Advanced Approaches to Characterizing Nonlinear Pavement System Responses

Halil Ceylan, Kasthurirangan Gopalakrishnan, and Alper Guclu

The use of falling weight deflectometer–based backcalculation techniques to determine pavement layer moduli is a cost-effective and widely used method for the structural evaluation of an existing pavement. The nonlinear stress-sensitive response of pavement geomaterials has been well established, and mechanistic-based pavement design can be improved by inclusion of these nonlinear material properties. To further the science of nonlinear backcalculation, the TRB Strength and Deformation Characteristics of Pavement Sections Committee has assembled four data sets that can be used to demonstrate the ability to derive stress-dependent moduli for pavement layers. In this study, validated artificial neural network (ANN)–based backcalculation-type flexible pavement analysis models were used to evaluate the TRB Nonlinear Pavement Analysis Project data sets. The Illi-Pave finite element (FE) model, considering nonlinear stress-dependent geomaterials characterization, was utilized to generate a solution database for developing the ANN-based structural models. Such use of ANN models enables the incorporation of needed sophistication in structural analysis, such as FE modeling with proper materials characterization, into routine practical design. This study illustrated the complexities associated with interpreting the backcalculated modulus values. In general, the predicted strains agreed reasonably well with the measured strain values, whereas the predicted stresses did not.

The elastic modulus (resilient modulus) is a fundamental material property required for characterization of pavement layers for use in mechanistic pavement analysis and design. The use of backcalculation techniques based on nondestructive testing (NDT) to determine layer moduli is a cost-effective and widely used method for the structural evaluation of an existing pavement. Among all NDT methods, the falling weight deflectometer (FWD) is probably the most widely used technique because of its ability to successfully simulate traffic loadings and its capacity to produce a larger amount of deflection data in unit time (*1–4*).

Elastic-layered programs used in flexible pavement analysis assume the pavement materials to be linear elastic. However, the unbound granular base and subbase aggregate materials and fine-grained subgrade soils, herein referred to as geomaterials, do not follow a linear type of stress–strain behavior under repeated traffic loading. In effect, the nonlinear stress-dependent response of pavement geomaterials has been well established (*5–7*). Unbound aggregates

exhibit stress hardening or stiffening, whereas fine-grained soils show stress softening behavior. Pavement structural analysis programs that take into account nonlinear geomaterials characterization, such as the Illi-Pave finite element (FE) program (*8*), need to be employed to predict more realistically the pavement response needed for mechanistic-based pavement design.

Mechanistic-based pavement design can be improved by inclusion of nonlinear material properties (*9–11*). To further the science of nonlinear backcalculation, the TRB Strength and Deformation Characteristics of Pavement Sections Committee has assembled four data sets that can be used to demonstrate the ability to derive stress-dependent moduli for pavement layers (*12*). This effort was named the TRB Nonlinear Pavement Analysis Project. Both FWD data and pavement response data, measured in situ, are provided for the four sites. The objective is to backcalculate nonlinear materials data for the pavement layers and then to use those data to predict the measured pavement response.

In this study, validated artificial neural network (ANN)–based backcalculation-type flexible pavement analysis models were used to evaluate the TRB Nonlinear Pavement Analysis Project data sets. ANNs are valuable computational tools that increasingly are being used to solve resource-intensive complex problems as an alternative to more traditional techniques. Although ANN modeling has been used in the past to aid in backcalculation (*13*), the structural models used to train the ANN models did not account for realistic stress-sensitive geomaterial properties. For this reason, the Illi-Pave FE program, considering nonlinear stress-dependent geomaterials characterization, was utilized to generate a solution database for developing ANN-based structural models to accurately predict pavement layer moduli from realistic FWD deflection profiles. Such use of ANN models enables the incorporation into routine practical design of needed sophistication in structural analysis, such as FE modeling with proper materials characterization.

PREVIOUS STUDIES

Researchers have tried to analyze the TRB Nonlinear Pavement Analysis Project data sets with different approaches and have presented their results at both the 2003 and 2004 TRB Annual Meetings. In this section, brief descriptions of test sites from which the data sets were collected are presented and the reported findings from previous research studies are summarized.

Four sites provided both the FWD data and pavement response data, measured in situ. Site 1 is located at the Frost Effects Research Facility (FERF) at the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, New Hampshire. The subgrade soil is an A-4 silt that appears to be stress-dependent. Site 2 is located near the Danish Road Institute in Roskilde, Denmark.

The subgrade soil is a fine sand that appears to be moderately stress-dependent. Site 3 is on State Highway 281, a two-lane road near Jacksboro, Texas. The subgrade soil is clayey, and it appears to be moderately stress-dependent. Site 4 is located in the Road Test Machine (RTM) at the Danish Technical University in Lyngby. The subgrade soil is an A-6 clayey silt that appears to be stress-dependent. Detailed descriptions of these test sites can be found elsewhere (*12*).

Uddin et al. (*14*) used a static linear-elastic backcalculation program, University of Mississippi version of Pavement Evaluation Based on Dynamic Deflections (UMPED), to backcalculate the in situ Young's modulus values from measured FWD deflections collected at the four TRB project sites, and subsequently the Pavement Structural Response Analysis (PAVRAN) linear elastic analysis program was used for response calculation (*15*). Uddin et al. (*14*) also employed a three-dimensional (3-D) FE model, LS-DYNA, for Site 1 (Location 10, S1/2) response analysis, and the results agreed reasonably well with the elastic static analysis results. In general, the backcalculation analysis programs showed generally acceptable results with the exception of Site 3 results. The strains calculated from elastic static analysis agreed reasonably well with the measured strain results. No agreement was found among the measured and computed stress results for Sites 1, 2, and 3. The calculated vertical stresses were generally 1.5 to 2.5 times higher than the measured values. Uddin et al. (*14*) highlighted the problems associated with static linear elastic response analysis for pavements with shallow bedrock (as in Site 3).

Uzan (*16*) performed both linear and nonlinear backcalculation analysis for Site 1 in Hanover, New Hampshire. Both analyses used all load levels to derive one set of moduli or material parameters (*17*). The backcalculation results (using FWD deflection bowls only) showed a better fit of the surface deflections with the nonlinear approach than with the linear approach (*16*). It was suggested that the nonlinear procedure should be used instead of the linear one in cases in which the structural response data indicated a nonlinear response. The results also showed that the computed responses (based on backcalculated moduli) differed from the measured ones by a factor of about 1.5. The prediction of stresses and strains was slightly better with the nonlinear approach than with the linear procedure.

Xu et al. (*18*) developed the Asphalt Pavement Layer Condition Assessment Program (APLCAP), which implements a new integrated procedure for condition assessment from FWD deflections based on dynamic nonlinear FE analysis and calibrated with field measurements (*19*). To test the prediction accuracy of algorithms incorporated into APLCAP, Xu et al. (*18*) examined the TRB Nonlinear Pavement Analysis Project data sets with APLCAP. The Site 1 (CRREL) pavement and the Site 4 (Danish RTM) pavement were used for this study. The APLCAP algorithms predicted the strains in the asphalt concrete (AC) layer and subgrade quite well. APLCAP underestimated the compressive strain on the top of the subgrade for the CRREL pavement by 15%, and it overestimated the tensile strain at the bottom of the AC layer for the RTM pavement by only 2%.

Chatti et al. (*20*) developed a dynamic time-domain method to backcalculate the layer moduli, damping ratios, and thicknesses of asphalt pavements from dynamic FWD test data. Both static backcalculation (with MICHBACK) and dynamic backcalculation (with the developed method) were performed on FWD data collected from Site 2 in Jacksboro on State Highway 281 as well as from a site in Kansas. Although the backcalculated AC and subgrade thicknesses with the dynamic backcalculation method were larger than the reported thicknesses from the borelog, the backcalculated AC and subgrade layer moduli compared reasonably well with static backcalculation (known thicknesses) results.

Observations from these case studies as well as a review of the literature indicate that, despite its widespread acceptance, backcalculation poses a highly indeterminate problem that may generate a nonunique set of moduli. For instance, the depth of a rigid bottom, if not guessed properly, would significantly affect the output moduli. So also would transverse cracks that might intercept the sensors (*21*).

Numerous techniques have been developed for the backcalculation of pavement layer moduli so far. The fundamental discrepancies among developed backcalculation models arise from the type of forward response model (linear or nonlinear, static or dynamic) and the optimization procedure (least squares, database search method, etc.) carried out for the determination of appropriate layer modulus values (*22–26*).

In terms of the predicted responses, the main questions raised in the TRB 2006 Annual Meeting Workshop on Validation of Pavement Response Models were whether predicted stresses, strains, and displacements are reasonably predicted and whether it is necessary to predict the pavement response. It appears that the agreement between the measured and predicted responses is far from satisfactory. Two basic sources of error for the observed lack of agreement may be the computation (error in materials characterization is included) and the measurement of the pavement response (soil–instrument interaction problem) itself. All these concerns need to be addressed in the development of the next generation of mechanistic-based pavement analysis and design concepts.

NONLINEAR GEOMATERIALS CHARACTERIZATION

Under the repeated application of moving traffic loads, most pavement deformations are recoverable and thus considered elastic. It has been customary to use the resilient modulus (M_R) for the elastic stiffness of the pavement materials, defined as the repeatedly applied wheel load stress divided by the recoverable strain. Repeated-load triaxial tests commonly are employed to evaluate the resilient properties of unbound aggregate materials and cohesive subgrade soils. Therefore, emphasis should be given in structural pavement analysis to realistic nonlinear material modeling in the base and subbase and subgrade layers primarily based on repeated-load triaxial test results (AASHTO T307-99, European CEN Std EN 13286-7).

Simple resilient modulus models are often suitable for FE programming and practical design use, for example,

K-θ model (*27*):

$$M_R = K\left(\theta / p_0\right)^n \tag{1}$$

Universal model (*28*):

$$M_R = K_1\left(\theta / p_0\right)^{K_2} \left(\tau_{oct} / p_0\right)^{K_3} \tag{2}$$

where

$$\theta = \sigma_1 + \sigma_2 + \sigma_3 = \sigma_1 + 2\sigma_3 = \text{bulk stress,}$$
$$\tau_{oct} = \text{octahedral shear stress} = \sqrt{2}/3 * \sigma_d \text{ (where } \sigma_d =$$
$$\sigma_1^- \sigma_3 = \text{deviator stress in triaxial conditions),}$$
$$p_0 = \text{unit reference pressure (1 kPa or 1 psi) used in}$$
$$\text{models to make stresses nondimensional, and}$$
$$K, n, \text{ and } K_1 \text{ to } K_3 = \text{multiple regression constants obtained from}$$
$$\text{repeated-load triaxial test data on granular}$$
$$\text{materials.}$$

The simpler K-θ model often adequately captures the overall stress dependency (bulk stress effects) of unbound aggregate behavior under compression-type field loading conditions. The universal model (28) considers in addition the effects of shear stresses and handles the modulus increase (unbound aggregates) or decrease (fine-grained soils) with increasing stress states very well even for extension-type field loading conditions.

The resilient modulus of fine-grained subgrade soils also is dependent on the stress state. Typically, the soil modulus decreases in proportion to the increasing stress levels, thus exhibiting stress-softening type behavior. As a result, the most important parameter affecting the resilient modulus becomes the vertical deviator stress on top of the subgrade due to the applied wheel load. The bilinear or arithmetic model (29) is a commonly used resilient modulus model for subgrade soils. As indicated by Thompson and Elliot (29), the value of the resilient modulus at the breakpoint in the bilinear curve, E_{Ri}, can be used to classify fine-grained soils as being soft, medium, or stiff.

PAVEMENT STRUCTURAL ANALYSIS WITH ILLI-PAVE FE MODEL

Developed at the University of Illinois (8), Illi-Pave is an axisymmetric FE program commonly used in the structural analysis of flexible pavements. The nonlinear, stress-dependent resilient modulus geomaterial models summarized in the previous section are incorporated into Illi-Pave. Numerous research studies have validated that the Illi-Pave model provides a realistic pavement structural response prediction for highway and airfield pavements (29, 30). Recent research at the FAA Center of Excellence established at the University of Illinois also supported the development of a new, updated version of the program, now known as the Illi-Pave 2000 (30).

The Illi-Pave 2000 FE program was used in this study as the main validated nonlinear structural model for analyzing conventional flexible pavements. The goal was to establish a database of Illi-Pave response solutions that would eventually constitute the training and testing data sets for developing ANN-based structural models for the rapid forward- and backcalculation analyses.

The top surface asphalt course was characterized as a linear elastic material with the Young's modulus, E_{AC}, and Poisson's ratio, ν. Because of its simplicity and ease in model parameter evaluation, the K-θ model (27) was used as the nonlinear characterization model for the unbound aggregate layer. On the basis of the work of Rada and Witczak (31) with a comprehensive granular material database, K and n model parameters can be correlated to characterize the nonlinear stress-dependent behavior with only one model parameter by using the following equation (31):

$$\log_{10}(K) = 4.657 - 1.807 \cdot n \qquad R^2 = 0.68; \ \mathrm{SEE} = 0.22 \qquad (3)$$

Fine-grained soils were considered as "no-friction" but cohesion-only materials and modeled by using the bilinear or arithmetic model for modulus characterization. The breakpoint deviator stress, E_{Ri}, was the main input for subgrade soils. The K_3 and K_4 slopes were taken as constants, 1,100 and 200, respectively, corresponding to medium soils given by Thompson and Elliott (29). According to a comprehensive Illinois subgrade soil study by Thompson and Robnett (32), the breakpoint deviator stress, σ_{di}, was taken as 6 psi (41.4 kPa), and 2 psi (13.8 kPa) was used for the lower-limit deviator stress, σ_{dll}. The soil's unconfined compressive strength, Q_u, or cohesion was used to determine the upper-limit deviator stress, σ_{dul}, as a function of the breakpoint deviator stress, E_{Ri}, by using the following relationship (32):

$$\sigma_{\mathrm{dul}}(\mathrm{psi}) = 2 \times \mathrm{cohesion}(\mathrm{psi}) = Q_u(\mathrm{psi}) = \frac{E_{\mathrm{Ri}}(\mathrm{ksi}) - 0.86}{0.307} \qquad (4)$$

Therefore, the AC modulus, E_{AC}; granular base K-θ model parameter K; and the subgrade soil breakpoint deviator stress, E_{Ri}, in the bilinear model were used as the layer stiffness inputs for all the different conventional flexible pavement Illi-Pave runs. The 9,000-lb (40-kN) wheel load was applied as a uniform pressure of 80 psi (552 kPa) over a circular area with a radius of 6 in. (152 mm). The thickness and modulus ranges used are summarized in Table 1 also.

ANN-BASED PAVEMENT ANALYSIS TOOLS

Recent research studies at Iowa State University and the University of Illinois have focused on the development of ANN-based forward- and backcalculation-type flexible pavement analysis models to predict critical pavement responses and layer moduli, respectively (33–36).

Backpropagation-type ANN models were trained in this study with the results from the Illi-Pave FE program and were used as analysis tools for evaluating the TRB Nonlinear Pavement Analysis Project data sets. Backpropagation-type ANNs are powerful and versatile networks that can be taught mapping from one data space to another by using examples of the mapping to be learned. The term "backpropagation network" actually refers to a multilayered, feed-forward neural network trained with an error backpropagation algorithm. The learning process performed by this algorithm is called backpropagation learning, which is mainly an error minimization technique (37).

A total of 24,093 Illi-Pave FE runs were conducted by randomly choosing the pavement layer thicknesses and input variables within

TABLE 1 Pavement Geometry and Material Property–Model Inputs for Illi-Pave FE Model Solutions

Material Type	Layer Thickness	Material Model	Layer Modulus Inputs	Poisson's Ratio
Asphalt concrete	h_{AC} = 3 to 15 in. (76 to 381 mm)	Linear elastic	E_{AC} = 100 to 2,000 ksi (690 to 13,800 MPa)	ν = 0.35
Unbound aggregate base	h_{GB} = 4 to 22 in. (102 to 559 mm)	Nonlinear K-θ model	$M_R = K\theta^n$ "K" = 3 to 12 ksi (20.7 to 82.7 MPa) n from Equation 3	ν = 0.35 for $K \geq$ 5 ksi (34.5 MPa) ν = 0.40 for $K <$ 5 ksi (34.5 MPa)
Fine-grained subgrade	300 in. (7,620 mm) minus total pavement thickness	Nonlinear bilinear model	$M_R = f(E_{Ri})$; see Figure 1 E_{Ri} = 1 to 14 ksi (6.9 to 96.5 MPa)	ν = 0.45

the given ranges in Table 1 to generate a knowledge database for ANN trainings and testing. The total analysis depth of the pavement system was taken as 7,620 mm (300 in.). The subgrade thicknesses were calculated by subtracting the thicknesses of the AC and the base from the total analysis depth. The outputs recorded were the pavement surface deflection basin and the critical pavement responses, radial strain at the bottom of the AC layer (ϵ_{AC}), vertical strain on top of the subgrade (ϵ_{SG}), and the deviator stress on top of the subgrade layer (σ_D).

The FWD surface deflections (D_0, D_8, D_{12}, D_{18}, D_{24}, D_{36}, D_{48}, D_{60}, and D_{72}) often are collected at several locations: at the drop location (0) and at radial offsets of 8 in. (203 mm), 12 in. (254 mm), 18 in. (457 mm), 24 in. (610 mm), 36 in. (914 mm), 48 in. (1,219 mm), 60 in. (1,524 mm), and 72 in. (1,829 mm). For the modeling work, surface deflections at these FWD sensor radial offsets were obtained from the Illi-Pave solutions and used as synthetic data to train ANNs.

The first backcalculation model, BCM-1, was designed to predict E_{AC} of the AC layer and the E_{Ri} value of the subgrade by using only four pavement surface deflections—D_0, D_{12}, D_{24}, and D_{36}—and two layer thicknesses—h_{AC}, h_{GB}. The ANN BCM-1 model therefore had six input parameters and two outputs, E_{AC} and E_{Ri}. A neural network architecture with two hidden layers was chosen exclusively in accordance with the satisfactory results obtained previously with such networks, considering their ability to better facilitate nonlinear functional mapping (34).

The 6-60-60-2 architecture was chosen as the best architecture for the ANN BCM-1 model on the basis of its lowest training and testing mean-square errors (MSEs) of the order of 1×10^{-4} (corresponding to a root-mean-squared error of 0.3%) for both output variables, E_{AC} and E_{Ri}. The testing curve is not as smooth as the training curve, because MSEs are based on the averages of only 1,000 data points in the independent testing and 23,094 data points in the training set, but the overlaying of the two curves shows that the network learned the functional mapping rather than memorizing the training set.

The development of a second backcalculation model, ANN BCM-2, was deemed necessary to predict accurately the K-parameter of the K-θ granular base model. The E_{AC} and E_{Ri} already computed from the ANN BCM-1 model were used as additional input variables in the BCM-2 model. The BCM-2 network architecture had 12 input variables (h_{AC}, h_{GB}, D_0, D_8, D_{12}, D_{24}, D_{36}, D_{48}, D_{60}, D_{72}, E_{AC}, and E_{Ri}) and a single output, the K-parameter. The trained ANN BCM-2 also had two hidden layers with 60 hidden nodes in each layer and successfully predicted the K-values with a low average absolute error value of 3.4% after 10,000 learning cycles.

Next, with the Illi-Pave solutions, a third backcalculation model, ANN BCM-3, was developed with the intention of directly predicting the critical pavement responses, ϵ_{AC}, ϵ_{SG}, and σ_D, from deflection basins. Several other backcalculation models also were developed successfully for different combinations of FWD deflection inputs depending on FWD sensor configuration and for different FWD load amplitudes ranging from 9 kips (40 kN) to 21 kips (93 kN), but these models are not described here because of space constraints.

In addition to the training and testing sets prepared for BCM-1, BCM-2, and BCM-3, four more ANN training sets were generated by introducing 10% (± 5%) and 20% (± 10%) noise to the FWD deflection values used in both backcalculation models. The purpose of introducing noise patterns in the training sets was to develop a more robust network that could tolerate the noisy or inaccurate deflection patterns collected from the FWD deflection basins. The details regarding the training and testing of noise-introduced ANN backcalculation models are described elsewhere (33).

EVALUATION OF FIELD DATA WITH ANN-BASED MODELS

The TRB Nonlinear Pavement Analysis Project data sets were evaluated by using the Illi-Pave–based ANN backcalculation models developed at Iowa State University. The goal was to backcalculate the stress-dependent pavement layer moduli by using the ANN-based models and possibly compare the results with those reported by previous studies. Also, the Illi-Pave program was used to model the test pavements and predict the distribution of stresses and strains with depth and compare them against the measured values, wherever applicable. The results for Site 1 (CRREL) and Site 2 (Denmark) are discussed here.

Site 1. CRREL

The Site 1 test pavement has a 3-in. (76-mm) thick AC layer, 9-in. (229-mm) thick unbound granular base layer, and approximately a 10-ft (3-m) deep subgrade constructed in 6-in. (152-mm) lifts. The FERF site, where the test pavement is located, has a 12- to 18-in. (305- to 457-mm) concrete floor beneath the subgrade placed on native silty soil (CL). To use the ANN-based backcalculation models, the concrete floor and the underlying soil layers were combined into one subgrade layer. Two FWD test data files are available: Sep_29_99.fwd has one station (referred to as S1/2 in this paper) and Sep_30_99.fwd has nine stations, from S1 to S9. At each station, FWD test data were recorded for four drop heights with nominal loads of 6, 9, 12, and 16 kips (27, 40, 53, and 71 kN) replicated three times per drop height (12). The FWD sensors were located at 0, 8, 12, 24, 36, 48, and 72 in. (0, 203, 305, 610, 914, 1,220, and 1,830 mm) from the center of the loading plate.

Table 2 shows the results of ANN-based backcalculation analysis for 9-kip (40-kN) normalized FWD test data for specific Site 1 locations. Results for the unbound granular base and subgrade layers correspond to the magnitudes of nonlinear stress-dependent moduli parameters K and E_{Ri}, respectively. The backcalculation results were obtained with ANN models both with noise introduced and those trained without introducing noise. For Site 1, the AC modulus values predicted with the noise-introduced ANN models (even with 2% to 3% noise) were significantly lower compared with the zero-noise ANN predictions.

On the basis of the FWD test data for the first drop of a 9-kip (40-kN) nominal peak load, Uddin et al. (14) obtained a mean AC modulus (E_{AC}) of 143,000 psi (986 MPa) and, with the backcalculation methodology of UMPED and of Pavement Evaluation Based on Dynamic Deflections (PEDD), 8,200 psi (57 MPa) and 9,600 psi (66 MPa), respectively, for the unbound granular base and subgrade layer nonlinear moduli. The ANN-based layer modulus predictions are considerably higher compared with the values reported by Uddin et al. (14). It is worth noting that the ANN backcalculation methodology incorporates nonlinear characterization of unbound pavement materials by using FE modeling, and both the Illi-Pave FE program (which was used in generating the solutions database for ANN training), and the ANN backcalculation models have been validated over a wide range of pavement structures encountered in the field. Therefore, the authors believe that more reliable results could be obtained with the ANN-based backcalculation methodology. It is acknowledged that the ANN-predicted K-values for Site 1, which had a relatively thin AC surface, are rather low considering the input range of K used in training the ANN.

In Site 1, response data were measured in the X-, Y-, and Z- (indicating the vertical direction) directions from four subsurface (Dynatest)

TABLE 2   Summary of ANN-Based Backcalculation Results for Site 1

FWD Data File	Location	AC Modulus (psi)	Granular Base Modulus Parameter, K (psi)	Subgrade Modulus Parameter, E_{Ri} (psi)
Sep_29_99.FWD	S½	323,552	6,245	14,630
Sep_30_99.FWD	S1	370,580	2,600	16,469
	S2	406,019	2,560	16,560
	S3	431,151	2,568	16,597
	S4	435,153	2,588	16,606
	S5	428,226	2,616	16,607
	S6	440,822	2,637	16,613
	S7	436,698	2,653	16,619
	S8	440,608	2,668	16,632
	Mean	412,535	3,015	16,370
	Std. dev.	40,307	1,212	654
	%COV	10	40	4

stress cells at two depths and from nine arrays of (εμ) strain coils at eight depths. The FWD test sequence was repeated nine times at the same point to get the following pavement response data:

• Peak stress in *X*-, *Y*-, and *Z*-directions in the subgrade at a depth of 15 in. (381 mm),
• Peak stress in the vertical direction in the subgrade at a depth of 25.75 in. (654.1 mm),
• Peak strain in the vertical direction in the base course at a depth of 8 in. (203.2 mm), and
• Peak strain in *X*-, *Y*-, and *Z*-directions in the subgrade at depths of seven levels from 12 to 48 in. (305 to 1,219 mm).

The Illi-Pave axisymmetric FE program was used to compute the pavement responses under the 9-kip (40-kN) FWD load for Site 1 pavement. Uzan (*16*) indicated that, in the case of an FWD with a circular loading plate, FE programs with axisymmetric conditions are adequate. The Illi-Pave response analysis was conducted with the average ANN-based backcalculated modulus values. In Table 3, the measured and computed pavement responses are compared for the 9-kip (40-kN) FWD load in each section. The 2% to 3% noise-introduced ANN modulus predictions were 175,000 psi, 2,200 psi, and 12,000 psi, respectively, for E_{AC}, K, and E_{Ri}.

For Station S1/2, the Illi-Pave computed vertical stresses were compared with the in situ measured values. Poor agreement was observed for stresses at 25.75 in. and strains at 8, 12, and 18 in. The zero-noise ANN-predicted strains did not compare well with the measured strains. The ANN with 2% to 5% noise provided a very good match between the measured and computed strains at depths of 24 in. and more but yielded a very poor match between predicted and measured stresses.

Several studies have indicated that the agreement between the measured and predicted responses is far from satisfactory for several reasons, including inaccurate characterization of in situ material properties and soil–instrument interaction interfering with the measurement of pavement response. The primary objective of this study was to demonstrate the use of ANN-based backcalculation methodology in nonlinear pavement analysis. Generic flexible pavement structures were used in Illi-Pave to generate the solutions database for training the ANN. These structural models also were used directly in computing the critical responses for Site 1. It is believed that better response predictions would result for Site 1 by considering site-specific information and appropriate mesh discretization during Illi-Pave modeling.

Site 2. Denmark

Site 2 is located near the Danish Road Institute in Roskilde, Denmark. The subgrade soil is a fine sand that appears to be moderately stress-

TABLE 3   Comparison of Computed and Measured Responses for Site 1

FWD Data File	Location	Load (lb)	Depth (in.)	Response Parameter	Measured Response	Illi-Pave Response (zero-noise ANN modulus)	Illi-Pave Response (2%–3% noise ANN modulus)
Sep_29_99.FWD	S½	9102	15	Comp. stress	11.28	12.9	15.7
	S½	9102	25.75	Comp. stress	2.93	7.47	8.33
Sep_30_99.FWD	S2	9014	8	Comp. strain	0.0005	0.0016	0.0027
	S3	8954	12.13	Comp. strain	0.0014	0.0006	0.0010
	S4	8898	18	Comp. strain	0.0012	0.0005	0.0007
	S5	8891	24.25	Comp. strain	0.0005	0.0003	0.0005
	S6	8887	30	Comp. strain	0.0003	0.0002	0.0003
	S7	8851	36	Comp. strain	0.0002	0.00015	0.0002
	S8	8848	42	Comp. strain	0.0001	0.0001	0.0001

dependent. The FWD test data consisted of four drop test points. Nineteen FWD drops were performed in sequence with three unrecorded seating drops followed by four drops at each of the four drop heights (*12*). The test pavement has a 2.32-in. (59-mm) thick AC layer, 5-in. (128-mm) granular base layer, and three sandy subbase layers approximately 5 in. (128 mm) each resting over the subgrade soil. To use the ANN backcalculation models, the granular base layer and the sandy subbase layers were combined into one layer of 20-in. (510-mm) thickness. However, the minimum AC thickness considered in the development of the ANN backcalculation models is 3 in. (76 mm), and therefore the ANN-based backcalculation results for this site may not be accurate.

In Figure 1, the results for E_{AC} and E_{Ri} are displayed for all FWD test data points in Site 2. An interesting pattern is observed in these plots. Sixteen recorded FWD drops were performed in sequence at each test point (see Figure 2*a*), with four drops at each of the four FWD load levels (4 × 4): 7,350 lb, 9,000 lb, 13,000 lb, and 18,000 lb. From Figures 1*a* and *b*, it is clearly observed that nearly a single AC modulus value is obtained for all four FWD test drops at a given FWD load level. This finding demonstrates the robustness of ANN-based modulus prediction models as well as the repeatability of

FWD testing. Figure 1*b* shows highly consistent E_{Ri}-values for the different FWD test points.

In the Site 2 pavement, vertical stresses and strains were measured in two positions. Peak responses were registered at four locations in Sand Layer 1 with an impact FWD load on top of the AC layer. The FWD tests were carried out immediately on top of the subsurface instrument for the two strain registrations; that is, the *X*- and *Y*-coordinates of instruments and FWD load plate were identical. The FWD test equipment was slightly offset compared with the instrument while the vertical stresses were measured. The test area layout for Site 2 is shown in Figure 2*a*.

Temperature measurements were carried out in a small borehole in the AC surface layer at a depth of 1.1 in. (30 mm). The same hole was used for temperature measurements for the FWD tests. The AC temperature during the entire time of FWD testing and response measurements ranged between 39.7°F (4.3°C) and 43.5°F (6.4°C). None of the FWD tests carried out as part of the pavement response testing could be used for backcalculation because a hydraulic pad was placed under the FWD footplate to ensure a uniform distribution of the FWD load on the pavement. The hydraulic plate necessitated movement of the second geophone (*12*).
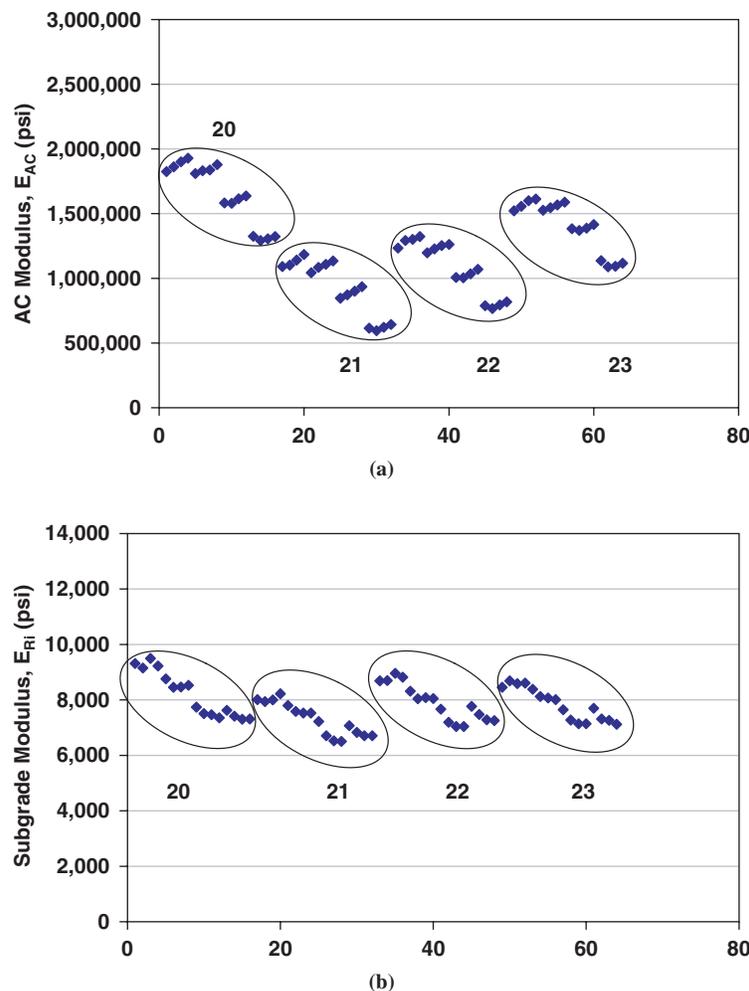

FIGURE 1   ANN-based modulus predictions for Site 2 at four FWD test points (*X*-axis represents number of FWD drops): (*a*) AC moduli and (*b*) subgrade moduli.
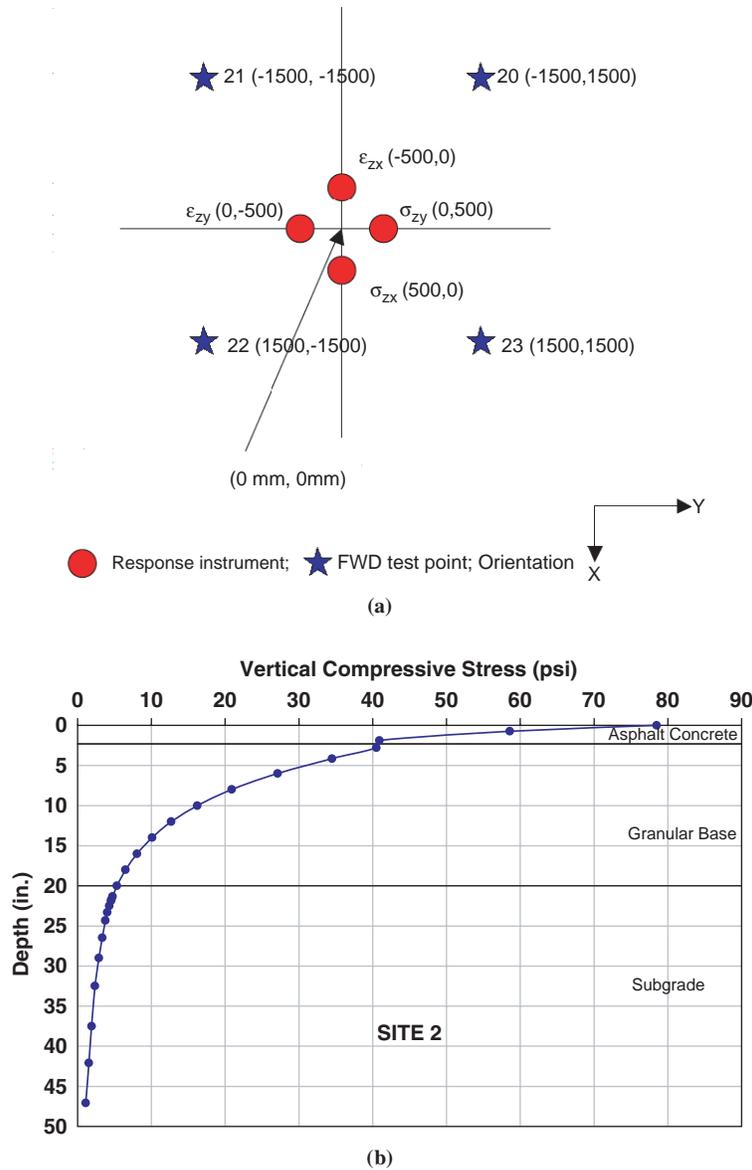
FIGURE 2   (a) Site 2 test area layout (12) and (b) Illi-Pave computed vertical compressive stress distribution for Site 2.

The following pavement responses were computed by using the Illi-Pave software and compared with the measured results:

• Peak vertical subgrade stresses, σ_{zy} and σ_{zx} (see Figure 2a), at a depth of 22 in. (559 mm), and
• Peak vertical subgrade strains, ϵ_{zy} and ϵ_{zx} (see Figure 2a), at depths of 21.65 and 21.73 in. (550 and 552 mm).

The averages of the ANN-based backcalculated layer modulus values were used as inputs for the Illi-Pave program to compute the pavement responses. Interestingly, for Site 2 the modulus predictions based on noise-introduced ANN models were very similar to those obtained by using the zero-noise ANN models. Since the Illi-Pave FE program models the pavement as a two-dimensional axisymmetric solid of revolution, the stresses and strains in the X-Y-plane are symmetrical with respect to the central Z-axis. The

predicted vertical subgrade stress at a depth of 22 in. (559 mm) was 3.6 psi (24.8 kPa), and the corresponding measured value was 7.5 psi (51.7 kPa). The measured vertical subgrade strain at 21.7-in. (550-mm) depth was 450 µε, whereas the predicted strain was 90 µε. The vertical compressive stress distribution in pavement layers (with depth) under the center of the loading computed with Illi-Pave is shown in Figure 2b.

CONCLUSION

The results of ANN-based nonlinear backcalculation and response analysis are presented for two sites of the TRB Nonlinear Pavement Analysis Project. The Illi-Pave FE program, considering the nonlinear stress-dependent geomaterials characterization, was utilized to generate a solution database for developing ANN-based

structural models to accurately predict pavement layer moduli from realistic FWD deflection profiles. Such use of ANN models enables the incorporation of needed sophistication in structural analysis, such as FE modeling with proper materials characterization into routine practical design. The ANN-based backcalculation results were consistent, and considering the complex pavement structural systems analyzed in this study, the ANN models performed satisfactorily.

ANN-based backcalculation models can output rapidly the required solutions in analyzing the large number of pavement deflection basins needed for routine pavement evaluation, thus making them perfect tools for analyzing FWD deflection data in real time for both project-specific and network-level FWD testing.

The Illi-Pave flexible pavement FE model was used to compute the structural responses in the test pavements, and the results were compared with the in situ measurements. In general, the computed strains agreed well with the measured strain results, whereas the stresses did not. Two basic sources of error for the observed lack of agreement may be in the computation (error in materials characterization is included) and in the measurement of the pavement response (soil–instrument interaction problem) itself. All of these concerns need to be addressed in the development of the next generation of mechanistic-based pavement analysis and design tools.

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