.802208V_{beff}}{V_{beff} + V_a}$ $\alpha = 3.871977 - 0.0021\rho_4 + 0.003958\rho_{38} - 0.000017\rho_{38}^2 + 0.005470\rho_{34}$ $\beta = -0.603313 - 0.393532\log(\eta_t)$ $\gamma = 0.313351$ <p>where ρ_{200} is percent passing on the 0.075mm sieve, ρ_4 is cumulative percent retained on the 4.76 mm sieve, V_a is percent air voids in the mix by volume, V_{beff} is percent effective bituminous content by volume, ρ_{38} is cumulative percent retained on the 9.5 mm sieve, ρ_{34} in cumulative percent retained on the 19 mm sieve, η_t is viscosity of the binder at a reference temperature.</p>

Base and Subgrade Layer: The linear-elastic model can also be selected in SMART for the foundation layers. As presented in Table 2, in addition to the linear-elastic model, a nonlinear model is also an option. An iterative process is employed to consider the nonlinearity of the pavement materials. In the equation presented in Table 2, k_1 , k_2 and k_3 are statistically determined coefficients from laboratory testing. The advantage of the model is that it is universally applicable to fine-grained and coarse-grained base and subgrade materials.

Table 2 – Material Models for Base and Subgrade Layers

<p>Linear-Elastic Model</p>	$E = E_{seis} = \frac{\sigma}{\varepsilon},$ <p>where E is the modulus at a given depth, E_{seis} is the seismic modulus of the layer σ is the related stress and ε is the corresponding strain.</p>
<p>Nonlinear Model</p>	$E = k_1 \sigma_c^{k_2} \sigma_d^{k_3},$ <p>modified to $E = E_{seis} \left(\frac{\sigma_{c-ult}}{\sigma_{c-init}} \right)^{k_2} \left(\frac{\sigma_{d-ult}}{\sigma_{d-init}} \right)^{k_3}$ by Ke et al. (2000)</p> <p>where E is the resilient modulus at a given depth under FWD or truck load, E_{seis} is the seismic modulus of the layer, k₂ and k₃ are statically determined coefficients. σ_{c-init} and σ_{c-ult} are respectively initial and ultimate confining pressures. σ_{d-init} and σ_{d-ult} are the initial and ultimate deviatoric stresses, respectively.</p>
<p>Nonlinear Plasticity Index Model</p>	$\frac{E}{E_{seis}} = K(\gamma, PI) (\sigma'_m)^{m(\gamma, PI) - m_0}$ by Ishibashi and Zhang (1993) <p>where PI is the plasticity index of the base or subgrade material and γ is the shear strain and</p> $K(\gamma, PI) = 0.5 \left\{ 1 + \tanh \left[\ln \left(\frac{0.000102 + n(PI)}{\gamma} \right)^{0.492} \right] \right\}$ $m(\gamma, PI) - m_0 = 0.272 \left\{ 1 - \tanh \left[\ln \left(\frac{0.000556}{\gamma} \right)^{0.4} \right] \right\} \exp(-0.0145 PI^{1.3})$ $n(PI) = \begin{cases} 0.0 & \text{for } PI = 0 \\ 3.37 \times 10^{-6} PI^{1.404} & \text{for } 0 < PI \leq 15 \\ 7.0 \times 10^{-7} PI^{1.976} & \text{for } 15 < PI \leq 70 \\ 2.7 \times 10^{-5} PI^{1.115} & \text{for } PI > 70 \end{cases}$

One of the major purposes of this study is to relate the seismic modulus with the load-induced nonlinear modulus. For this reason, universal equation is modified by Ke et al. (2000) to include the seismic modulus and the stresses under seismic test (See Table 2). This model is more elaborate and is detailed in Abdallah et al. (2003). The remaining nonlinear parameters k₂ and k₃ can be obtained from laboratory tests such as the resilient modulus test. In the absence of laboratory testing, the k₂ and k₃ values can be approximated based on the material quality.

The equivalent-linear model is constrained at very small or at very large deviatoric stresses to avoid modulus to reach infinity or zero, respectively. Kramer (1996) has shown that below a certain strain level the modulus is constant and equal to the small-strain linear-elastic modulus of the material. Similarly, at higher strain levels, the modulus approaches a constant value. Therefore, a set of boundary limitations is

applied to both conditions. In the case where the equation exhibits very small strain the modulus becomes greater than the seismic modulus measured in the field, and the seismic modulus is then adopted as the modulus of the material. On the other hand, if at higher vertical strain levels the modulus becomes lower than 5% of the seismic modulus measured in the field, 5% of seismic modulus will be adopted as the modulus of the material. These limitations are implemented in the SMART program. The equivalent linear model is adopted for the base, subbase and subgrade layers.

Another model is incorporated into the program for base and subgrade layers that utilizes as input only the plasticity index (PI) of the material. Ishibashi and Zhang (1993) provide a detail of the model that shows the effects of the confining pressure and plasticity index on modulus behavior. The model is also provided in Table 2.

SMART Algorithm and Analysis Process

Data from a farm-to-market road in Texas is used to demonstrate the analysis employed in SMART. The site consisted of about 3 in. of ACP over 17 in. of stiff base over a moist clayey subgrade.

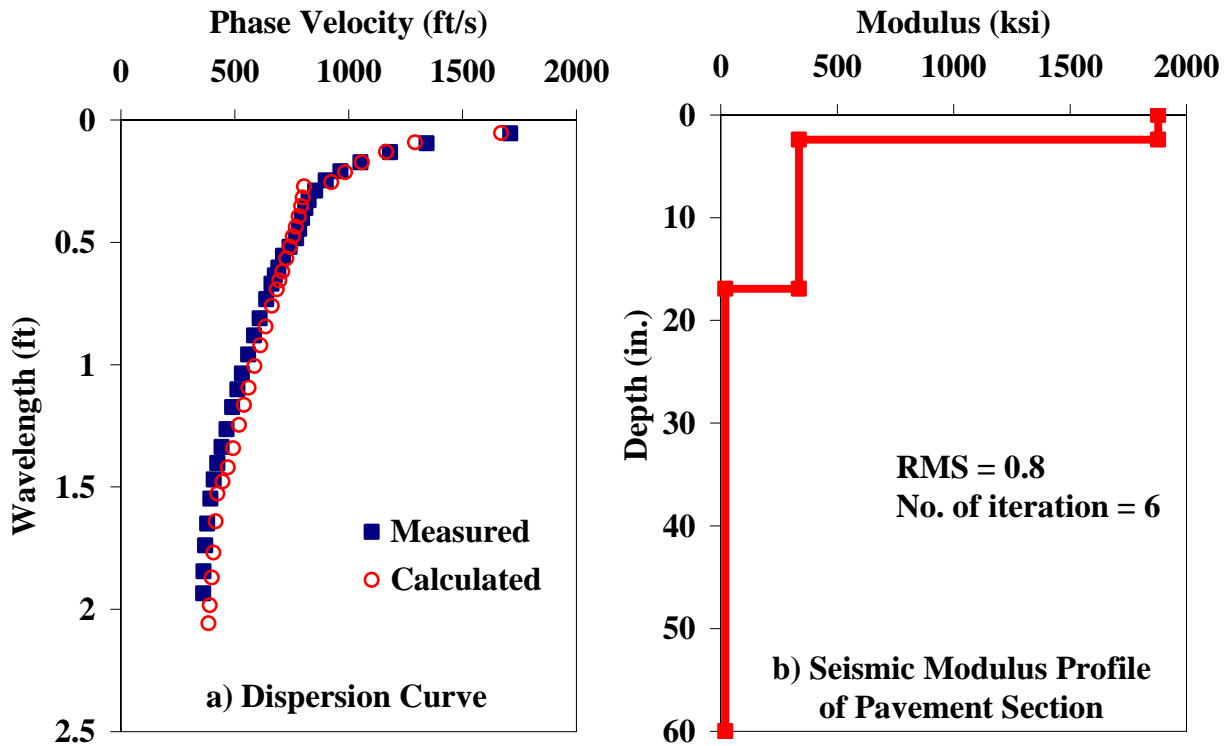
Field Testing: SPA data was collected data at eleven locations each about 30 ft apart. The data from SPA was analyzed using the SASW method to determine the seismic modulus profile. The reduction of the SASW data is a two-step process (see Nazarian et al., 1995). As discussed earlier, the first step consists of constructing an idealized dispersion curve; which represents a variation in phase velocity with wavelength. Once a dispersion curve is determined, an inversion algorithm estimates the seismic modulus profile of the pavement section. Figure 3 shows the data and results from the SASW process.

The dispersion curve and seismic modulus profile at the trench location are presented in Figure 3. The measured and calculated dispersion curves are compared in Figure 3a. The calculated dispersion curve is generated by the inversion process using the seismic modulus profile depicted in Figure 3b. The RMS error and number of iterations in Figure 3b refer to the closeness of the fit between the measured and calculated dispersion curves. Table 1 present the results for all test at the site. The average, standard deviation and coefficient of variation (COV) for the site are also presented.

Laboratory Testing: Laboratory testing is useful in this process to determine values of k_2 and k_3 parameters from resilient modulus tests. Material from the site for both the base and subgrade layers were retrieved and tested using the standard resilient modulus to determine the nonlinear parameters k_2 and k_3 of the base and subgrade. The k_2 and k_3 values for the base are 0.50 and -0.30, and for the subgrade are -0.04 and -0.4, respectively.

SMART Analysis: SMART uses different material models for each layer in a pavement system, the level of inputs vary dependent on the importance of the project being analyzed. Another feature of SMART is the equivalent-linear process based on the static linear elastic layered theory.

Figure 3 - Dispersion Curve and Inversion Profile for the Center Location



The equivalent-linear algorithm can be selected for base, subbase and subgrade layers. The program allows up to six structural layers with the depth to rigid layer that can be specified as either semi-infinite or rigid.

As discussed previously, the level of inputs used in the program depends on the type of material models selected for each layer. For the site presented in this study, a three layer system with a viscoelastic ACP, and nonlinear base and subgrade is used. As such the inputs required are the results from a) the SASW results summarized in Table 3 and b) laboratory testing for the base and subgrade, which are the k_2 and k_3 values determined from the resilient modulus test.

Figure 4 presents a general flowchart that shows the analyses process using the equivalent linear routine. First, in SMART, a project folder is created to store all information from the analysis. Next, field data is retrieved. In this case, field data is the output of the SASW analysis. Once field data is retrieved the pavement layer system is automatically generated. The next step in the process is to select material models for each layer in the system. In the case of AC layer, the viscoelastic model is selected and in the case of base and subgrade layers the nonlinear model is selected. Once the material models selected and their respective parameters defined, the equivalent-linear analysis is performed. The equivalent-linear process is an iterative process that calculates modulus values at various sublayers. Ke et al. (2000) describes the development of the equivalent-linear process. The results of the analysis for the middle section of the site are presented in Figure 5. The top layer was considered as a linear viscoelastic layer,

Table 3 - Results of SASW Data Reduction Process

Point	ACP		Base		Subgrade
	Modulus (ksi)	Thickness (in.)	Modulus (ksi)	Thickness (in.)	Modulus (ksi)
-5	2267	2.2	346	15.6	30
-4	2070	2.2	375	16.0	26
-3	2199	1.9	276	16.1	28
-2	2094	2.0	276	17.3	25
-1	2028	2.8	348	17.5	23
0*	1878	2.4	335	16.9	20
1	2108	2.5	404	16.3	26
2	2133	2.7	385	16.7	32
3	2011	2.6	172	18.2	27
4	1978	2.6	448	16.4	29
5	2240	2.0	286	16.1	29
Avg.	2091	2.4	332	16.7	27
Std. Dev.	117	0.3	76	0.8	3.4
C.O.V.	6%	12%	23%	5%	13%

* - Center Location of the test section

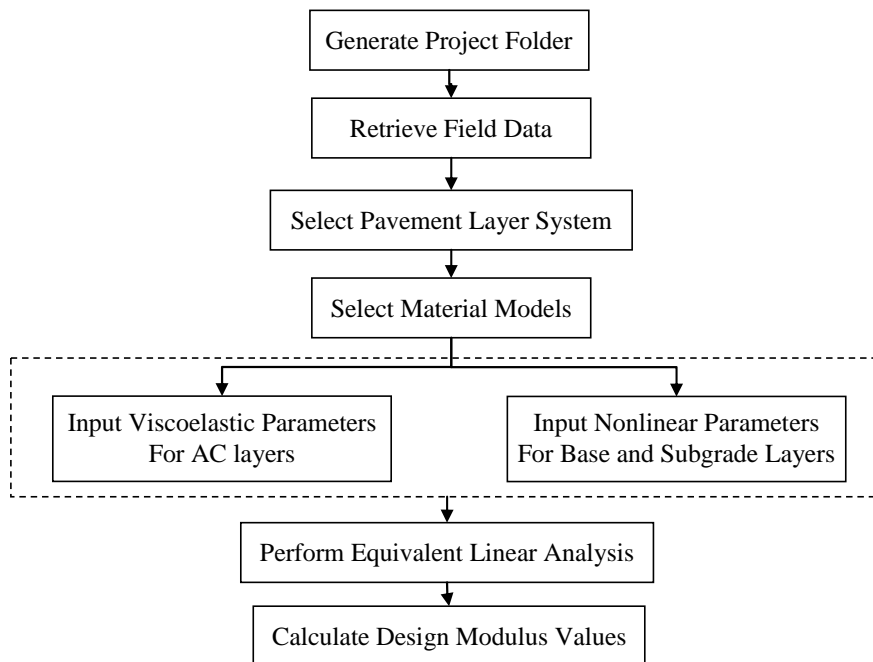


Figure 4 - Flowchart Illustrating the Process in SMART

and therefore its modulus is a constant value of 586 ksi. The variations in the modulus values within the base and subgrade layers under a standard dual-tandem axle are also shown in the figure. The modulus of the base layer varies from 200 ksi (located at the bottom of the base under the load) to 320 ksi (located away from the loading area). As for the subgrade the modulus varies from 14 ksi (located near the loaded area) to 20 ksi (located at the bottom of the subgrade).

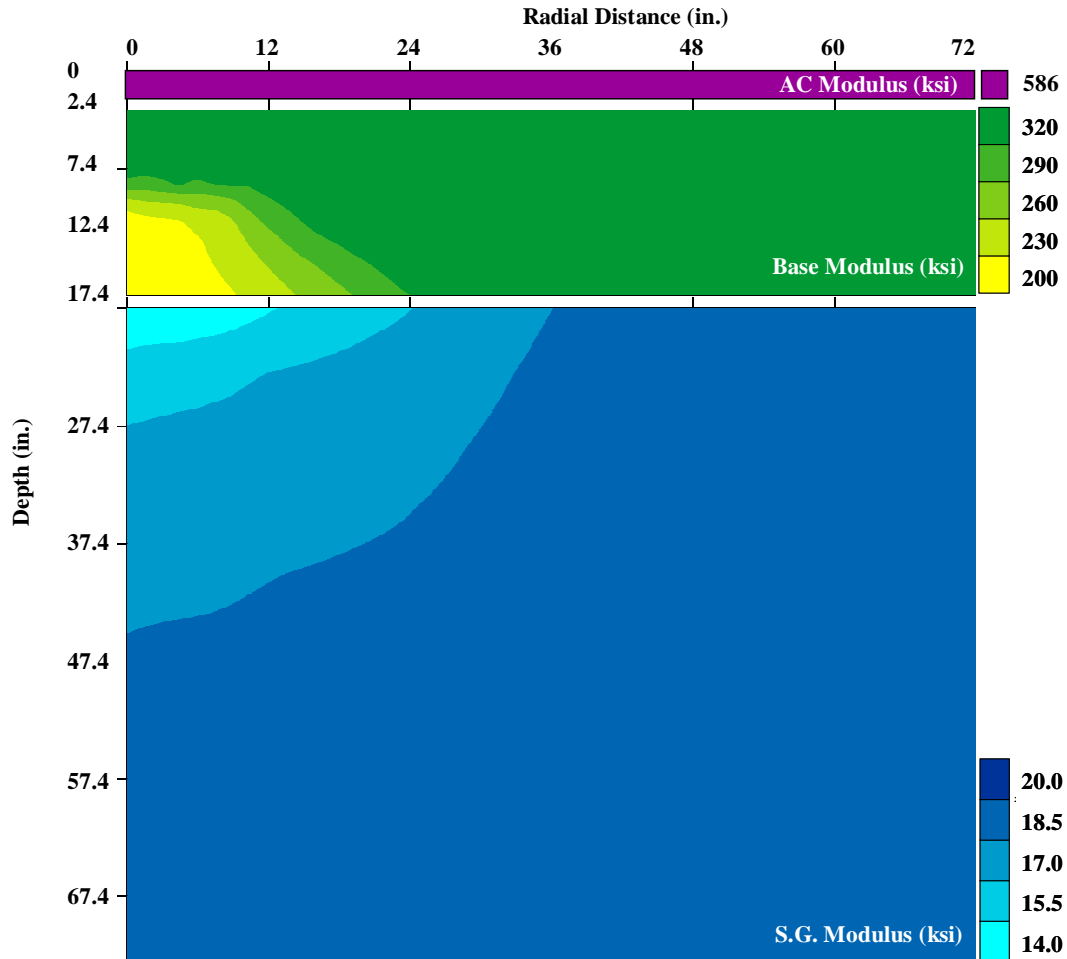


Figure 5 - Modulus Profiles Based on the Center of the Site Location

As reflected in the figure, the modulus in the base and subgrade show the extent of the nonlinearity exhibited under traffic load. The further distance away from the load is, the less nonlinear the material becomes. Although the extent of the nonlinear behavior varies from one system to another for the base and subgrade, the shape of the nonlinear behavior is consistent. The largest nonlinearity is exhibited between the interface of the base and subgrade. The critical stresses and strains obtained from the interface zone based on these results will vary significantly from those obtained from typical linear analysis. This is evident that the impact of considering the load-induced variation in modulus of each layer has a large impact on the pavement performance.

The final step in the process is to determine the design moduli. Although the variation in modulus within each nonlinear layer can be used visually to appreciate the degree of load-induced nonlinearity in the layer, they may not be quantitative enough for engineering design. Therefore, graphs like those shown in Figure 5 have to be further summarized. One set of moduli need to be presented and used in current design programs. The minimum (conservative) and a weighted average modulus (average) under the load within a layer is provided as an output to the user.

The moduli for the entire site are presented in Table 4. The table contains both the conservative and average moduli. Users can decide which of the two modulus values to use based on the importance of the project and the required level of confidence of the project. For this site, the minimum design modulus for the base and the subgrade are about 20% to 30% less than the average values.

Table 4 - Design Moduli Using SMART

Point	Modulus (ksi)					
	Conservative			Average		
	AC	Base	Subgrade	AC	Base	Subgrade
-5	708	209	19	708	280	26
-4	646	228	17	646	306	22
-3	687	158	18	687	219	24
-2	654	163	16	654	222	21
-1	633	222	16	633	288	20
0	586	204	14	586	271	17
1	658	258	18	658	335	22
2	666	251	21	666	322	28
3	628	93	17	628	133	23
4	618	296	20	618	378	25
5	700	166	18	700	228	25
Avg.	653	204	18	653	271	23
Std. Dev.	37	57	2	37	68	3
COV	6%	28%	11%	6%	25%	13%

Validation of SMART: An independent process validating the results using FWD measurements collected at the same location as seismic data was performed. An FWD measures a response (seven deflections) of a pavement to a known load. Normally, the load and deflections can be input into a backcalculation program to determine the modulus of each layer. Given the uncertainty associated with the backcalculation process, we attempted to avoid it as a primary validation tool. A more straight forward means of validating the process is to estimate the seven deflections that would have been measured by the FWD using the seismic moduli. Seismic moduli and lab test results were input into SMART to determine the variation in modulus within each layer. Using the moduli suggested by SMART, the seven deflections were then calculated. The closeness between the measured deflection basins and those calculated from the output of SMART was used to determine the appropriateness of the algorithms.

The comparison of results is presented using the average deflection as shown in Figure 6. Figure 6 presents the normalized FWD deflections and corresponding \pm standard deviation were plotted against the calculated deflection from SMART. The average deflections from SMART match well with the FWD deflections. This is verified by the RMS error with respect to the FWD measurements shown in the figure. These results are good indications of the applicability of the seismic methods to determine design values that can be used for pavement design and analysis.

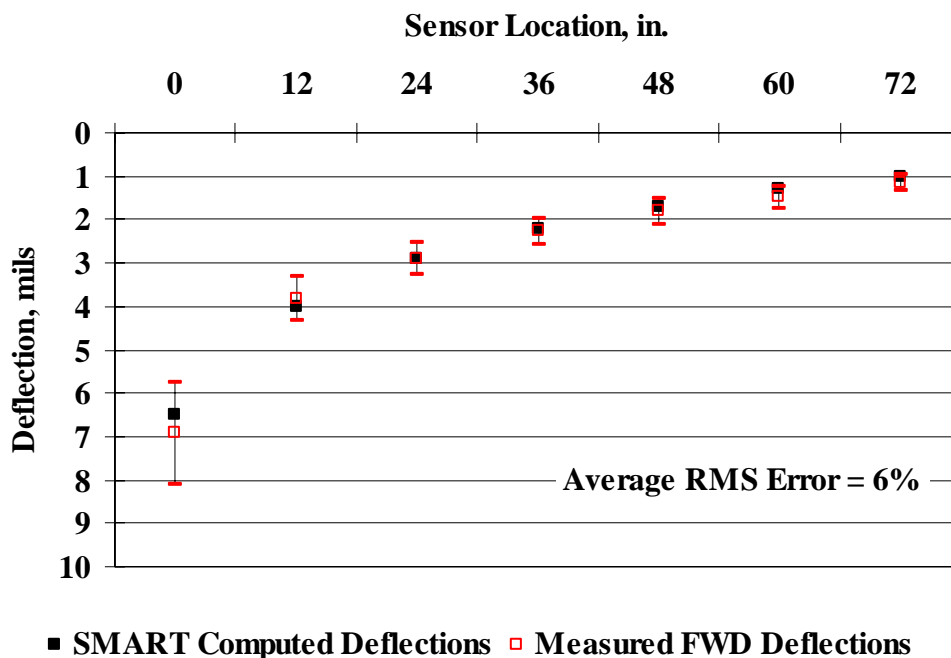


Figure 6 – Comparison of Average Deflection Results from Equivalent-Linear Methods Using SMART with Measured FWD Deflections

The significance of this case study was that the seismic analysis can yield moduli that can estimate the measured deflection basin with a reasonable closeness, at the same time it provides a means of incorporating the nonlinear behavior of the layer in a more rational manner.

SUMMARY AND CONCLUSIONS

Nondestructive testing (NDT) methods are typically used to measure the variations in the modulus of different pavement layers. The Seismic Pavement Analyzer (SPA) is one of the NDT devices used for this purpose.

The Seismic Pavement Analyzer is based on generating and detecting stress waves in a layered system. The elastic moduli of different layers are obtained from an inversion process. The SPA imparts small external loads to the pavement; therefore, seismic moduli are linear elastic moduli. To incorporate in pavement design and analysis, seismic moduli of different layers have to be adjusted to represent moduli at strain and stress levels that are close to those applied by truck traffic. To do so, the nonlinear and viscoelastic behaviors of different layers should be accurately determined. These nonlinear parameters vary widely for different types of granular base and subgrade materials. The nonlinear parameters of each pavement layer can be preferably obtained from laboratory testing. However, adequate published information is available to be used as a first approximation.

The major objective of the study presented in this paper is to develop an algorithm for predicting the design modulus of each layer given the seismic modulus and the nonlinear and/or viscoelastic parameters of each pavement layer. The efforts have yielded a software package called SMART (Seismic Modulus Analysis and Reduction Tool). This software incorporates various algorithms that enable several material models to be selected depending on the complexity and importance of the project analyzed.

An example from an actual site was presented. Field testing was performed collecting seismic data and a trench was dug to retrieve material for lab testing. The nonlinear parameters k_2 and k_3 of the base and subgrade were determined from the resilient modulus test. The seismic data was analyzed using

SASW to obtain seismic profiles. Finally seismic profiles combined with k2 and k3 values for base and subgrade were input to SMART to obtain design modulus values. Results from the case study show the use of the process to determine design modulus values from seismic data. Also presented was the soundness of the algorithm by validating the results of SMART with measured FWD data. The results from the validation indicate that the SMART program is capable of providing reasonable values to design engineers.

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REFERENCE

Abdallah, I., Yuan, D. and Nazarian, S. (2003), "Validation of software Developed for Determining Design Modulus from Seismic Testing," Research Report 1780-5, Center for Highway Materials Research, the University of Texas at El Paso, TX

Aouad, M. F., Stokoe, K. H., and Briggs, R. C. (1993), "Stiffness of Asphalt Concrete Surface Layer from Stress Wave Measurements," Transportation Research Record 1384, Washington, D.C., pp. 29-35.

Ferry, J.D, (1970), "Viscoelastic Properties of Polymers," 2nd edition, John Willy, New York.

Ishibashi, I. and Zhang, X. (1993), "Unified Dynamic Shear Moduli and Damping Ratios of Sand and Clay," Soils and Foundations, Vol. 33, No. 1, pp. 182-191.

Ke, L., Nazarian, S., Abdallah, I., and Yuan, D., (2000), "A Sensitivity Study of Parameters Involved in Design with Seismic Moduli," Research Report 1780-2, Center for Highway Materials Research, the University of Texas at El Paso.

Kramer, S. L. (1996), Geotechnical Earthquake Engineering, Prentice Hall, Inc., Englewood Cliffs, NJ, 653 p.

Li, Y. and Nazarian, S. (1994), "Evaluation of Aging of Hot-Mix Asphalt Using Wave Propagation Techniques," Proceedings, Engineering Properties of Asphalt Mixtures And the Relationship to Their Performance, ASTM STP 1265, Philadelphia, PA, pp.166-179.

Mirza, M. W., and Witczak, M.W. (1995), "Development of a Global Aging System for Short and Long Term Aging of Asphalt Cements," Journal of Association of Asphalt Paving Technologies, Volume 64, Association of Asphalt Paving Technologies, St Paul, Minnesota, pp. 393-430.

Meshkani, A., Abdallah, I., and Nazarian, S. (2001), "Determination of Nonlinear Parameters of Flexible Pavement Layers from Nondestructive Testing," Research Report 1780-3, Center for Highway Materials Research, the University of Texas at El Paso, TX, 97 p.

Nazarian, S. and Desai, M. R. (1993), "Automated Surface Wave Method: Field Testing," Journal of Geotechnical Engineering Division, ASCE, Vol. 119, No. GT7, New York, NY, pp. 1094-1111.

Nazarian, S., Yuan D. and Baker M. R. (1995), "Rapid Determination of Pavement Moduli with Spectral-Analysis-of-Surface-Waves Method," Research Report 1243-1F, Center for Geotechnical and Highway Materials Research, The University of Texas at El Paso, El Paso, TX, 76 p.

Nazarian, S., and Stokoe, II, K.H. (1986), "In Situ Determination of Elastic Moduli of Pavement Systems by Spectral-Analysis-of-Surface-Waves Method (Practical Aspects)." Research Report 368-1 F, Center for Transportation Research, University of Texas, Austin.

Nazarian, S., and Stokoe, II, K.H. (1987), "In Situ Determination of Elastic Moduli of Pavement Systems by Spectral-Analysis-of-Surface-Waves Method (Theoretical Aspects)," *Research Report 437-2, Center for Transportation Research, University of Texas, Austin.*

Witczak, M.W., Bonaquist, R., Von Quintus, H., and Kaloush, K. (1999), "Specimen Geometry and Aggregate Size Effects in Uniaxial Compression and Constant Height Shear Tests," *Journal of Association of Asphalt Paving Technologist*, Volume 69, pp 733-793.