Determination of In-Place Elastic Layer Modulus: Backcalculation Methodology and Procedures

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**Organizing Committee**
TRB Committee on Pavement Structural Modeling and Evaluation
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Outline

• Introduction to backcalculation
  • Tools/programs available
• Guidelines for backcalculation
  • Dealing with anomalies and unreasonable values
• Procedures adopted in the LTPP project
  • Results and lessons learned
• Backcalculated modulus in mechanistic-empirical (M-E) design
  • Use of backcalculation results in M-E rehabilitation design
• Questions and answers
Acknowledgements

Determination of In Place Elastic Layer Modulus: Backcalculation Methodology and Procedures

- Long-Term Pavement Performance Data Analysis Project DTFH61-11-C-00051
- Publication Number: FHWA-HRT-15-036
Learning Objectives

• Understand the process and the tools available to backcalculate elastic layer moduli from deflection basin data
• Describe the backcalculated layer modulus values integrated into the computed parameter tables in LTPP
• Use of backcalculated modulus in M-E design
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  • Application and use of backcalculation results

• Questions and answers
Falling Weight Deflectometer (FWD) Testing

- NDT procedure
- Impact load device
  - Simulate a moving wheel load
  - Measure pavement response-deflection basin
  - Require no fixed reference
  - Relatively fast
- Several applications
  - Backcalculation of layer properties – most common
Typical Sensor Configuration & Deflection Basin

Loading Wheel Contact Area

Sensor

Deflection Basin
Typical Normalized Deflection Basin
Typical Normalized Deflection Basin—Type I
Typical Normalized Deflection Basin—Type II
Typical Normalized Deflection Basin—Type III
Deflection Testing at Different Load Levels

**Linear Response**

- Four drop heights
  - 6,000 lb. (378 kPa)
  - 9,000 lb. (566 kPa)
  - 12,000 lb. (755 kPa)
  - 16,000 lb. (1007 kPa)
Deflection Response
An Indicator of Material Behavior
Backcalculation Methods and Software

<table>
<thead>
<tr>
<th>Methods</th>
<th>By Pavement Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Iterative Search Methods</td>
<td>• Flexible pavements</td>
</tr>
<tr>
<td>• Database Search Methods</td>
<td>• EVERCALC, MODCOMP/MODTAG, MODULUS, ELMOD, and others</td>
</tr>
<tr>
<td>• Equivalent Thickness Methods</td>
<td>• Rigid pavements</td>
</tr>
<tr>
<td>• Forward Calculation Methods/Closed form solutions</td>
<td>• Best-fit method, Area Method, EVERCALC, etc</td>
</tr>
<tr>
<td>• Other/Evolving</td>
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</tbody>
</table>
Simulation of Structure for Backcalculation

**Mapping Layers**

- **EVERCALC** – 5 layers
- **MODTAG** – 7 layers
- **MODULUS** – 4 layers
Selection of Backcalculation Program

*Depends on User’s Needs*

- Underlying theory (same as that used in design procedure?)
- Number of layers permitted in the analyses
- Convergence criterion
  - RMSE, absolute error, error term accounting for specific sensors
- Accuracy of the program
- Operational characteristics
- Ease of use of the program
- Stability of the program
LTPP Data Analyses Project
Hypotheses & Findings

• Hypotheses:
  • Backcalculation packages result in the same set of elastic layer modulus values.
  • Backcalculated elastic layer modulus values are correlated to but have a bias related to laboratory measured modulus values.

• Findings:
  • For deflection basins consistent with elastic layer theory:
    • Hypotheses accepted.
  • For deflection basins diverging from elastic layer theory:
    • Hypotheses rejected.
Findings

Programs resulted in similar elastic layer modulus values for many case study sites.
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Backcalculation of E Values

In place elastic layer moduli from deflection basins for forensic investigations or rehabilitation design.

1. **Limited to a specific number of layers:**
   a) Structure simulation is important.
   b) Results are a composite E value for individual layers.

2. **Most procedures, based on elastic layer theory:**
   a) E values do not vary vertically or horizontally for an individual layer.
   b) Layer is intact and continuous in the horizontal plane.

**Reality versus Simulation?**
Backcalculation Challenges

Assessment of Results, Categories:
• Errors between measured & calculated values.
• Compensating adjacent layer E-values.
• Inappropriate E-values.

Overcoming the Issues:
• First – try to identify what is causing the issue.
• Do not make random changes to structure.

How does one know that the results are good/poor?
How does one identify the cause of bad results?
Assessment of Results

**Error Term**

Error between the measured and calculated deflection basins.

1. Absolute error per sensor—MODULUS.
2. Root mean squared error—EVERCALC, MODCOMP

Make error as small as possible. (RMSE<5%)

RMSE = 0.4%

RMSE = 2.1%

RMSE = 7.6%

RMSE = 4.2%
Assessment of Results

*RMSE*

- Error between the measured and calculated deflection basins
- BUT:

  - Low RMSE—does not mean you have accurate values for in place layers.
  - High RMSE—does not mean you have inaccurate values for the in place layers.

RMSE is not an indicator of accuracy in backcalculation!
Assessment of Results

**Compensating Layer**

Compensating adjacent layer E values

1. Layer E is inversely proportional to an adjacent layer E value.

2. The resulting E values for adjacent layer can be:
   a) Independent of one another.
   b) Proportional to one another.

![Graph showing relationship between Layer 4 and Layer 3](image)

Layer 4 is inversely proportional to Layer 3

![Graph showing relationship between Layer 2 and Layer 1](image)

Layer 2 is independent of Layer 1
Assessment of Results

Inappropriate $E$ Values for a Material

- **HMA**
  - Thick. = 6 in.; $E = 878,000$ psi

- **Aggregate Base**
  - Thick. = 12 in.; $E = 215,343$ psi

- **Embankment**
  - Thick. = 24 in.; $E = 48,655$ psi

- **Subgrade**
  - Thick. = Inf.; $E = 33,359$ psi
Assessment of Results

Inappropriate E Values for a Material

- BUT, for unbound layers:
  - E decreases as layer becomes wetter; near saturation E values can be low.
  - E increases as layer becomes drier; for some materials/soils layer can respond as a bound layer.

Try to find out why the E values are inappropriate before not using them.
Overcoming Backcalculation Issues

The more information you have, the fewer backcalculation challenges you have.

In other words:

Bad assumptions in → Invalid values out!

or

Garbage in → Garbage out!
Overcoming Backcalculation Issues

Quantify or understand the issue:

- Scattered across the entire project length?
- Common to a specific site feature?
- Confined to specific areas of the project?
Types of Errors or Issues

• Input Errors
• Measurement Issues
• Simulation Issues
  • No discontinuities
  • Homogeneous layers
  • Uniform contact pressures under the loading plate
Types of Errors or Issues

**Input Errors**

Typos (sometime blunders) in selected inputs

- Layer Thickness
- Sensor spacing
- Plate size
- Units
Types of Errors or Issues

**Measurement Errors**

- Sensor spacing relative to layer structure
- FWD Calibration Issues
- Condition of Surface
  - Loose surface material
  - Cracks, discontinuities
  - Severe distortions
Types of Errors or Issues

Errors in Simulation of Structures

- Combining “like” layers, that may not be “like” layers.
- Number of layers
- Variability of layer thickness

- Thin layers
- Rigid layers
- Stripping
- Voids
- Water table depth
Identify Error or Issue

• When issues are identified, what should be done?
• Do the easier steps first:
• Review and check inputs to make sure they are correct – Check for Blunders.
Identify Error or Issue

**Evaluate Basins**

- Evaluate basins to determine applicability to elastic layered solutions for backcalculation.
Identify Error or Issue

*Check Sensor Spacing*

• Make sure sensor spacing inputs match what was used to collect deflection basin data.
Identify Error or Issue

**Surface Condition**

- Cracks
- Loose material, raveling
- Severe distortions

Notes on surface condition during FWD testing can prove very valuable!
Identify Error or Issue

**Structural Layer Information**

- Good quality pavement structural layer information.
- Ensure sufficient destructive tests to define layer thicknesses and subsurface features.

Drill cores & borings in areas with significantly different basin shapes.
Identify Error or Issue

*Layer Insensitive to Load*

- Thin layers under thicker layers.
- Change in modulus values have little effect on the deflection basin.

Assume a typical $E$ value for the layer or combine with a “like” adjacent layer.

Thin layer?
Identify Error or Issue

Subsurface Features

- Stripping in HMA mixtures between layers.
- “Like” unbound layers with opposite stress sensitivity.
Identify Error or Issue

Subsurface Features

• Loss of bond or horizontal cracks near surface.
• Vertical cracks below surface.
Thickness variations & subsurface features: bedrock, high water table, etc.
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• Questions and answers
LTPP FWD Test Plan for Flexible Pavement

- 4 Drop Heights (6, 9, 12, and 16 kips)
- No. of drops = 4 per drop height
- Total Drops per test point = 16
LTPP FWD Test Plan for Rigid Pavement

- 3 Drop Heights (9, 12, and 16 kips)
- No. of drops = 4 per drop height
- Total Drops per test point = 12
LTPP FWD Deflection Test Data

A Snapshot

- **Number of sections**
  - 1,744 HMA surface + 1,008 PCC surface
  - 381 sections under HMA and PCC
  - 3,133 unique sections in all States

- **Automate** 97 percent deflection basins fell under Type 2/Typical categories

- **Requirements**
  - Automated backcalculation procedure
  - Less dependency on user
  - Recreate the results by others not involved in the development process

- **Backcalculation Procedures**
  - EVERCALC
  - MODTAG (MODCOMP)
  - Best Fit for all RIGID Sections

**5,847,770 deflection basins (typical and type 2)**
Definition of Error Status
*Based on RMSE and Backcalculated E Value*

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Acceptable</th>
<th>Atypical</th>
<th>Error or Unacceptable</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMSE</td>
<td>≤3.0</td>
<td>≤3.0</td>
<td>&gt;3.0</td>
</tr>
<tr>
<td>and</td>
<td>and</td>
<td>and</td>
<td>or</td>
</tr>
<tr>
<td>Modulus value (by material type)</td>
<td>Within Acceptable range limits</td>
<td>Outside acceptable but within atypical limits</td>
<td>Outside Atypical range limits</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Acceptable</th>
<th>Atypical</th>
<th>Error</th>
</tr>
</thead>
</table>

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Automated Backcalculation Process

- Makes process less dependent on the users
- Users can use the tools and procedures to recreate the results.
Preprocess Data

- Issues with sensor or deflection data
- ModTag/Program Slic
- Deflection basin characterization
  - Unacceptable - Type I & Type III
  - Acceptable – Type II or Typical
- Load response characterization – post processing of backcalculation results
  - Deflection hardening
  - Deflection softening
  - Elastic/linear elastic
Decision Tree

1. Extract & assemble data
2. Preprocess data
3. Apply rules of simulation
4. Execute BC – program
5. Apply error evaluation criteria
6. Resolve/flag inappropriate results
7. Enter into CPT

Analyses performed by State to optimize computational needs
# Computed Parameter Tables

**LTPP Database**

## Layer Structure Information

1. Section Information
2. Structures, EVERCALC
3. Structures, BEST FIT

## Backcalculated Modulus Values

<table>
<thead>
<tr>
<th></th>
<th>Individual Basins</th>
<th>Summary for Test Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Elastic layer moduli from EVERCALC/MODCOMP</td>
<td>Elastic layer moduli from EVERCALC/MODCOMP</td>
</tr>
<tr>
<td>2.</td>
<td>Elastic layer moduli from BEST FIT</td>
<td>Elastic layer moduli from BEST FIT</td>
</tr>
<tr>
<td>3.</td>
<td>Load transfer efficiency from BEST FIT</td>
<td>Load transfer efficiency from BEST FIT</td>
</tr>
</tbody>
</table>

All results included in CPTs

Only results defined as acceptable and atypical included in CPTs
Findings

• 97 percent of LTPP deflection data – good to use in backcalculation
• Over 76 percent of deflection basins resulted in elastic layer moduli considered acceptable or atypical
• Deflection testing provides valuable information & data
• Use of 4 drop heights not necessary for rehabilitation designs.

<table>
<thead>
<tr>
<th>Result</th>
<th>Total Number of Drops</th>
<th>Percent of Total Drops</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drops</td>
<td>5,662,494</td>
<td>100</td>
</tr>
<tr>
<td>Unacceptable Results</td>
<td>1,350,680</td>
<td>23.9</td>
</tr>
<tr>
<td>Atypical Results</td>
<td>2,494,628</td>
<td>44.1</td>
</tr>
<tr>
<td>Acceptable Results</td>
<td>1,817,186</td>
<td>32.1</td>
</tr>
<tr>
<td>Total Acceptable &amp; Atypical</td>
<td>4,311,814</td>
<td>76.1</td>
</tr>
</tbody>
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Application and Use

• Use of backcalculated data for rehabilitation design
  • Location for sampling.
  • Layer E values.
  • In place damage.
  • Schedule rehabilitation or preservation.
  • Load transfer efficiency.
Location for Destructive Sampling

- Strategically identify areas with different pavement responses and stiffness.

Allows better assumptions for simulation and identify anomalies.
Layer E Values as Inputs to Design

Stress sensitivity effect is low compared to water content.
Layer E Values as Inputs to Design

Controversy and debate over appropriateness of the c-factor. Depends on calibration of transfer function.
Layer E Values as Inputs to Design

Ratio between lab measured resilient modulus and backcalculated elastic modulus values for subgrade soils.

\[ C = \frac{M_{R-Lab}}{E_{FWD}} \]

<table>
<thead>
<tr>
<th>Backcalculation Program</th>
<th>Average c-Factor</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evercalc</td>
<td>0.35</td>
<td>0.136</td>
</tr>
<tr>
<td>Modcomp</td>
<td>0.36</td>
<td>0.146</td>
</tr>
<tr>
<td>Modulus</td>
<td>0.41</td>
<td>0.266</td>
</tr>
</tbody>
</table>
In Place Damage Assessment

Within and between wheel path test locations can be different, probably related to the in place damage.

**Result:** if combined, it increases variability in modulus.
AC Damage Assessment

None to little damage

Very high damage

Damage present

Damage present
AC Damage Assessment

*In-Place damage for Rehabilitation Design*

Using backcalculated modulus data to estimate in-place damage for rehabilitation design.

![Dynamic modulus input level table](image)

![Modulus of existing AC layer obtained from NDT testing table](image)
AC Damage Assessment

*In-Place damage for rehabilitation design*

\[ \log(d_{AC}) = 0.2 \times \left[ \ln \left( \frac{E_{PRED} - E_{FWD}}{E_{FWD} - 10^\delta} \right) + 0.3 \right] \]

\[ E_{PRED} = \text{Laboratory dynamic modulus} \]

<table>
<thead>
<tr>
<th>NDT Modulus (psi)</th>
<th>Frequency (Hz)</th>
<th>Temperature (deg F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>885000</td>
<td>30</td>
<td>79</td>
</tr>
<tr>
<td>652000</td>
<td>30</td>
<td>86</td>
</tr>
<tr>
<td>459000</td>
<td>30</td>
<td>96</td>
</tr>
</tbody>
</table>
AC Damage Assessment

In place damage related to the amount of fatigue cracking for estimating the coefficients of the fatigue cracking transfer function.

$$DI_{E-ratio} = 1 - \frac{E_{FWD}}{E_{Undamaged}}$$
AC Damage Assessment

*In-Place damage for rehabilitation design*

![Graph showing damage assessment criteria](image)
Load Transfer Efficiency for Rehabilitation Design

- Differential deflections across cracks in flexible and semi-rigid pavements is the more critical mechanism for cracking predictions for HMA overlay design.
Load Transfer Efficiency for Rehabilitation Design

Differential deflections across cracks in flexible and semi-rigid pavements for cracking predictions.

**Result:** allows better assumptions for reflection cracking predictions.
Questions and Answers

Comments & suggestions for future webinars are welcomed.

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