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Abstract

The Iowa Department of Transportation (DOT) has been collecting falling weight deflectometer (FWD) data on a regular basis. However, the pavement layer moduli backcalculation techniques used so far have been cumbersome and time consuming. More efficient and faster methods in FWD test data analysis were demanded and deemed necessary for routine analysis. Researchers at Iowa State University (ISU) have developed a suite of advanced pavement layer moduli backcalculation models using the artificial neural networks (ANN) methodology for flexible, rigid, and composite pavements. The current study aims to develop a fully automated backcalculation software system, referred to as I-BACK, with improved accuracy and usability of Iowa FWD data. Evolutionary optimization/nonlinear optimization algorithms were implemented with the developed ANN models to improve the accuracy of predictions.

Keywords

algorithms, neural networks, optimization, composite pavements, department of transportation, evolutionary optimizations, falling weight deflectometer, optimization algorithms, pavement layer moduli backcalculation

Disciplines

Civil Engineering | Construction Engineering and Management

Comments

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I-BACK: Iowa's Intelligent Pavement Backcalculation Software

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Abstract

The Iowa Department of Transportation (DOT) has been collecting the Falling Weight Deflectometer (FWD) data on regular basis. However, the pavement layer moduli backcalculation techniques used so far have been cumbersome and time consuming. More efficient and faster methods in FWD test data analysis were demanded and deemed necessary for routine analysis. Researchers at Iowa State University (ISU) have developed a suite of advanced pavement layer moduli backcalculation models using the Artificial Neural Networks (ANN) methodology for flexible, rigid, and composite pavements. The current study aims to develop a fully-automated backcalculation software system, referred to as I-BACK, with improved accuracy and usability of Iowa FWD data. Evolutionary optimization/nonlinear optimization algorithms were implemented with the developed ANN models to improve the accuracy of predictions.

Introduction

Highway agencies periodically evaluate the structural condition of roads as part of their routine maintenance and rehabilitation activities. The falling-weight deflectometer (FWD) test measures road surface deflections resulting from an applied impulse loading, simulative of a truck passing on the highway. The measured surface deflections are utilized to determine pavement layer stiffnesses through a backcalculation type structural analysis.

Although the Iowa Department of Transportation (DOT) has been collecting the FWD data on a regular basis, the pavement layer moduli backcalculation techniques used so far have been cumbersome and time consuming. More efficient and faster methods in FWD test data analysis were deemed necessary for routine analysis.

Previous Iowa DOT research projects focused on developing advanced pavement layer moduli backcalculation models using the artificial neural networks (ANN) methodology (Ceylan et al. 2007; Ceylan et al. 2009). The developed models were successfully validated using field data and incorporated into a Microsoft Excel spreadsheet-based backcalculation software toolbox with a user-friendly interface.

A recently completed study at ISU focused on improving the accuracy and usability of Iowa FWD data and the pavement inverse analysis tools by incorporating the following significant enhancements into the fully-automated software system for rapid processing of the FWD data:

- Refined prediction of pavement layer modulus through deflection basin matching/optimization
- Temperature correction of HMA layer modulus
- Computation of 1993 AASHTO design guide-based effective structural number (SN_{eff}) and effective k-value (k_{eff})
- Enhancement of user-friendliness of input and output from the software tool

Overview of I-BACK Enhancement Features and Modules

A screenshot of the I-BACK program main menu is captured in FIG. 1. A flowchart depicting the various processing/analysis steps including the enhancements incorporated as part of this study is shown in FIG. 2 for flexible pavements (conventional HMA and full depth HMA pavements). Similar charts were prepared for rigid (PCC surfaced pavements) and composite pavements (HMA overlaid PCC pavements), but are not included here due to space limitations. As a first step in the I-BACK analysis, the pre-final pavement layer moduli are calculated from the ANN backcalculation models (Ceylan et al. 2007, Ceylan et al. 2009). Then, the pre-final pavement layer moduli are adjusted through a deflection basin optimizer in I-BACK to match the actual measured FWD deflection basin. Note that the backcalculated moduli resulting from deflection basin optimization in I-BACK are moduli at pavement temperature at the time of FWD testing.

In the case of flexible pavement analysis, the temperature normalization routine is then invoked to correct the adjusted HMA moduli from optimizer to a standard reference temperature. The Effective Structural Number (SN_{eff}) values are computed for conventional flexible and full-depth pavements in accordance with the AASHTO design procedure as follows. The temperature normalized HMA moduli are inputted into ANN forward models to produce FWD deflection basin at a standard reference temperature. The predicted FWD deflection basin at the standard reference temperature is then utilized to compute the overall section SN_{eff} for flexible pavements in accordance with the 1993 AASHTO pavement design procedure (AASHTO 1993).

For rigid pavement analysis, the adjusted subgrade stiffness values from the deflection basin optimizer are utilized to compute effective subgrade support (k_{eff}) in accordance with the 1993 AASHTO design procedure (AASHTO 1993).

In the case of composite pavement (HMA overlaid PCC pavements) analysis, the adjusted HMA moduli from the deflection basin optimizer are corrected to a standard reference temperature through temperature normalization routine similar to flexible pavement analysis. Similar to rigid pavement analysis, the adjusted subgrade stiffness values from the deflection basin optimizer are utilized to compute k_{eff} values in accordance with the 1993 AASHTO design procedure (AASHTO 1993).

The Structural Rating (SR) and k values are also computed for all three types of pavement in accordance with Iowa DOT Road Rater based AC overlay design procedure.

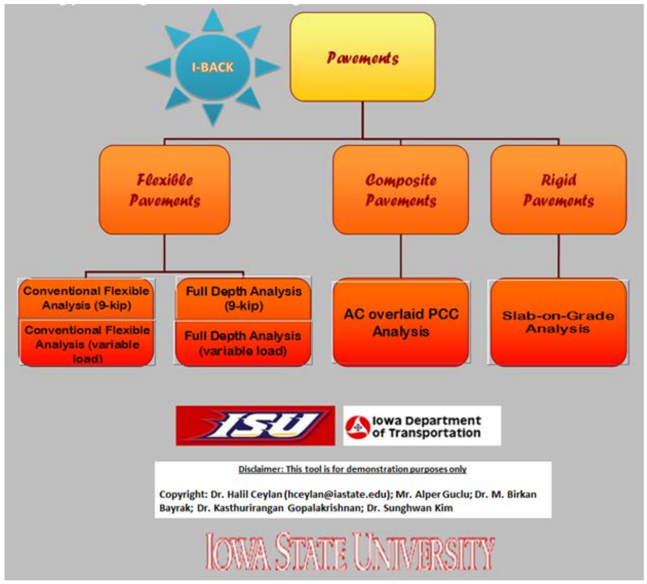

FIG. 1. Screenshot of I-BACK program main menu

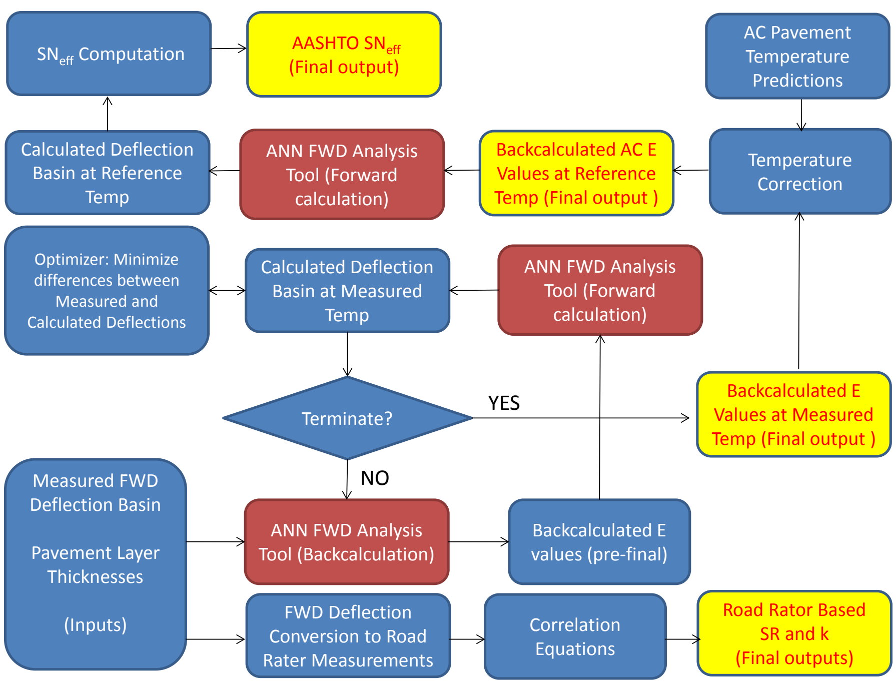

FIG. 2. I-BACK analysis flow chart: flexible pavement module

Deflection Basin Matching

Deflection basin matching provides a fool-proof method to validate the ANN-based backcalculation results since the predicted pavement layer moduli are optimized or fine-tuned to obtain a very close match between the actual FWD and predicted deflections. The pre final-pavement layer moduli from ANN backcalculation models are inputted into the ANN forward models to predict the deflection basin and compare how closely the predicted deflection basin matches the measured deflection basin. The differences between the field measured and predicted deflection basins are minimized by adapting the in-built Excel Solver tool (employing evolutionary optimization or GRG Nonlinear optimization) in I-BACK. Thus, the robustness of I-BACK predictions has been greatly improved by incorporating the deflection basin matching/optimization routine. Also, the deflection basin matching step ensures that the final backcalculation moduli are global or near-global solutions, in case the ANN-based backcalculation step provides only locally optimized solutions. A snapshot of the deflection basin matching analysis results is displayed in FIG. 3.

The deflection basin matching/optimization based backcalculation analysis refines ANN-based backcalculation results for each pavement type to obtain a very close match between the actual FWD and predicted deflections. Reported results are refined/optimized modulus for each pavement type, FWD deflection predictions, and Mean Absolute Error (MAE) between measured and predicted FWD deflections for assessment of the accuracy of refined/optimized modulus.

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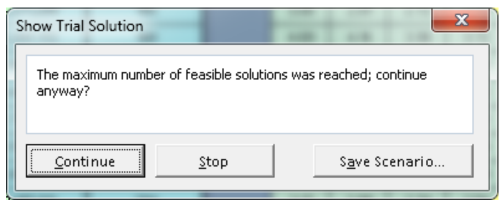
AC Modulus, Eac (psi) - Actual Temp	Subgrade Modulus, Eri (psi) - Actual Temp	Granular Base Modulus Param., K (psi) - Actual Temp	Computed FWD Deflections after Deflection Basin Matching (mils)								Mean Abs. Error bet. Meas and Comp. FWD Deflections
After Deflection Basin Matching			D-0	D-8	D-12	D-18	D-24	D-36	D-48	D-60	MAE
4,488,319	1,040	3,000	5.01	4.83	4.68	4.43	4.15	3.57	3.03	2.53	0.0477
5,757,290	1,000	11,260	4.14	3.99	3.87	3.68	3.47	3.03	2.61	2.21	0.1104
6,000,000	1,364	12,000	3.95	3.80	3.68	3.50	3.30	2.88	2.47	2.09	0.0989
6,000,000	1,716	4,596	4.00	3.85	3.73	3.54	3.33	2.90	2.49	2.10	0.0343
6,000,000	2,125	9,167	3.81	3.66	3.55	3.35	3.15	2.74	2.34	1.96	0.0458
6,000,000	2,808	11,999	3.63	3.48	3.36	3.18	2.98	2.58	2.18	1.82	0.0579
4,843,995	3,074	3,000	4.30	4.12	3.99	3.75	3.50	2.99	2.50	2.06	0.0254
4,988,833	3,342	3,000	4.18	4.00	3.87	3.64	3.40	2.90	2.43	2.00	0.0276
5,090,039	4,089	3,000	4.01	3.83	3.70	3.48	3.24	2.76	2.30	1.89	0.0232
5,999,994	2,504	12,000	3.69	3.54	3.42	3.24	3.04	2.63	2.24	1.87	0.0512
5,995,312	2,786	11,998	3.63	3.48	3.37	3.18	2.99	2.58	2.19	1.82	0.0538
5,999,994	5,256	12,000	3.25	3.10	2.99	2.81	2.62	2.23	1.86	1.52	0.0567
4,993,991	2,876	3,000	4.27	4.09	3.96	3.73	3.48	2.98	2.50	2.07	0.0372
5,482,614	3,025	3,000	4.02	3.85	3.73	3.52	3.29	2.83	2.39	1.98	0.0343
5,738,201	3,716	3,000	3.80	3.64	3.52	3.31	3.10	2.66	2.24	1.86	0.0303
6,000,000	3,431	11,999	3.51	3.36	3.25	3.07	2.87	2.47	2.08	1.73	0.1635
6,000,000	4,374	12,000	3.36	3.22	3.11	2.92	2.73	2.34	1.96	1.61	0.1682

(a)



(b)

FIG. 3. Deflection basin matching/optimization backcalculation analysis: (a) Optimized backcalculation analysis result outputs, (b) Trial solution check message box

Temperature Normalization for HMA Modulus

The stiffness, or modulus, of HMA is very temperature-sensitive. The temperature normalization routine was incorporated into I-BACK in close consultation with the TAC in order to correct the backcalculated HMA moduli to a standard reference temperature for the section being analyzed. The incorporated temperature normalization routine consists of: (1) HMA (mid-depth) pavement temperature estimation and (2) temperature correction algorithm for HMA modulus.

Before correction of the backcalculated HMA moduli to a standard reference temperature, the mid-depth pavement temperature at which FWD deflections were taken should be identified. The direct measurement of this temperature requires the time-consuming process of installation of temperature probe in depth of pavement. Alternatively, this temperature may be estimated from approximate methods based on air and surface temperatures measured at the time of FWD testing. Lukanen et al. (2000) developed a set of equations called as BELLS models for predicting in-depth pavement temperatures in LTPP testing based on empirical data. Among these equations, the BELLS3 model accounts for shaded condition of pavement surface under routine testing conducted by most highway agencies. Consequently, the

BELLS3 model was incorporated into I-BACK to determine pavement temperature at mid-depth and subsequent HMA modulus temperature correction equations.

Several equations and approaches (Ullidtz 1987, Baltzer and Jansen 1994, Deacon et al. 1994, Noureldin 1994, Kim et al. 1995, Ali and Lopez 1996, Lukanen et al. 2000, Chen et al., 2000, Crovetti et al., 2005) have been proposed relating the HMA modulus to a standard reference temperature. However, different values of standard reference temperature are found in literature for HMA modulus characterization. The commonly used standard reference temperatures are 68ºF in AASHTO 1993 design procedure (AASHTO 1993), 70 ºF in AASHTO Mechanistic-Empirical Pavement Design Guide (MEPDG) (AASHTO 2008) and Pavement ME (formerly, DARWin-ME) (AASHTO 2012), 77 ºF in some previous studies (Noureldin 1994). Among them, the temperature correction equation developed by Chen et al. (2000) using Texas Mobile Load Simulator (MLS) data (see Eq. 1) has the advantage of the flexibility to normalize to any reference temperature with good accuracy and was therefore adopted in this study.

$$E_{Tw} = E_{Tc}/[(1.8T_W + 32)^{2.4462} * (1.8T_C + 32)^{-2.4462}] \quad (1)$$

Where:

E_{Tw}= the adjusted modulus of elasticity at T_w, MPa

E_{Tc} = the adjusted modulus of elasticity at T_c, MPa

T_w = the temperature to which the modulus of elasticity is adjusted, ℃

T_c = the mid-depth temperature at the time of FWD data collection, ℃

Computation of Effective Structural Number (SN) and Subgrade Support (k-value): AASHTO Pre ME-Design Approach

The concept of SN_{eff} is typically used for evaluating the overall structural condition of flexible pavements. Similarly, the k_{eff} is used for determining the subgrade support for PCC rigid pavement and composite pavement analysis. Typically, when the ratio of SN_{eff} to as-built SN based on in-place pavement structure falls below 90%, the evaluated section is recommended for structural improvement. The AASHTO 1993 design procedure (AASHTO 1993) outlines a method for calculation of SN_{eff} and the k_{eff} using the measured deflection data. The SN_{eff} and the k_{eff} equations in the AASHTO 1993 design procedure (AASHTO 1993) are expressed as follows:

$$SN_{eff} = 0.0045D\sqrt[3]{E_p} \quad (2)$$

$$k_{eff} = k_{dynamic} /2 \quad (3)$$

Where:

D = total pavement thickness, inch

E_P = effective modulus of pavement layers, psi

$k_{dynamic}$ = effective dynamic modulus of pavement layers calculated from deflection basin, psi

Following the AASHTO 1993 design procedure, the pseudo-codes and algorithms for implementing the computation of these two parameters (SN_{eff} and k_{eff})

in I-BACK were developed . First, the deflection basin at the reference temperature is computed using the temperature normalized AC modulus and the ANN forward models. Next, the computed deflection at the center of the load plate (d_0) is related to the effective modulus of pavement layers (E_P), subgrade resilient modulus (M_R) and other parameters as shown in the following equation:

$$d_0 = 1.5pa\left\{\frac{1}{M_R\sqrt{1+\left(\frac{D}{a}\sqrt[3]{\frac{E_p}{M_R}}\right)^2}} + \frac{\left[1-\frac{1}{\sqrt{1+\left(\frac{D}{a}\right)^2}}\right]}{E_P}\right\} \quad (4)$$

Where:

d_0 = deflection measured at the center of the load plate (inch) at the reference temperature (68°F)
p = load pressure, psi
a = load plate radius, inch

Summary

The objective of this study was to incorporate significant enhancements into the fully-automated software system for rapid processing of the FWD data with the goal of improving the accuracy and usability of collected Iowa FWD data. These enhancements included: (1) deflection basin matching/optimization, (2) temperature normalization of HMA layer modulus, (3) computation of 1993 AASHTO design guide based effective SN (SN_{eff}) and effective k-value (k_{eff}), and (4) enhancement of user-friendliness of input and output from the software.

A high-quality, easy-to-use backcalculation software package referred to as, I-BACK: the Iowa Pavement Backcalculation Software, was developed to achieve goals with the following highlighted benefits:

- Provide more fine-tuned ANN pavement backcalculation results by implementation of deflection matching optimizer for conventional flexible, full-depth, rigid, and composite pavements
- Provide temperature normalized/corrected HMA layer modulus at a standard reference temperature for conventional flexible, full-depth and composite pavements
- Provide effective Structural Number (SN_{eff}) and the effective k-value (k_{eff}) as final outputs for pavement/asset management purposes
- Produce separate smaller sized output files from high-quality, real-time backcalculation analysis

Implementation of this tool within Iowa DOT is expected to facilitate accurate pavement structural evaluation and rehabilitation designs for pavement/asset management purposes.

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