Stress Rotations Due to Moving Wheel Loads and Their Effects on Pavement Materials Characterization

Erol Tutumluer

June 9, 2005

OMP Brown Bag Seminar Presentation
FAA Center of Excellence for Airport Technology – Advanced Testing & Material Modeling

University of Illinois - ATREL
Outline

- Introduction
- Findings from Full-Scale Field Studies
- Stresses In the Pavement System
- Field and Laboratory Stress States
- Moving Wheel Load Effects on Resilient Modulus
- Moving Wheel Load Effects on Permanent Deformation
  - Development of rutting models
  - Testing for Approaching and Departing Wheel
- Summary / Current & Future Challenges
Introduction

Questions to Ponder!

- How different are pavements loaded under stationary or moving wheel loads?
- What different stress states are generated and felt by pavement layers?
- How close to field loading conditions do we test and characterize pavement materials?
- How critical is materials characterization for better/advanced pavement analysis and design?
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Full-Scale Test Studies

Laboratoire Central des Ponts et Chausées (LCPC)

$$\delta_p^{plate} \approx (3 \sim 4) \cdot \delta_p^{wheel}$$

(Hornych et al., 2000)
Full-Scale Test Studies

University of Nottingham

<table>
<thead>
<tr>
<th>Test Section</th>
<th>Asphalt Thickness (mm)</th>
<th>Granular Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>40</td>
<td>120</td>
</tr>
<tr>
<td>b</td>
<td>50</td>
<td>130</td>
</tr>
<tr>
<td>c</td>
<td>50</td>
<td>160</td>
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</table>

(Brown and Brodrick, 1999)

Repeated Plate Loading

Moving Wheel Loading

Principal Stress Rotations ??
Full-Scale Test Studies

University of Nottingham

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</table>

(Brown and Brodrick, 1999)

Unidirectional Loading

Bidirectional Loading

Shear stress reversals ??
FAA’s National Airport Pavement Facility (NAPTF) Atlantic City, NJ, USA – 2002

**Full-Scale Test Studies**

**Compression**

**Extension**

**LFS Section**
10 in. Asphalt
29.6 in. P209

**DUAL GEAR**
TRANSVERSE OFFSET #2
TRAFFIC PATH SOUTH

[Graph and Chart Details]
Full-Scale Test Studies

FAA – National Airport Pavement Test Facility

**Stress states due to 1 gear pass**

- Dual Gear TO#1--Traffic Path North
- Dual Gear TO#1--Traffic Path South
- Dual Gear TO#2--Traffic Path North
- Dual Gear TO#2--Traffic Path South

**LFS sections**

- Compression
- Extension

\[ p^* = \frac{2 \sigma_h + \sigma_v}{3}, \text{ psi} \]

\[ q^* = (\sigma_v - \sigma_h), \text{ psi} \]
Full-Scale Test Studies

U.S. Army Engineers Waterways Experiment Station

Multiple-Wheel Heavy Gear Load (MWHGL) study in mid 1970s

Negative q stage (extension zone) should be considered and simulated to better predict the permanent deformation!

Richard H. Ledbetter
General Deformation and Stress Distribution Theory in Soils (1977)
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Stresses Beneath Rolling Wheel Load

- Moving wheel load
- Vertical stress
- Horizontal stress
- Shear stress
- Typical pavement element

Stresses

Extension

Time

\( \sigma_v \)

\( \sigma_h \)

\( \tau \)
Rotation of the Principal Stress Axes Beneath A Rolling Wheel Load

$\sigma_{11}$ : geo-elements

$\alpha$ : degree of principal stress axes rotation
Principal Stresses Rotate as the Wheel Passes
Slope of Stress Path, \( m \)

\[
p = \frac{\sigma_1 + 2\sigma_3}{3}; \quad q = \sigma_1 - \sigma_3
\]

- \( \sigma_{1s} \) and \( \sigma_{1d} \) = major/minor principal stresses due to overburden
- \( \sigma_{3s} \) and \( \sigma_{3d} \) = major/minor principal stresses due to wheel load

\[
m = \frac{q_d}{p_d}
\]

K0 - line

\[
\frac{3(1-K_0)}{(1+2K_0)}
\]
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Repeated Load Triaxial Test for Determining Resilient Modulus

\[ M_R = \frac{\sigma_d}{\varepsilon_r} \]

- \( M_R \) = Resilient modulus
- \( \sigma_d \) = Repeated wheel load stress
- \( \varepsilon_r \) = Recoverable strain
- \( \varepsilon_p \) = Permanent strain

Axial Strain vs. No. of Load Cycles

- \( \varepsilon_r \) = Recoverable strain
- \( \varepsilon_p \) = Constant
The Repeated Load Triaxial Test (AASHTO T307-99)

\[ \sigma_{1d} = \sigma_1 - \sigma_3 = \text{Dynamic/Cyclic Deviator Stress} \]

AASHTO T307-99: CCP (\(\sigma_{3d} = 0\))

\[ p_d = (\sigma_{1d} + 2\sigma_{3d})/3 = \sigma_{1d}/3 \]

\[ q_d = \sigma_{1d} - \sigma_{3d} = \sigma_{1d} \]

\[ m = \frac{q_d}{p_d} = 3.0 \]

Static/Constant Confining Pressure (CCP)
Stress Path Testing - Variable Confining Pressure (VCP)

**Applied Dynamic Stresses:**

\[ p_d = \frac{\sigma_{1d} + 2\sigma_{3d}}{3} \]

\[ q_d = \sigma_{1d} - \sigma_{3d} \]

\[ m = \frac{q_d}{p_d} \]

= slope of stress path

**Compression**

VCP: \( \sigma_{3d} \neq 0 \)

CCP: \( \sigma_{3d} = 0 \)
vertical pulsing only

**Extension**

horizontal pulsing only

\( \sigma_{1d} = 0 \)
Stress Path Tests & Permanent Strains

\[ q = (\sigma'_1 - \sigma'_3) \]

\[ p' = \frac{\sigma'_1 + 2\sigma'_3}{3} \text{ kPa} \]

\( m \neq 3 \)

Shaw (1980)

rutting = \( f(\text{shear strain}) \)

(a) Stress paths

(b) Permanent strains recorded relative to the strain state after 10 cycles
Stress Path Tests & Permanent Strains

University of Nottingham

Principal Stress Direction Rotates

Number of Load Applications

Permanent Axial Strain (µε)

- No Rotation
- With Rotation

Graph showing the relationship between permanent axial strain (µε) and number of load applications for cases with and without principal stress direction rotation.
Stress Paths Under Approaching and Departing Wheel

(Ledbetter & NAPTF)
Need for Research

- Current standard laboratory test procedures based on CCP testing, such as the AASHTO T307-99, are not adequate for characterizing modulus and permanent deformation behavior because

  - **Moving wheel load conditions** resulting in the rotation of principal stress directions & variable confining and deviator stresses not accounted for
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FAA NAPTF Permanent Deformation Testing Program – Univ. of Illinois

► Advanced Test Equipment: UI-FastCell

- Compression and **Extension** Stress States
- Constant (CCP) & **Variable (VCP)** Confining Stress Paths
Stress Path Testing Program: Tutumluer and Seyhan (1999)

**Dolomite**

\[ p_0 = \sigma_{\text{hydrostatic}} = \sigma_{1s} = \sigma_{3s} \text{ (kPa)} \]

<table>
<thead>
<tr>
<th>( \sigma_{1d} ) (kPa)</th>
<th>21 (^1)</th>
<th>34 (^4)</th>
<th>69 (^7)</th>
<th>103 (^{10})</th>
<th>138 (^{13})</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma_{3d} ) (kPa)</td>
<td>41 (^2)</td>
<td>69 (^5)</td>
<td>138 (^8)</td>
<td>103 (^{11})</td>
<td>138 (^{14})</td>
</tr>
</tbody>
</table>

\(^1\): testing sequence number, \( \sigma_{1d} \): compression, \( \sigma_{3d} \): extension.

\[ \sigma_{3d} = 0 \]

\[ \sigma_{1d} = \sigma_{3d} / 2 \]

\[ \sigma_{1d} = \sigma_{3d} / 4 \]
Moduli from Compression Tests

- Resilient Modulus, $M_R$ (MPa)
- Bulk Stress, $\theta$ (kPa)

- $m=0.75$
- $m=1.5$
- $m=3.0$

$M_R = 426 \times \theta^{0.7063}$

Uzan et al. Model:

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

- $\theta = I_1/3$
- $\tau_{oct} = [(2/3)J_{2d}]^{0.5}$

$R^2 = 0.95-0.99$
Moduli from Extension Tests

Uzan et al. Model:

\[ M_R = K_1 \left( \frac{\theta}{p_0} \right)^{K_2} \left( \frac{\tau_{oct}}{p_0} \right)^{K_3} \]

\[ \theta = I_1/3 \]

\[ \tau_{oct} = \left[ \frac{2}{3} J_{2d} \right]^{0.5} \]

\[ R^2 = 0.95-0.99 \]
Typical Airport Pavement Analyzed
Under B777 Moving Wheel Load

**B777-200A:**
- Single wheel load = 189 kN
  = 42.5 kips

R = 220 mm = 8.6 in.
 q = 1255 kPa = 182 psi

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness</th>
<th>Material Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>127 mm</td>
<td>(1380 MPa, 200 ksi)</td>
</tr>
<tr>
<td>BTB</td>
<td>203 mm</td>
<td>(1380 MPa, 200 ksi)</td>
</tr>
<tr>
<td>Unbound</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aggregate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subbase</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Subgrade

(CBR = 4%, M_R = 41.4 MPa = 6 ksi)
Subbase Thicknesses from LEDFAA Runs for the B777-200 Departures Only

<table>
<thead>
<tr>
<th>Total Departures (20 years)</th>
<th>$h_{AC}$ (cm)</th>
<th>$h_{BTB}$ (cm)</th>
<th>$h_{SUBBASE}$ (cm)</th>
<th>$\varepsilon_t$ ($\mu$ε)</th>
<th>$\sigma_v$ (kPa)</th>
<th>$\varepsilon_v$ ($\mu$ε)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10000</td>
<td>12.7</td>
<td>20.3</td>
<td>86.6</td>
<td>149</td>
<td>-46.5</td>
<td>-1070</td>
</tr>
<tr>
<td>40000</td>
<td>12.7</td>
<td>20.3</td>
<td>102.4</td>
<td>146</td>
<td>-39.6</td>
<td>-925</td>
</tr>
<tr>
<td>80000</td>
<td>12.7</td>
<td>20.3</td>
<td>111.3</td>
<td>142</td>
<td>-36.7</td>
<td>-863</td>
</tr>
</tbody>
</table>

Notes: 1. $E_{AC} = 1380$ MPa, $E_{BTB} = 1380$ MPa, $E_{SUBGRADE} = 41.4$ MPa
2. “-” indicates compression in pavement responses
GT-PAVE Finite Element Mesh

q = 1255 kPa = 182 psi

Linear Elastic

Granular Subbase 102.4 cm

Nonlinear

Subgrade

12.7 cm AC
20.3 cm BTB

† Not in Scale
Stress Path Testing Program on Crushed Dolomite Aggregate

\[ p_0 = \sigma_{\text{hydrostatic}} = \sigma_{1s} = \sigma_{3s} \text{ (kPa)} \]

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<th>103</th>
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</tr>
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<tr>
<td>( \sigma_{3d} ) (kPa)</td>
<td>21\textsuperscript{1}</td>
<td>34\textsuperscript{4}</td>
<td>69\textsuperscript{7}</td>
<td>103\textsuperscript{10}</td>
<td>138\textsuperscript{13}</td>
</tr>
<tr>
<td></td>
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<td>138\textsuperscript{8}</td>
<td>103\textsuperscript{11}</td>
<td>138\textsuperscript{14}</td>
</tr>
<tr>
<td></td>
<td>62\textsuperscript{3}</td>
<td>103\textsuperscript{6}</td>
<td>207\textsuperscript{9}</td>
<td>207\textsuperscript{12}</td>
<td>276\textsuperscript{15}</td>
</tr>
</tbody>
</table>

\textsuperscript{1}: AASHTO 307-99 testing sequence number, \( \sigma_{1d} \): compression, \( \sigma_{3d} \): extension

\[ \sigma_{1d} = 0 \quad \sigma_{3d} = 0 \]

Compression

Extension

\( p_0 \)

\( q \)

CCP 1

CCP 2

VCP 1

VCP 2

VCP 3

VCP 4

3=m

1.5

0.75

-0.6

-1

-1.5

11

103

138

276

207

103

69

34

21

1867
**Uzan et al. (1992) Model:**

\[ M_R = K_1 \left( \frac{\theta}{p_0} \right)^{K_2} \left( \frac{\tau_{oct}}{p_0} \right)^{K_3} \]

\[ \theta = \sigma_1 + \sigma_2 + \sigma_3 = \sigma_1 + 2\sigma_3 \]

\[ \tau_{oct} = \frac{\sqrt{2}}{3} q = \frac{\sqrt{2}}{3} \sigma_d \]

(when \( \sigma_2 = \sigma_3 \), triaxial conditions)

<table>
<thead>
<tr>
<th>Stress Path Loading</th>
<th>Uzan Model Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>m = 3.0 (MPa)</td>
<td>K_1</td>
</tr>
<tr>
<td>2.371</td>
<td>1.145</td>
</tr>
<tr>
<td>m = 1.5</td>
<td>2.385</td>
</tr>
<tr>
<td>m = 0.75</td>
<td>2.251</td>
</tr>
<tr>
<td>m = -0.6</td>
<td>1.720</td>
</tr>
<tr>
<td>m = -1.0</td>
<td>1.830</td>
</tr>
<tr>
<td>m = -1.5</td>
<td>1.597</td>
</tr>
</tbody>
</table>
Fatigue Model:

\[ \log_{10}(C) = 2.68 - 5 \times \log_{10}(\varepsilon_h) - 2.665 \times \log_{10}(E_{AC}) \]

Subgrade Rutting Model:

\[ C = 10000 \times \left[ 0.000247 + 0.000245 \times \log_{10}(E_{SG}) \right]^{0.0658 \times E_{SG}^{0.559}} / \varepsilon_v \]

C: Number of coverages to failure
## GT-PAVE Predicted Responses/
Performances under Rolling B-777 Wheel

<table>
<thead>
<tr>
<th>h\text{(_{\text{SUBBASE}})} (cm)</th>
<th>m, stress path slope</th>
<th>\varepsilon_{\text{BTB tensile}} (\mu\varepsilon)</th>
<th>N\text{(_{f})} Fatigue</th>
<th>\varepsilon_{\text{Sub vert}} (\mu\varepsilon)</th>
<th>\sigma_{\text{Sub vert}} (kPa)</th>
<th>N\text{(_{f})} Rutting</th>
</tr>
</thead>
<tbody>
<tr>
<td>102.4</td>
<td>3.0</td>
<td>556</td>
<td>67,277</td>
<td>-505</td>
<td>-25.6</td>
<td>13,025,615</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>674</td>
<td>25,744</td>
<td>-520</td>
<td>-27.0</td>
<td>10,125,943</td>
</tr>
<tr>
<td></td>
<td>0.75</td>
<td>709</td>
<td>19,991</td>
<td>-518</td>
<td>-27.1</td>
<td>10,444,152</td>
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<tr>
<td></td>
<td>-0.6</td>
<td>741</td>
<td>16,022</td>
<td>-504</td>
<td>-26.5</td>
<td>13,268,794</td>
</tr>
<tr>
<td></td>
<td>-1.0</td>
<td>663</td>
<td>27,939</td>
<td>-506</td>
<td>-26.0</td>
<td>12,846,714</td>
</tr>
<tr>
<td></td>
<td>-1.5</td>
<td>712</td>
<td>19,494</td>
<td>-496</td>
<td>-25.8</td>
<td>15,288,834</td>
</tr>
</tbody>
</table>

Notes:
1. h\text{\(_{AC}\)} = 12.7 cm, h\text{\(_{BTB}\)} = 20.3 cm
2. “-” indicates compression in pavement responses
Stresses Predicted within the Subbase

$q = 1255 \text{kPa} = 182 \text{psi}$

Granular Subbase 102.4 cm

Subgrade

Top Row
Middle Row
Bottom Row

$\sigma$ calculated @ center of elements

† Not in Scale
Field & Laboratory Applied Stress States

(1) Heavy (Aircraft) Wheel Loads
(2) Moving Wheel Load Conditions

Airport Pavement: Boeing 777 single wheel loading

AASHTO T307-99
15 Stress-State Sequence

(1) Higher Magnitude
(2) Variable Confinement

Predicted Stress States
Top Base
Middle Base
Bottom Base

$ q = \sigma_1 - \sigma_3 \text{ (kPa)}$

$p = \frac{\sigma_1 + 2\sigma_3}{3} \text{ (kPa)}$
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Predicting Rutting / Permanent Deformations

**PRIMARY PERFORMANCE INDICATOR**

Base/Subbase Materials and Subgrade Soils

Permanent Deformation:

\[ \delta_p \]

**Load Repetitions**

Wheel Rutting!..
FAA – National Airport Pavement Test Facility (NAPTF), Atlantic City, NJ

- Low & Medium strength flexible sections (5 to 10 in. Asphalt & CBR 4 to 8 subgrade soils) failed with up to 4 in. ruts.

- Highest contribution to permanent deformations often from:
  - 8 to 30 in. thick P209 base, or
  - 12 to 36 in. thick P154 subbase

6-wheel (B777) & 4-wheel (B747) Gear Assemblies
NAPTF Trafficking Results (1)

5-inch P-401 Surface
5-inch P-401 Stabilized Base
30-inch P-209 Subbase

Wheel Load: 45,000-lbs (20.4 metric tonnes) per wheel

After 20,000 passes: 65,000-lbs (29.5 metric tonnes) per wheel

(Garg, 2003)
http://www.airporttech.tc.faa.gov
NAPTF Trafficking Results (2)

Wheel Load: 45,000-lbs **(20.4 metric tonnes)** per wheel

After 20,000 passes: 65,000-lbs **(29.5 metric tonnes)** per wheel

(Garg, 2003)

http://www.airporttech.tc.faa.gov
FAA NAPTF Permanent Deformation Testing Program – Univ. of Illinois

► Advanced Test Equipment: UI-FastCell

- Compression and Extension Stress States
- Constant (CCP) & Variable (VCP) Confining Stress Paths
Permanent Deformation Testing for Heavy Aircraft Wheel Loads

Constant Confining Pressure (CCP) Test Program - Tests on P209 and P154 aggregates

*CCP: $\sigma_d$ is pulsed only in the vertical direction!*..

<table>
<thead>
<tr>
<th>Stress Ratio $\sigma_1/\sigma_3 = 4$</th>
<th>Stress Ratio $\sigma_1/\sigma_3 = 6$</th>
<th>Stress Ratio $\sigma_1/\sigma_3 = 8$</th>
<th>Stress Ratio $\sigma_1/\sigma_3 = 10$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_d$ (psi)</td>
<td>$\sigma_3$ (psi)</td>
<td>$\sigma_1$ (psi)</td>
<td>$\sigma_d$ (psi)</td>
</tr>
<tr>
<td>9</td>
<td>3</td>
<td>12</td>
<td>15</td>
</tr>
<tr>
<td>15</td>
<td>5</td>
<td>20</td>
<td>25</td>
</tr>
<tr>
<td>24</td>
<td>8</td>
<td>32</td>
<td>40</td>
</tr>
<tr>
<td>30</td>
<td>10</td>
<td>40</td>
<td>50</td>
</tr>
</tbody>
</table>
Development of Rutting Models

Based on P209 CCP test results only!

Models considered

1. \( \varepsilon_p = A \sigma_3^B N^C \)
2. \( \varepsilon_p = A \sigma_d^B N^C \)
3. \( \varepsilon_p = A (\sigma_d/\sigma_3)^B N^C \)
4. \( \varepsilon_p = A \sigma_d^B \sigma_3^C N^D \)

A, B, C and D: Model Parameters
\( \sigma_d \): Deviator stress
\( \sigma_3 \): Confining pressure
N: Number of load applications

Model | 1 | 2 | 3 | 4
--- | --- | --- | --- | ---
R\(^2\) | 0.03 | 0.50 | 0.62 | 0.84
Permanent Deformation Testing for Moving Wheel Loads

- Tests on P209 and P154 aggregates

<table>
<thead>
<tr>
<th>Variable Confining Pressure (VCP) Test Program</th>
<th>Stress Path Slope = 1.5 Compression</th>
<th>Stress Path Slope = 0</th>
<th>Stress Path Slope = -1 Extension</th>
</tr>
</thead>
<tbody>
<tr>
<td>σ₃ (psi)</td>
<td>σ₁d (psi)</td>
<td>σ₃d (psi)</td>
<td>σ₃ (psi)</td>
</tr>
<tr>
<td>3.00</td>
<td>10.54</td>
<td>2.63</td>
<td>3.00</td>
</tr>
<tr>
<td>3.00</td>
<td>17.53</td>
<td>4.38</td>
<td>3.00</td>
</tr>
<tr>
<td>3.00</td>
<td>24.52</td>
<td>6.13</td>
<td>3.00</td>
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<tr>
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<td>31.62</td>
<td>7.90</td>
<td>3.00</td>
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<td>5.00</td>
<td>17.53</td>
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<td>5.00</td>
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<td>29.29</td>
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<td>8.00</td>
<td>28.07</td>
<td>7.02</td>
<td>8.00</td>
</tr>
<tr>
<td>8.00</td>
<td>46.82</td>
<td>11.70</td>
<td>8.00</td>
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<td>65.45</td>
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<tr>
<td>10.00</td>
<td>58.47</td>
<td>14.62</td>
<td>10.00</td>
</tr>
</tbody>
</table>
Permanent Deformation Testing for Moving Wheel Loads

Deviator Stress, $q$

VCP Tests

Or should know:

Pulsed horizontal stress, $\sigma_{3d}$
Pulsed vertical stress, $\sigma_{1d}$

Mean Normal Stress, $p$

Stress Path Slope = $m$
Stress Path Length = $L$

$q_{\text{min}}$ $q_{\text{max}}$

$p_{\text{min}}$ $p_{\text{max}}$
Development of Rutting Models

Based on both P209 and P154 VCP test results!

<table>
<thead>
<tr>
<th>Model</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1</td>
<td>$\varepsilon_p = a \cdot \sigma_s^b \cdot N^c$</td>
</tr>
<tr>
<td>Model 2</td>
<td>$\varepsilon_p = a \cdot \sigma_s^b \cdot \sigma_{1d}^c \cdot N^d$</td>
</tr>
<tr>
<td>Model 3</td>
<td>$\varepsilon_p = a \cdot \sigma_s^b \cdot \sigma_{3d}^c \cdot N^d$</td>
</tr>
<tr>
<td>Model 4</td>
<td>$\varepsilon_p = a \cdot \sigma_s^b \cdot \sigma_{1d}^c \cdot \sigma_{3d}^d \cdot N^e$</td>
</tr>
<tr>
<td>Model 5</td>
<td>$\varepsilon_p = a \cdot \sigma_s^b \cdot L^c \cdot N^d$</td>
</tr>
<tr>
<td>Model 6</td>
<td>$\varepsilon_p = a \cdot \sigma_s^b \cdot N^c \cdot \left(1 + \frac{1}{10^m}\right)^d$</td>
</tr>
<tr>
<td>Model 7</td>
<td>$\varepsilon_p = a \cdot \sigma_s^b \cdot L^c \cdot N^d \cdot \left(1 + \frac{1}{10^m}\right)^e$</td>
</tr>
</tbody>
</table>

$\sigma_s$: Static confining pressure  
$\sigma_{1d}$: Vertical dynamic stress  
$\sigma_{3d}$: Horizontal dynamic stress  
$L$: Stress path length  
$m$: Stress path slope  
a, b, c, d, & e: regression parameters
## Rutting Model Performances (CCP+VCP data)

<table>
<thead>
<tr>
<th>Model No.</th>
<th>R² Values for All data</th>
<th>R² Values for Stress Path Slope (m)</th>
<th>P209 FAA Base Material</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>-1</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0.02</td>
<td>0.17</td>
<td>0.11</td>
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<td>2</td>
<td>0.56</td>
<td>0.24</td>
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<tr>
<td>3</td>
<td>0.41</td>
<td>0.42</td>
<td>0.72</td>
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<tr>
<td>4</td>
<td>0.80</td>
<td>0.38</td>
<td>0.78</td>
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<tr>
<td>5</td>
<td>0.05</td>
<td>0.41</td>
<td>0.71</td>
</tr>
<tr>
<td>6</td>
<td>0.73</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>7</strong></td>
<td><strong>0.86</strong></td>
<td><strong>-</strong></td>
<td><strong>-</strong></td>
</tr>
</tbody>
</table>

**Model 7 includes stress path slope m**

<table>
<thead>
<tr>
<th>Model No.</th>
<th>R² Values for All data</th>
<th>R² Values for Stress Path Slope (m)</th>
<th>P154 FAA Subbase Material</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>-1</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0.02</td>
<td>0.05</td>
<td>0.35</td>
</tr>
<tr>
<td>2</td>
<td>0.46</td>
<td>0.62</td>
<td>0.53</td>
</tr>
<tr>
<td>3</td>
<td>0.16</td>
<td>0.44</td>
<td>0.52</td>
</tr>
<tr>
<td>4</td>
<td><strong>0.60</strong></td>
<td>0.62</td>
<td>0.53</td>
</tr>
<tr>
<td>5</td>
<td>0.02</td>
<td>0.42</td>
<td>0.53</td>
</tr>
<tr>
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<td>-</td>
<td>-</td>
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<tr>
<td><strong>7</strong></td>
<td><strong>0.65</strong></td>
<td><strong>-</strong></td>
<td><strong>-</strong></td>
</tr>
</tbody>
</table>

**Models 7 includes stress path slope m**
Outline

- Introduction
- Findings from Full-Scale Field Studies
- Stresses In the Pavement System
- Field and Laboratory Stress States
- Moving Wheel Load Effects on Resilient Modulus
- Moving Wheel Load Effects on Permanent Deformation
  - Development of rutting models
  - Testing for Approaching and Departing Wheel
- Summary / Current & Future Challenges
Stress Paths Under Approaching and Departing Wheel Loads

FAA – National Airport Pavement Test Facility

**Stress states due to 1 gear pass**

- Dual Gear TO#1 – Traffic Path North
- Dual Gear TO#1 – Traffic Path South
- Dual Gear TO#2 – Traffic Path North
- Dual Gear TO#2 – Traffic Path South

**Graphical Representation**

- **Compression**
- **Extension**
- **LFS sections**

**Equation**

\[ p^* = (2\sigma_h + \sigma_v) / 3, \text{ psi} \]

**Graph Elements**

- **Axes**
  - X-axis: Gear locations (TO #1 and TO #2)
  - Y-axis: \( q^* = (\sigma_v - \sigma_h), \text{ psi} \)

**Legend**

- Dual Gear TO#1 – Traffic Path North: Green line
- Dual Gear TO#1 – Traffic Path South: Blue line
- Dual Gear TO#2 – Traffic Path North: Red line
- Dual Gear TO#2 – Traffic Path South: Yellow line

**Sensor Locations**

- Sensor X points along the gear paths.
Permanent Deformation Testing for Approaching and Departing Wheel

Tests Considering Actual Rolling Wheel Stress Path

Stress History Effects Included

According to stress path order, each cycle switch to next one

1\textsuperscript{st} cycle : Path 1
2\textsuperscript{nd} cycle : Path 2
3\textsuperscript{rd} cycle : Path 3
4\textsuperscript{th} cycle : Path 4
5\textsuperscript{th} cycle : Path 1
6\textsuperscript{th} cycle : Path 2
7\textsuperscript{th} cycle : Path 3

\[ p = \left(\frac{2\sigma_3 + \sigma_1}{3}\right) \]

\[ q = (\sigma_1 - \sigma_3) \]
Multiple Path Test Program

Stress States for Multiple Path Test (psi)

<table>
<thead>
<tr>
<th>Part</th>
<th>$\sigma_{1s}$</th>
<th>$\sigma_{3s}$</th>
<th>$\sigma_{1d}$</th>
<th>$\sigma_{3d}$</th>
<th>Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
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<td>5.0</td>
<td>2.6</td>
<td>10.2</td>
<td>-1</td>
</tr>
<tr>
<td>B</td>
<td>7.6</td>
<td>15.2</td>
<td>38.4</td>
<td>0.0</td>
<td>3</td>
</tr>
<tr>
<td>C</td>
<td>45.9</td>
<td>15.2</td>
<td>-38.4</td>
<td>0.0</td>
<td>3</td>
</tr>
<tr>
<td>D</td>
<td>7.6</td>
<td>15.2</td>
<td>-2.6</td>
<td>-10.2</td>
<td>-1</td>
</tr>
</tbody>
</table>

q-p States for Multiple Path Test (psi)

<table>
<thead>
<tr>
<th>Part</th>
<th>$p_{min}$</th>
<th>$q_{min}$</th>
<th>$p_{max}$</th>
<th>$q_{max}$</th>
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</thead>
<tbody>
<tr>
<td>A</td>
<td>5.0</td>
<td>0.0</td>
<td>12.7</td>
<td>-7.7</td>
</tr>
<tr>
<td>B</td>
<td>12.7</td>
<td>-7.7</td>
<td>25.5</td>
<td>30.7</td>
</tr>
<tr>
<td>C</td>
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<td>-7.7</td>
</tr>
<tr>
<td>D</td>
<td>12.7</td>
<td>-7.7</td>
<td>5.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Vertical stress $(\sigma_{1s} + \sigma_{1d})$

Shear stress

Horizontal stress $(\sigma_{3s} + \sigma_{3d})$
## Experimental Program – Summary

<table>
<thead>
<tr>
<th>Materials</th>
<th>Test Type</th>
<th>Compaction Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>P209 (Base)</td>
<td>Single Path</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>Multiple Path</td>
<td>100%</td>
</tr>
<tr>
<td>P154 (Subbase)</td>
<td>Single Path</td>
<td>95%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>85%</td>
</tr>
<tr>
<td></td>
<td>Multiple Path</td>
<td>95%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>85%</td>
</tr>
</tbody>
</table>

- **Number of Load Repetitions:** 40,000
- **Total 10 tests performed**
Multiple Path Test Program

Test Results – P209

Both the volumetric and deviatoric strains of the multiple stress path tests consistently higher than the ones from the single path test.

Moving wheel load effect is properly accounted for in laboratory testing.
Most Moving Wheel Damage
- Multiple Path Testing

Laboratory Test Results (moving wheel load simulation)

- Largest deformations accumulate with approaching wheel

Contractive & Dilative Behavior
Multiple Path Test Program

Test Results – P154

The permanent strains rapidly increased with a decrease in the degree of compaction.
Multiple stress path tests gave much higher volumetric & deviatoric permanent strains than the single path tests.

Related FAA NAPTF Observation

Increased amounts of shearing and continuous horizontal movement or heave of pavement materials in the transverse direction to traffic when the aircraft gear loading was applied with a wander pattern!
Multiple Path Test Program

Test Results – P154

Compaction affecting the rate at which the strains accumulate in the multiple path tests

Compaction affecting the rate at which the strains accumulate in the single path tests

Multiple path tests indicated much higher impact of compaction on permanent deformation accumulation
Multiple Path Test Program

Test Results - P154

Findings:

High shear or deviatoric strains commonly linked to excessive rutting type shear failures:

- Multiple stress path loading or moving wheel loads can cause significantly higher permanent deformations or damage in the loose base/subbase layers.

Supported by:

- By applying to the pavement element shear stress reversals through extension and compression loading, up to 3 times higher permanent deformations can accumulate when compared to those obtained from plate loading.

(French LCPC: Hornych et al., 2000)

Multiple path tests
(much higher impact of compaction)
Summary

- For a given pavement element, principal stress axes rotate as the wheel load moves away.

- In pavement layers, stress states & hence stress path slopes \((m)\) vary depending on the varying magnitudes of the applied dynamic stresses.

- Lacking the ability to pulse in the horizontal direction, the AASHTO T307-99 test procedure can only conduct tests under \(m=3.0\).
Summary

- Former research indicates higher permanent shear strains and therefore more rutting may occur under stress path slopes other than CCP $m = 3.0$

- Advanced stress path tests can take into account the effects of actual moving wheel loads & VCP conditions for a better simulation and characterization of pavement material behavior
Summary

- Modulus and permanent deformation models that analyze simultaneously the **static and dynamic** components of the applied stresses or **the stress path length and slope** of dynamic loading produced a high degree of accuracy.

- Both compression and extension type loadings occur under rolling wheel loads. **Extension loading** due to moving wheel load effects may cause a **reduction in modulus**.
Summary

- Two different test procedures, single stress path and multiple stress path, were studied in the laboratory to simulate applied stress states due to stationary and moving (approaching and departing) wheel load conditions, respectively.

- The permanent strains (volumetric and deviatoric or shear) obtained from the multiple stress path tests were consistently higher than those from the single path tests.
Conclusion

Pavement material characterization models should consider

- the effects of rotating extension-compression-extension type field stress states and
- shear stress reversals that take place under moving wheel loads (VCP testing)

Further considerations or challenges include...
Current & Future Challenges – NAPTF Trafficking Data

Sensor Time History

- Stress History Effects

Pavement Response

Time (sec)

0 2 4 6 8 10 12 14

Max Response
Rebound Response
End Response
Residual Response
Initial Response

Direction of Aircraft Movement
Current & Future Challenges – NAPTF Trafficking Data

Base / Subbase
Contractive & Dilative Behavior
Current & Future Challenges – NAPTF

Trafficking Data

Residual Permanent Deformations After Wheel Pass

East Direction Traffic First

Traffic Direction (Stress History) Effect

West Direction Traffic Later
Current & Future Challenges – NAPTF Trafficking Data

Load path (stress history) effect