Investigation of Applicability and Use of a Pavement Response Model with High Speed Deflection Devices (HSDDs)

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Raj Siddharthan & Mahdi Nasimifar (UNR)
Gonzalo Rada (AMEC)
Soheil Nazarian (UTEP)
Nadarajah Sivaneswaran & Senthil Thyagarajan (FHWA)
**Outline**

**Introduction: High Speed Deflection Devices (HSDDs)**

- Dynamic Surface Disp. of Response of Layered Systems

**Issues:**
- 3D- Viscoelastic Continuum (Vehicle Velocity?)
- Moving Surface Load (Non-stationary)
- 3D Loading - Normal and Shear (Breaking?)

**Analytical Modeling: 3D-Move**

- Formulation of a Generalized Analytical Model
- Material Characterization
- Calibration of Analytical Model
  - Existing Classical Solutions
  - Model Tests _ Lab Calibration
  - Field Calibration

**Use of 3D-Move** to FHWA Network Level Project DTFH61-12-C-00031
- Calibration with Field Measurement (Surface Disp.)
- Calibration with MnROAD Measurements (Stress & Strains)
- Future Work in Sensitivity Studies
**Existing Methods:** - ELSYM5/WinLEA/JULEA

Static/Stationary/Circular/Uniform, q/ Linear Elastic/Multi-Layer/“Work Horse”; Developed in 1970s;

- Finite Element – (Recent “Large” Studies)
  Wide-Base Tire (Pool-funded study) - 2011
  PANDA Software (Texas A&M) - 2010
  ABAQUS (Version 6.7)
  3D – Brick Elements

**NOTE:** “Problems” – Stationary Load
Loaded area & and layers are of same size

“Computer Intensive”
Solution for Single Harmonic Pressure

It can be shown that $U_{nm}$ is given by: (6th order differential equation)

$$D_1 \frac{d^6 U_{nm}}{dz^6} + D_2 \frac{d^4 U_{nm}}{dz^4} + D_3 \frac{d^2 U_{nm}}{dz^2} + D_4 U_{nm} = 0$$

- $D_1, D_2, D_3, \text{ and } D_4$ = constants that depends on
  - layer material properties,
  - velocity of wave propagation,
  - $\lambda_n$ and $\mu_m$. 
Summary: Elements of 3D-Move

(1) Uses Finite-Layer Continuum Approach – Takes Advantage of Horizontally-Layered Pavement Layers; No Discretization; No Lateral Boundary Effects. – Computer Efficient

(2) Models Moving 3D-Surface Stresses (Dynamic; Normal & Shear Contact Stresses) – Handles Vehicle Speed

(3) Direct Use of Frequency-Sweep Data (Viscoelastic Modeling)

(4) Ideally-Suited when Responses are Needed at a Selected Few Locations - Computer Efficient
Material Characterization: Pavement Layers

Pavement Layer Properties
Horizontally-Layered; HMA can be Viscoelastic

- Unbound Materials (?) - Elastic
Dynamic Modulus, |E*|
Comparison Between 3D-Move and ViscoRoute (2.0)

HMA thickness = 7.9"

Temp. -20°C – 20°C

Transverse strain $\varepsilon_{yy}$, micron

Vehicle speed, mph

Both Models are: Dynamic and Viscoelastic.

Ref. 14
### Important Attributes of Pavement Modeling: Load-Related

<table>
<thead>
<tr>
<th>Factor</th>
<th>Layered Elastic Analysis (LEA) e.g.: ELSYM5, WESLEA, JULEA</th>
<th>Finite Element Method (FEM)</th>
<th>3D-Move Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-Circular Loaded Shape</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Non-Uniform Vertical Contact Stress</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Contact Shear Stresses (Braking &amp; Sloping Pavements)</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Moving Load (Non-Stationary) and Inertia Included (i.e. Dynamic)</td>
<td>NO</td>
<td>NO/YES</td>
<td>YES</td>
</tr>
</tbody>
</table>

### Important Attributes of Pavement Modeling: Material Properties

<table>
<thead>
<tr>
<th>Feature</th>
<th>Layered Elastic Analysis (LEA) e.g.: ELSYM5, WESLEA, JULEA</th>
<th>Finite Element Method (FEM)</th>
<th>3D-Move Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viscoelastic Properties (Modulus and Phase Shift)</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Vehicle Speed</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Direct use of Freq. Sweep Data</td>
<td>NO</td>
<td>NO</td>
<td>YES</td>
</tr>
</tbody>
</table>
Pavement Responses from 3D-Move

Responses: Vertical Disp., HMA strain, Earth Pressure
Use of 3D-Move in FHWA Network Level Project - DTFH61-12-C-00031

Focus: High Speed Deflection Devices (HSDDs)

HSDDs: TSD & RWD

Main Goals:

Phase 1: Calibration of 3D-Move using Surface Disp. (UTEP) and with MnROAD Measurements (Stresses & Strains)
Three HMA Cells (3, 19 & 34)

Phase 2: Sensitivity Studies: Robust Indicators for Pavement Deterioration
## MnROAD Cells under Investigation

<table>
<thead>
<tr>
<th>Cell 3</th>
<th>Cell 19</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HMA</strong></td>
<td><strong>HMA</strong></td>
</tr>
<tr>
<td>FWD Modulus = 554 ksi</td>
<td>FWD Modulus = 301 ksi</td>
</tr>
<tr>
<td>$\sigma = 34$ ksi</td>
<td>$\sigma = 65$ ksi</td>
</tr>
<tr>
<td><strong>Base</strong></td>
<td><strong>Base</strong></td>
</tr>
<tr>
<td>E = 68.8 ksi</td>
<td>E = 32 ksi</td>
</tr>
<tr>
<td>$\sigma = 8.5$ ksi</td>
<td>$\sigma = 5.8$ ksi</td>
</tr>
<tr>
<td><strong>Subgrade</strong></td>
<td><strong>Subgrade</strong></td>
</tr>
<tr>
<td>E = 17.7 ksi</td>
<td>E = 6.1 ksi</td>
</tr>
<tr>
<td>$\sigma = 2.9$ ksi</td>
<td>$\sigma = 0.6$ ksi</td>
</tr>
<tr>
<td>3 in</td>
<td>5 in</td>
</tr>
<tr>
<td>43 in</td>
<td>31 in</td>
</tr>
<tr>
<td>122.4 in</td>
<td>18.1 in</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cell 34</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HMA</strong></td>
</tr>
<tr>
<td>FWD Modulus = 299 ksi</td>
</tr>
<tr>
<td>$\sigma = 67$ ksi</td>
</tr>
<tr>
<td><strong>Base</strong></td>
</tr>
<tr>
<td>E = 15.7 ksi</td>
</tr>
<tr>
<td>$\sigma = 3.1$ ksi</td>
</tr>
<tr>
<td><strong>Subgrade</strong></td>
</tr>
<tr>
<td>E = 8.5 ksi</td>
</tr>
<tr>
<td>$\sigma = 0.9$ ksi</td>
</tr>
<tr>
<td>4 in</td>
</tr>
<tr>
<td>12 in</td>
</tr>
<tr>
<td>46.3 in</td>
</tr>
</tbody>
</table>
Material Characterization: FWD Field Measurements
### Backcalculated Stiffnesses of Pavement Layers for Accuracy Cells

<table>
<thead>
<tr>
<th>Cell</th>
<th>Material</th>
<th>Thickness, in. (cm)</th>
<th>Average Modulus, ksi, (MPa)</th>
<th>Standard Deviation, ksi, (MPa)</th>
<th>Coefficient of Variation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>HMA</td>
<td>3 (7.6)</td>
<td>554 (3820)</td>
<td>34 (234)</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>Base</td>
<td>43 (109.2)</td>
<td>68.8 (474)</td>
<td>13.6 (94)</td>
<td>19.8</td>
</tr>
<tr>
<td></td>
<td>Subgrade</td>
<td>122.4 (310.9)</td>
<td>17.7 (122)</td>
<td>2.2 (15)</td>
<td>12.3</td>
</tr>
<tr>
<td>19</td>
<td>HMA</td>
<td>5 (12.7)</td>
<td>301 (2075)</td>
<td>65 (448)</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>Base</td>
<td>31 (78.7)</td>
<td>32 (221)</td>
<td>5.8 (40)</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>Subgrade</td>
<td>18.1 (46)</td>
<td>6.1 (42)</td>
<td>0.6 (4)</td>
<td>10.2</td>
</tr>
<tr>
<td>34</td>
<td>HMA</td>
<td>4 (10.2)</td>
<td>299 (2062)</td>
<td>67 (462)</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>Base</td>
<td>12 (30.5)</td>
<td>15.7 (108)</td>
<td>3.1 (21)</td>
<td>19.9</td>
</tr>
<tr>
<td></td>
<td>Subgrade</td>
<td>46.3 (117.6)</td>
<td>8.5 (59)</td>
<td>0.9 (6)</td>
<td>10.2</td>
</tr>
</tbody>
</table>
HMA Modulus is sensitive to temp.

- Require Ave. HMA temp. @ time of testing (FWD & HSDDs)
  All FWD and HSDDs Trials “within” 3 Weeks

Use thermocouple measurements made within HMA (Incomplete data for Cells 19 & 34)

Use BELLS equation to find appropriate temperature for missing data
<table>
<thead>
<tr>
<th>CELL</th>
<th>Temperature at time of FWD, °F (°C)</th>
<th>Temperature at time of TSD, °F (°C)</th>
<th>Temperature at time of RWD, °F (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>99 (37)</td>
<td>91 (33)</td>
<td>99 (37)</td>
</tr>
<tr>
<td>19</td>
<td>81 (27)</td>
<td>68 (20)</td>
<td>63 (17)</td>
</tr>
<tr>
<td>34</td>
<td>108 (42)</td>
<td>91 (33)</td>
<td>90 (32)</td>
</tr>
</tbody>
</table>
Procedure:

- Backcalculate “Existing” Layer Moduli
  - Use FWD Data (HMA, Base & Subgrade)
    - All FWD and HSDDs Trials “within” 3 Weeks
- Use Wictzack Equn. to find Master Curve for HMA Modulus (Temp. & Freq.)
  - Note: $f_{FWD} = 30Hz$; Use FWD Test Temp.

Parameters needed for the dynamic modulus predictive equation are:

- Air void content.
- Asphalt content.
- Gradation.
- A & VTS for the recovered binder.
Obtaining Damaged/Existing Modulus: Witczak Equn.

\[
\log E^* = \delta + \frac{\alpha}{1 + e^{\beta + \gamma \log t_r}}
\]

Solve for fatigue damage, \(d_{AC}\)

\[
E^*_{dam} = 10^\delta + \frac{E^* - 10^\delta}{1 + e^{-0.3 + 5 \times \log(d_{AC})}}
\]
HMA Modulus at HSDDs Trial Temps

Master Curve - Cell 34

- Log E*
- Log(f)

TSD-T=91°F
RWD-T=90°F
CRV- T=86°F
## HSDDs Trials at MnROAD

<table>
<thead>
<tr>
<th>Cell</th>
<th>HSDD</th>
<th>Passes</th>
<th>Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell 3</td>
<td>TSD</td>
<td>3 Passes</td>
<td>48, 72 km/h</td>
</tr>
<tr>
<td></td>
<td>RWD</td>
<td>3 Passes</td>
<td>48, 72, &amp; 97 km/h</td>
</tr>
<tr>
<td></td>
<td>CRV</td>
<td>3 Passes</td>
<td>17.6 km/h</td>
</tr>
<tr>
<td>Cell 19</td>
<td>TSD</td>
<td>3 Passes</td>
<td>48, 72, &amp; 97 km/h</td>
</tr>
<tr>
<td></td>
<td>RWD</td>
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<tr>
<td>Cell 34</td>
<td>TSD</td>
<td>3 Passes</td>
<td>48 &amp; 72 km/h</td>
</tr>
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<td></td>
<td>RWD</td>
<td>3 Passes</td>
<td>48 &amp; 72 km/h</td>
</tr>
<tr>
<td></td>
<td>CRV</td>
<td>3 Passes</td>
<td>17.6 km/h</td>
</tr>
</tbody>
</table>

**Total:** 15 Cases (TSD & RWD) + 3 Cases (CRV)
TSD Loading and UTEP Instruments

Lateral Wander
Typical UTEP Measurements

Cell #34 - Pass #1 - V = 48 km/h

**NOTE:** Ideally GEO1 & GEO3 should yield same results (Indication of variability)
For 3D-Move Calibration use Highest UTEP Geophone Disp. Sensor Measurements (i.e., GEO3)
RWD Sensor Locations for Disp. Measurements

Locate sensor behind wheel, when looking for $w_{\text{max}}$
Looking for Maximum Displacement (Transverse Plane)

Vehicle Path

Location of Max Disp

Responses on Transverse Plane

3D-Move Runs
Location of Max. Disp. (3D-Move)

Plane of HSDD Measurements

Role of Transverse Wander

Displacement (mm)

Center of the Wheel

Max Disp

Centerline of the Load Axle

Location of TSD Sensors - HSDD Measurement Plane

Wheel #2

Wheel #1

Transverse Wander (mm)
Role of Variation in Tire Load in TSD

NOTE: Uneven Load Distribution within Axle
3D-Move Case Scenarios

**Case 1:** Three layer pavement structure with same thicknesses as used in the FWD backcalculation and corresponding mean layer moduli derived from the FWD backcalculation results;

**Case X:** Three layer pavement with: (a) thicknesses used in the FWD backcalculation except decreasing the HMA layer thickness by 1 in, (b) (mean – σ) of FWD backcalculated layer moduli for HMA and base layers, (c) (mean + σ) of FWD backcalculated layer moduli for subgrade, and (d) +25% of nominal tire load;

**Case X1:** Same as Case X, but with no reduction in HMA layer thickness.
3D-Move Results in TSD Trials

University of Nevada, Reno
3D-Move Results in RWD Trials
Computed vs Measured Maximum Displacements

Constant = -1.47 mils
Slope = 1.1087
$R^2 = 0.939$
SEE = 2.26 mils

15 Datasets (TSD & RWD)
Computed vs Measured Pulse Width

- Constant = -0.2951 ft
- Slope = 0.9843
- \( R^2 = 0.8734 \)
- SEE = 0.43 ft

45 Datasets (TSD & RWD)
3D-Move Comparisons with MnROAD Measurements

Vertical Earth Pressures and Long. Strains in HMA

**Issues:** Lateral wheel wander
Size of sensors

Size: 9”

Size: 6”
Computed and Measured MnROAD Earth Pressures in TSD Trials

"Wheel Wander"
Computed and Measured Longitudinal Strains in TSD Trials

-200 -100 0 100 200 300 400 500
-10 -8 -6 -4 -2 0 2 4 6 8 10

Longitudinal Strain (µs)

Distance (ft)

-10 -8 -6 -4 -2 0 2 4 6 8 10

MnRoad SG/MAX
3D-Move /Case 1
3D-Move/ Case x1
Computed and Measured Normal Pressure in RWD trial

University of Nevada, Reno

![Graph showing computed and measured normal pressure in RWD trial.](image-url)
Computed and Measured Longitudinal Strain in RWD trial

- Longitudinal Strain ($\mu$s)
- Distance (ft)

Lines:
- Green: MnRoad SG/MAX
- Blue dashed: 3D-Move /Case 1
- Red dashed: 3D-Move/ Case x1
Maximum longitudinal strains from MnROAD sensors and 3D-Move computations

- MNROAD
- 3D-Move/Upper Bound
- 3D-Move/Lower Bound
Phase 2: What are the Robust Indicators that can Capture HMA Deterioration?

Following Issues are to be Investigated by 3D-Move Solutions:

(1) What is the sensitivity of measured deflections in HSDDs with respect to: (a) speed of test vehicle; (b) change in material properties of all pavement layers (i.e., temperature, aging and moisture related stiffness changes); and (c) sloping pavements (require inclusion of interface shear);

(2) Are there any other pavement response parameters that may be sensitive to pavement condition? For example, can the velocities measured in TSD be directly used as indicators, instead of relying on displacement bowl obtained using the slopes at a few locations (potentially introducing errors) recognizing that the focus is on surface bound layer;
Phase 2: 3D-Move Investigations

(3) 3D-Move analyses to understand best way to implement devices
  a) What are the ideal locations for measurements (e.g., between the
tires, in front or back of the tires)
  b) Are there any pavement response parameters other than the
deflection between tires (RWD) and SCI 300 (TSD) that may be sensitive
to pavement condition?
  c) Are there any indices that can be used where the existing
measurements made by HSDDs can be utilized? (e.g., \( w_o \), SCI300,
Thompson: \( \frac{5D_0 - 2D_{12}'' - 2D_{24}'' - D_{36}''}{2} \); BCI = \( D_{24}'' - D_{36}'' \); SD = \( \tan^{-1} \frac{D_0 - D_r}{r} \)
etc.)

(4) What are the “error” margins when periodically measured HSDD
responses obtained at various times of a year during the life of a
pavement are compared?
This is important, when looking for progressive deterioration of pavement.
REFERENCES


REFERENCES


Inexperienced Engineer

Then

Experienced Engineer

Now

Questions???