Lecture 3:

Stresses in Rigid Pavements
Nature of Responses under Flexible and Rigid Plates

**Flexible plate:**
- Uniform Contact Pressure
- Variable Deflection Profile

**Rigid Plate:**
- Non-Uniform Contact Pressure
- Equal Deflection

**Flexible Plate**

\[
\text{Uniform Pressure } q
\]

**Rigid Plate**

\[
q(r) = \frac{qa}{2(a^2 - r^2)^{0.5}}
\]

\[
w_0 = \frac{2(1-v^2)qa}{E}
\]

\[
w_0 = \frac{\pi(1-v^2)qa}{2E}
\]
Comparison of Deflections at the Surface
Rigid vs. Flexible Plate

Flexible Plate
\[ d_o = \frac{2\sigma_0 a(1-\mu^2)}{E} \]

Rigid Plate
\[ d_o = \frac{\pi\sigma_0 a(1-\mu^2)}{2E} \]

\[ \frac{d_o^{\text{flexible}}}{d_o^{\text{rigid}}} = \frac{2\sigma_0 a(1-\mu^2)}{\frac{\pi}{2}\frac{\sigma_0 a(1-\mu^2)}{E}} = \frac{4}{\pi} = 1.27 \Rightarrow \frac{d_o^{\text{rigid}}}{d_o^{\text{flexible}}} = \frac{\pi}{4} = 0.79 \]

The deflection under a rigid plate is 79% of that under a flexible plate.
Contact Pressure and Deflection Calculation under the Rigid plate

- Ullidtz (1987) gave the distribution of contact pressure under a rigid plate as:
  \[
p(r) = \frac{pa}{2(a^2 - r^2)^{0.5}}
\]

- Notice that the distribution of the contact pressure is a function of radial offset from the load centerline.

- By integrating a point load over the contact area of the plate, the deflection can be calculated as:
  \[
  \Delta_o = \frac{\pi(1 - \mu^2)pa}{2E}
  \]

- Assuming \(\mu=0.5\), the surface deflection at centerline can be calculated as:
  \[
  \Delta_o = \frac{1.18 \, pa}{E}
  \]
Stresses in Rigid Pavements

A. Stresses due to Environment

- Warping (or Curling) Stresses
  - Stresses due to temperature differential or change in humidity (temperature or moisture gradient)
    - Location:
      - ✓ Interior Loading
      - ✓ Edge loading
      - ✓ Corner Loading

- Shrinkage/Expansion Stresses

B. Stresses due to External Loading

- Such as stresses induced by traffic loads
  - Location:
    - ✓ Interior Loading (sufficiently away from the joints- no discontinuity effect)
    - ✓ Edge loading
    - ✓ Corner Loading

C. Other Stresses

- Such as frictional forces between the slab and foundation
Warping Stress - Day Time

\[ T_s \geq T_b \]

Slab Surface Temperature > Slab Bottom Temperature

\[ T_s = \text{Slab surface temperature} \]
\[ T_b = \text{Slab bottom temperature} \]
Warping Stress - Night Time

Slab Bottom Temperature > Slab Surface Temperature

$T_b > T_s$

$T_s < T_b$
Constrained Transverse Joints

Slab Surface Temperature > Slab Bottom Temperature
Temperature Variation for Precast Concrete Panel Installed using HDP Deep Injection (Ashtiani, 2011)
Typical Day Time Warping

Top of the PCC Layer is **Warmer**
Bottom of the PCC Layer is **Cooler**

Typical Night Time Warping

Top of the PCC Layer is **Cooler**
Bottom of the PCC Layer is **Warmer**
Calculation of Warping Stresses

Edge Stress

$$\sigma_t = \frac{C E e \Delta T}{2}$$

- \(\sigma_t\) = Slab edge warping stress (psi)
- \(E\) = Modulus of elasticity of PCC (psi)
- \(e\) = Thermal coefficient of PCC (approximately 0.000005 /F)
- \(\Delta T\) = Temperature differential between the top and bottom of the slab (F)
- \(C\) = Coefficient, function of slab length and the radius of relative stiffness, \(l\)
Radius of Relative Stiffness
Definition

\[ l = \frac{4\sqrt{Eh^3}}{12k(1-\nu^2)} \]

\[ \nu = \text{Poisson Ratio} \]
\[ E = \text{Modulus of Elasticity (psi)} \]
\[ l = \text{Radius of Relative Stiffness (in)} \]
\[ k = \text{Modulus of Subgrade Reaction (pci)} \]
\[ h = \text{Slab Thickness (in)} \]
Westergaard’s Model of Subgrade Reaction

- Elastic layered theory can’t be applied for jointed rigid pavements due to the fact that one of the assumptions of the layered theory was that layers are infinitely long in horizontal direction (no effect of discontinuity at joints). To solve this problem Westergaard (1925) assumed that a rigid pavement could be considered as a slab on a Winkler foundation. In other words, the foundation reaction (or vertical stress) equals to the deflection times a constant (k) called modulus of subgrade reaction.

- Note that the modulus of subgrade reaction (k) has unit of (pci).
Determination of the Warping Stresses, Coefficient (C)

- $B =$ Free length of width of slab in inches
- $\ell =$ Radius of relative stiffness (in.)
- $C =$ Longitudinal or transverse warping-stress coefficient
Calculation of Warping Stresses, Cont.

Interior Stress

\[ \sigma_t = \frac{E e \Delta T}{2} \left[ \frac{C_1 + \nu C_2}{1 - \nu^2} \right] \]

- \( \sigma_t \): Slab interior warping stress (psi)
- \( E \): Modulus of elasticity of PCC (psi)
- \( e \): Thermal coefficient of PCC (~0.000005/F)
- \( \nu \): Poisson’s ratio for PCC
- \( C_1 \): Coefficient in direction of calculation
- \( C_2 \): Coefficient in direction perpendicular to \( C_1 \)
Calculation of Warping Stresses, Cont.

Corner Stress

\[ \sigma_t = \frac{E e \Delta T}{3(1-\nu)} \sqrt{\frac{a}{l}} \]

- \( \sigma_t \) = Corner Warping Stress (psi)
- \( E \) = Modulus of Elasticity of PCC (psi)
- \( e \) = Thermal Coefficient of PCC (~0.000005/F)
- \( \Delta T \) = Temperature Differential between the Top and Bottom of the Slab (F)
- \( \nu \) = Poisson’s Ratio for PCC
- \( a \) = Contact Radius for Corner Load
- \( l \) = Radius of Relative Stiffness
Stresses due to External Loads
Westergaard Equations

- Interior loading (tensile stress at the bottom of the slab)
  \[ \sigma_i = \frac{0.3162(W)}{h^2} \left[ 4 \log_{10} \left( \frac{a}{b} \right) + 1.069 \right] \]

- Edge loading (tensile stress at the bottom of the slab)
  \[ \sigma_e = \frac{0.572(W)}{h^2} \left[ 4 \log_{10} \left( \frac{a}{b} \right) + 0.359 \right] \]

- Corner loading (tensile stress on the top of the slab)
  \[ \sigma_c = \frac{3(W)}{h^2} \left[ 1 - \left( \frac{av\sqrt{2}}{l} \right)^{0.6} \right] \]

W = Wheel load (lb)
h = Slab thickness (in.)
a = Radius of Wheel Contact Area (in.)
l = Radius of Relative Stiffness (in.)
b = Radius of Resisting Section (in.)
\[ b = \sqrt{1.6(a^2 + h^2)} - 0.675(h) \]
Slab Expansion/Contraction

\[ z = CL[e \Delta t + \delta] \]

- \( z \) = Joint opening (or change in slab length, in.)
- \( C \) = Base/slab frictional restrain factor (0.65 for stabilized bases; 0.80 for granular bases)
- \( L \) = Slab length (in.)
- \( e \) = PCC coefficient of thermal expansion by aggregate type (e.g., \( 6.0 \times 10^{-6}/F \) for gravel; \( 3.8 \times 10^{-6}/F \) for limestone)
- \( \Delta t \) = Maximum temperature range
- \( \delta \) = Shrinkage coefficient of concrete (e.g., 0.00045 in./in. for indirect tensile strength of 500 psi)
Load Transfer Efficiency (LTE) in Rigid Pavements
Bonding Agent
(ep)l
(ep)ul
(σv)l (σv)ul
Subgrade
Loaded Slab
Unbound Granular Base
Unloaded Slab
Loss of Foundation Support

Subgrade
Loaded Slab
Unbound Granular Base
Bonding Agent
Unloaded Slab
Loss of Foundation Support
(εp)l
(σv)l
(σv)ul
(εp)ul
Load Transfer Efficiency (LTE) in Rigid Pavements

- Load Transfer Efficiency (LTE)
  - Deflection based, LTE$_\delta$
  - Stress based, LTE$_\sigma$
  - FAA Criteria (stress based), LT

$$LT = \frac{\text{Stress}_{\text{free edge}} - \text{Stress}_{\text{loaded slab}}}{\text{Stress}_{\text{free edge}}}$$

$$LTE = 1 - \frac{\text{Stress}_{\text{loaded slab}}}{\text{Stress}_{\text{free edge}}}$$

$$LTE_{\delta} = \frac{\text{Deflection}_{\text{unloaded slab}}}{\text{Deflection}_{\text{loaded slab}}}$$

$$LTE_{\sigma} = \frac{\text{Stress}_{\text{unloaded slab}}}{\text{Stress}_{\text{loaded slab}}}$$

$$LT = \frac{LTE_{\sigma}}{1 + LTE_{\sigma}}$$

$$LTE_{\delta} = \frac{1206 \left( \frac{a}{l} \right) + 377}{1 + 689 \left( \frac{a}{l} \right) LTE_{\sigma} + 370 - 154 \left( \frac{a}{l} \right) LTE_{\sigma}^2} LTE_{\sigma}^2 - 393 \left( \frac{a}{l} \right) LTE_{\sigma}^3$$
A falling weight deflectometer (FWD) is a device designed to simulate deflection of a pavement surface caused by a fast-moving truck. The FWD generates a load pulse by dropping a weight.

This load pulse is transmitted to the pavement through a 300-millimeter (mm) diameter circular load plate.

The load pulse generated by the FWD momentarily deforms the pavement under the load plate into a dish or bowl shape.

Based on the force imparted to the pavement and the shape of the deflection basin, it is possible to estimate the stiffness of the pavement layers by using various computational methods.
Falling Weight Deflectometer (FWD) General Definitions

✓ Non-destructive test equipment for pavements.
✓ Imparts an impact load to a pavement structure.
✓ Measures deflection of the pavement surface at different radial offsets.
✓ Different types based on the application: Light Weight Deflectometer (LWD), Falling weight Deflectometer (FWD), and Heavy Weight Deflectometer (HWD).
Components of FWD

- Load Cell
- LVDT, Geophones, Accelerometers
  - Displacement measurement
- Infrared temperature gages
  - Pavement Surface Temperature
  - Air Temperature
- Electronic Distance Measurement
- Control/Data Acquisition Unit
Impact Load created from dropping weights from specified height.
Load cell used to measure the impulse loading.
Heavy-duty load cell required to support in excess of 60 kips in magnitude.
Deflection profile is key output.
Temperature and load data used with deflections to back-calculate pavement structure characteristics.
Temperature Dependency of Deflection Profile in a Flexible Pavement
Application of FWD/HWD in Pavement Engineering

- Determination of the in-situ layer moduli.
- Estimation of the structural capacity and analysis of the remaining life.
- Determination of the load transfer efficiency of joints in concrete pavements.
- Pavement management.
Deflection based LTE (ratio of plastic strains at the two sides of the joints) is the most common method to determine LTE and joint stiffness of PCC slabs in pavement industry.

\[ LTE_\delta = \frac{\text{Deflection}_{\text{unloaded slab}}}{\text{Deflection}_{\text{loaded slab}}} \]
Case Study (I)
Superposition of Thermal Stresses and HWD Load
Rapid Damage Repair using Precast Concrete Slabs
Tyndall AFB, (Ashtiani, 2010)
Day Time Super Position of Thermal and Load induced Stresses for FWD Loading (Ashtiani, 2011)
Distribution of Vertical Stresses at the Top of the Subgrade (Day Time)

Stresses in Z-direction
Night Time Super Position of Thermal and Load Induced Stresses for HWD Loading
Distribution of Vertical Stresses at the Top of the Subgrade (Night Time)

Stresses in Z-direction
Case Study (II)

Superposition of Thermal Stresses and Stresses due to C17 Aircraft Landing Gear

Rapid Damage Repair using Precast Concrete Slabs
Tyndall AFB, (Ashtiani, 2010)
1. Corner Loading
2. Mid-Slab Loading
3. Edge Loading
4. Landing in the direction of dowel bars
5. Landing perpendicular to the direction of dowel bars
Distribution of Vertical Stresses at the Top of the Subgrade (Corner/Edge Loading for Slab #1)
Sensitivity Analysis of Parameters of Different Measures of Load Transfer Efficiency (LTE)
### Sensitivity Analysis of the parameters of the LTE model.

\[
LTE_\delta = \frac{1206 \left(\frac{a}{l}\right) + 377 \cdot LTE_\sigma^2 - 393 \left(\frac{a}{l}\right) LTE_\sigma^3}{1 + 689 \left(\frac{a}{l}\right) LTE_\sigma + \left[370 - 154 \left(\frac{a}{l}\right)\right] LTE_\sigma^2}
\]

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Sensitivity of the Load Transfer Efficiency to the Parameters of the Model, effect of \((a/l)\)

\[
LTE_\sigma = \frac{\left[ 1206 \left(\frac{a}{l}\right) + 377 \right] LTE_\sigma^2 - 393 \left(\frac{a}{l}\right) LTE_\sigma^3}{1 + 689 \left(\frac{a}{l}\right) LTE_\sigma + \left[ 370 - 154 \left(\frac{a}{l}\right) \right] LTE_\sigma^2}
\]
For plate loading with \( r=6 \) in, \( k=100 \) pci and \( h=9 \) in, LTE is not very sensitive to modulus of the PCC slab.
Table 1. Variables of the Finite Element Simulations

<table>
<thead>
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<th>Simulation ID</th>
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<th>FE Calculated $\varepsilon_p$</th>
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Impact of Orthogonal Load Transfer Efficiency On Deformed Mesh.
Traffic Considerations in Rigid Airfield Pavements
Traffic Mix for Airfield Pavement Design

Must use the entire traffic mix, no more “Design Aircraft”.

- Traffic Model - Cumulative Damage Factor (CDF) sums damage from each aircraft based upon its unique pavement loading characteristics and Location of the main gear from the runway centerline.

- DOES NOT use the “design aircraft” method of condensing all aircraft into one design aircraft.
Sample Aircraft Traffic Mix CDF Contribution

<table>
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<th>Aircraft Name</th>
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<th>Annual Departures</th>
<th>CDF Contribution</th>
<th>CDF Max For Aircraft</th>
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<td>0.09</td>
<td>0.09</td>
</tr>
<tr>
<td>B-727</td>
<td>172,000</td>
<td>1,200</td>
<td>0.23</td>
<td>0.24</td>
</tr>
<tr>
<td>B-757</td>
<td>250,000</td>
<td>1,200</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td>A300-B2</td>
<td>304,000</td>
<td>1,200</td>
<td>0.01</td>
<td>0.16</td>
</tr>
<tr>
<td>B-767-200</td>
<td>335,000</td>
<td>1,200</td>
<td>0.02</td>
<td>0.15</td>
</tr>
<tr>
<td>A330</td>
<td>469,000</td>
<td>100</td>
<td>0.01</td>
<td>0.23</td>
</tr>
<tr>
<td>B-747-400</td>
<td>873,000</td>
<td>100</td>
<td>0.23</td>
<td>0.28</td>
</tr>
<tr>
<td>B-777-200</td>
<td>537,000</td>
<td>500</td>
<td>0.00</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Condition specific and not a general representation of noted aircraft.
Sample Aircraft Traffic Mix
CDF Contribution

Condition specific and not a general representation of noted aircraft
Large Aircraft Gear Locations

Distance From Centerline (in)

0 25 50 75 100 125 150 175 200 225 250 275 300 325 350 375 400

Runway Centerline

B-777-200
B-747-400
A-330
B-767-200
A-300-B2
B-757
B-727
B-737-400
MD-83
MD-90-30
DC-9-50
DW 100,000
Regional Jet 700
Regional Jet 200
DW 45,000
DW 30,000
SW 30,000
Cumulative Damage Factor (CDF) Graph

CDF
1.0

Lateral Distance [in]

B747-400
B747-400 Belly
B767-200
Cumulative CDF

Job: 5320-6_Example
Section: Flexible
CDF max. = 1
Sample Cumulative Damage Factor (CDF) Graph
Design of Airfield Pavement Shoulders

- Shoulder must provide sufficient support for unintentional or emergency operation of any airplane in the traffic mix.

- Shoulders are primarily intended to provide:
  - Protection from erosion and generation of debris from jet blast (no loose materials close to the runway).
  - Enhanced drainage.
Gear Naming Conventions

Single
S

2 Singles in Tandem
2S

Dual
D

2 Duals in Tandem
2D

Triple
T

2 Triples in Tandem
2T

Quadruple
Q

2 Quadruples in Tandem
2Q

3 Singles in Tandem
3S

3 Duals in Tandem
3D

3 Triples in Tandem
3T

3 Quadruples in Tandem
3Q
Gear Naming Conventions - Examples

- **Single Wheel (S)**
- **Dual Wheel (D)**
- **Dual Tandem (2D)**

**Examples**

- **3D B777**
- **2D/D1 DC-10**
- **2D/2D1 A340-600**
Aircraft Gear - Examples

2D/2D2
B747

2D/3D2
A380

C5
Lockheed C5
Calculation depth is at a layer interface, a negative value sets the calculation point just above interface. [Max Depths = 100]
Problem 1.

Perform a sensitivity analysis of the modular ratios of two consecutive layers (e.g. $E_{AC}/E_{Base}$) in a three layer system. Provide plots of vertical and shear stress distributions vs. depth for the following scenarios and discuss your findings.

- Assume the modulus of the base layer as your last 5 digits of university ID number and develop plots of vertical and shear stress distributions vs. pavement depth along the load centerline for $E_{AC}/E_{Base} = 5, 10, 20, 30, 40, 50, 100$.
- Assume the thickness of the surface layer as 4 inches, and the thickness of the second layer (base layer) as 12 inches.
- Consider a soft subgrade with modulus of 4,000 psi and a stiff subgrade of 12,000 psi for your simulations.
- Assume a tire pressure of 100 psi acting on the surface of the pavement; assume the tire contact radius of 5.5 inches.
- Assume any other parameter/material property that you might need for your simulations; provide a justification for your assumptions.
Problem 2.

A proposed pavement design under construction for a highway consists of 6 inches of Hot Mix Asphalt (HMA) layer with modulus of 500,000 psi, and 10 inches of unbound granular base (UAB) layer over a relatively soft subgrade with modulus of 5,000 psi.

Determine the number of 18,000 lbs. ESALs that this pavement structure can support to reach rutting and fatigue failure. Use both Asphalt Institute (AI) and Shell transfer functions and discuss your results.

a) Vary the modulus of the base layer from 15,000 psi to 60,000 psi in 15,000 psi increments.

b) Assume proper Poisson ratio for each layer when you analyze the pavement system in a layered elastic software (such as WINJULIA or KENLAYER).

c) Assume the contact radius for the tire footprint on the pavement as 5.5 inches.

d) Discuss the influence of base layer modulus on the critical pavement responses.