Mechanistic Load Restriction Decision Platform for Pavement Systems Prone to Moisture Variations

“A System Dynamics Simulation Framework”

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Outline

1. Project Overview
2. System Dynamics Modeling (SDM)
3. SDM development
4. Hydrological Structure
5. Geotechnical Structure
6. Pavement Response Structure
7. Upcoming Tasks and Discussion
1. Project Overview

- **Project Objectives**
  - Develop a mechanistic framework to improve robustness of the load restriction decision process.
  - Improve post-flooding and seasonal pavement capacity assessment.
  - Implement a flexible platform that incorporates multi-variant effects with forecasting capability.

*System dynamics modeling and analysis*

*integrating climate forecasting, soil-moisture state, pavement mechanics and traffic spectrum*

- Develop a toolkit validated using field data for load restriction decision, specially for post-flooding load closures and openings.
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What is system dynamics modeling?

An approach to study and manage complex systems (includes multiple structures and components) that change over time.
What is system dynamics modeling?

An approach to study and manage complex systems (includes multiple structures and components) that change over time.

- Quantitative and qualitative (visual) assessment
- Identify interactions among system structures
  - Structures → Subset of a system (e.g., hydrological analysis)
- Real time coupled modeling (e.g., hydraulic and mechanical behavior)
- Can be formulated in computer software (e.g., Vensim Pro® in this research)
2. System Dynamics Modeling (2/8)

- **Basic components**
  - Stock/level Variable
  - Flow Variable
  - Information Variable
2. System Dynamics Modeling (3/8)

- Basic components
  - Stock/level Variable
  - Flow Variable
  - Information Variable
2. System Dynamics Modeling (4/8)

- **Basic components**
  - Stock/level Variable
  - Flow Variable
  - Information Variable
Basic components

- Stock/level Variable
- Flow Variable
- Information Variable
2. System Dynamics Modeling (6/8)

- Capabilities of SDM using computer tools:
  1) Visualize interrelationship between variables
  2) Diagrams of causes and uses
  3) Functions (IF THEN ELSE, etc.)

![Diagram showing system dynamics with variables such as ponded water height, infiltration rate, evaporation rate, and accumulated outflow.](image)
2. System Dynamics Modeling (7/8)

4) Simulation and Analysis

✓ Visualize the simulation results
✓ Simultaneous simulation of different scenarios and models
2. System Dynamics Modeling (8/8)

5) Data Use

✓ Different forms of data: time series, data with missing values, subjective data.

6) Sensitivity Testing

✓ Monte-Carlo multivariate sensitivity simulations

**Example:**

Sensitivity of ponded water height to effective grain size ($D_{10}$) and void ratio (multivariant effect)
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3. SDM development (1/2)

System dynamics main structures

- Hydrological structure
- Geotechnical structure
- Pavement response structure
3. SDM development (2/2)

Conventional flexible pavement example

- The SDM is discussed using example of a conventional flexible pavement system under moisture variations for 60 hours:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC layer thickness</td>
<td>0.1 m (~4 inch)</td>
</tr>
<tr>
<td>Base layer thickness</td>
<td>0.3 m (~12 inch)</td>
</tr>
<tr>
<td>Subbase layer thickness</td>
<td>0.1 m (~4 inch)</td>
</tr>
<tr>
<td>GWT depth (from subgrade surface)</td>
<td>2 m (~6.6 ft)</td>
</tr>
<tr>
<td>Subgrade sublayers height (10 layers)</td>
<td>0.2 m (~8 inch)</td>
</tr>
<tr>
<td>Bedrock depth</td>
<td>10 m (~32.8 ft)</td>
</tr>
</tbody>
</table>
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4. Hydrological Structure (1/15)

Main components:

1. Climate information:
   - Ponded water height
   - Precipitation and evaporation rate
   - Forecasted climate data or average hourly rate

2. Unsaturated soil flow analysis:
   - Initial soil moisture profile using van Genuchten (1980) SWRC and initial ground water depth:
   - Moisture-dependent hydraulic conductivity
   - Moisture movement analysis by numerical integration of Richard (1931)’s equations in discretized depth

\[
\frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[\frac{1}{1 + (\alpha h)^{n_{vG}}}\right]^{m_{vG}}
\]

\[
K(\theta) = K_{sat} \left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)^{0.5} \left[1 - \left(1 - \frac{\theta - \theta_r}{\theta_s - \theta_r}\right)^{m_{vG}}\right]^2
\]

\[
\frac{\delta \theta}{\delta t} = \frac{\delta}{\delta z} \left[K(\theta) \left(\frac{\delta h}{\delta z} + 1\right)\right]
\]
Flexible pavement example:

Material properties used in example

<table>
<thead>
<tr>
<th>Properties</th>
<th>Attributes/Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil type</td>
<td>Silty sand</td>
</tr>
<tr>
<td>Void ratio ((e))</td>
<td>0.5</td>
</tr>
<tr>
<td>Effective grain size ((D_{10}))</td>
<td>0.035 (mm)</td>
</tr>
<tr>
<td>(n_{vG})</td>
<td>5</td>
</tr>
<tr>
<td>(a_{vG})</td>
<td>2</td>
</tr>
<tr>
<td>Residual volumetric water content ((\theta_r))</td>
<td>0.02</td>
</tr>
<tr>
<td>Saturated water content ((\theta_s))</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Initial moisture and hydraulic conductivity profiles

Assumed climate condition in example

- Two periods of precipitation
- No evaporation and surface runoff
4. Hydrological Structure (3/15)

Water movement simulation using the SDM

Moisture profile

Depth (m)

Degree of saturation

Precipitation rate (m/hour)

Degree of saturation

Time (hour)

Base Subbase

GWT (t=0)

0 hour

Subgrade layer 5
Water movement simulation using the SDM

Moisture profile

- Depth (m)
  - 0
  - 0.3
- Degree of saturation
  - 0
  - 1
- 2 hours
- Base
- Subbase
- GWT (t=0)

Precipitation rate (m/hour)

Degree of saturation

Time (hour)

Subgrade layer 5

Base
4. Hydrological Structure (5/15)

Water movement simulation using the SDM

Moisture profile

- Depth (m)
- Degree of saturation

Precipitation rate (m/hour)

Degree of saturation

Time (hour)

- Base
- Subbase

GWT (t=0)

7 hours
4. Hydrological Structure (6/15)

- Water movement simulation using the SDM

Moisture profile

![Graph showing moisture profile with depth and degree of saturation over time.]

- Base
- Subbase

- 10 hours

GWT (t=0)

Graphs showing precipitation rate and degree of saturation over time.
4. Hydrological Structure (7/15)

Water movement simulation using the SDM

Moisture profile

Degree of saturation

Depth (m)

-20 hours

GWT (t=0)

Precipitation rate (m/hour)

Degree of saturation

Time (hour)

Base

Subbase

Subgrade layer 5
Water movement simulation using the SDM
4. Hydrological Structure (9/15)

- Water movement simulation using the SDM

Moisture profile

- Depth (m)
  - 0
  - 0.3
- Degree of saturation
  - 0
  - 1
- Base
- Subbase

- 30 hours

Precipitation rate (m/hour)

Degree of saturation

Time (hour)
4. Hydrological Structure (10/15)

Water movement simulation using the SDM

Moisture profile

- Depth (m)
  - 0.3
  - 0.0
  - -0.3
  - -0.6
  - -0.9
  - -1.2
  - -1.5
  - -1.8
  - -2.1

- Degree of saturation
  - 0.0
  - 0.2
  - 0.4
  - 0.6
  - 0.8
  - 1.0

- Time (hour)
  - 0
  - 5
  - 10
  - 15
  - 20
  - 25
  - 30
  - 35
  - 40
  - 45
  - 50
  - 55
  - 60

- Precipitation rate (m/hour)
  - 0
  - 0.05
  - 0.1
  - 0.15
  - 0.2
  - 0.25

- Degree of saturation

- GWT (t=0)

- Base
- Subbase
- 33 hours
4. Hydrological Structure (11/15)

- Water movement simulation using the SDM

Moisture profile

- Depth (m)
  - 0
  - -0.3
  - -0.6
  - -0.9
  - -1.2
  - -1.5
  - -1.8
  - -2.1

- Degree of saturation
  - 0
  - 0.2
  - 0.4
  - 0.6
  - 0.8
  - 1

- Base
- Subbase

- GWT (t=0)

- Precipitation rate (m/hour)
  - 0
  - 0.05
  - 0.1
  - 0.15
  - 0.2
  - 0.25

- Time (hour)
  - 0
  - 5
  - 10
  - 15
  - 20
  - 25
  - 30
  - 35
  - 40
  - 45
  - 50
  - 55
  - 60

- Degree of saturation
  - 0
  - 0.2
  - 0.4
  - 0.6
  - 0.8
  - 1

- Subgrade layer 5

- 35 hours
Water movement simulation using the SDM

Moisture profile

Depth (m)

Degree of saturation

Precipitation rate (m/hour)

Degree of saturation

Time (hour)
4. Hydrological Structure (13/15)

- Water movement simulation using the SDM

Moisture profile

- Depth (m)
- Degree of saturation

40 hours

Base
Subbase

Precipitation rate (m/hour)

Degree of saturation

Time (hour)
4. Hydrological Structure (14/15)

- Water movement simulation using the SDM

Moisture profile

- Depth (m)
  - 0.3
  - 0.2
  - 0.1
  - 0
  - -0.1
  - -0.2
  - -0.3
  - -0.4
  - -0.5
  - -0.6
  - -0.7
  - -0.8
  - -0.9
  - -1
  - -1.1
  - -1.2
  - -1.3
  - -1.4
  - -1.5
  - -1.6
  - -1.7
  - -1.8
  - -1.9
  - -2
  - -2.1

- Degree of saturation
  - 0
  - 0.2
  - 0.4
  - 0.6
  - 0.8
  - 1

- Precipitation rate (m/hour)
  - 0
  - 0.05
  - 0.1
  - 0.15
  - 0.2
  - 0.25

- Degree of saturation
  - 0
  - 0.2
  - 0.4
  - 0.6
  - 0.8
  - 1

- Time (hour)
  - 0
  - 5
  - 10
  - 15
  - 20
  - 25
  - 30
  - 35
  - 40
  - 45
  - 50
  - 55
  - 60

- 50 hours
- Base
- Subbase
- GWT (t=0)
4. Hydrological Structure (15/15)

Water movement simulation using the SDM

![Moisture profile and precipitation chart](chart.png)
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Moisture dependent resilient modulus

- Uses real time moisture profile from hydrological structure
- Estimates based on available moisture dependent resilient modulus equations
- Example: MEPDG (Zapata et al. 2007)

\[
\log \left( \frac{M_R}{M_{R-\text{OPT}}} \right) = a + \frac{b - a}{1 + \exp \left( \ln \left( \frac{b}{a} \right) + k_m(S - S_{\text{OPT}}) \right)}
\]
Flexible pavement example:

- Assumed material properties

- Typical results from SDM:

<table>
<thead>
<tr>
<th>Property/parameter (at optimum moisture content)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base resilient modulus ($M_{R,B-OPT}$)</td>
<td>200 MPa (~30 ksi)</td>
</tr>
<tr>
<td>Subbase resilient modulus ($M_{R,SB-OPT}$)</td>
<td>137 MPa (~20 ksi)</td>
</tr>
<tr>
<td>Subgrade resilient modulus ($M_{R,Sg-OPT}$)</td>
<td>70 MPa (~10 ksi)</td>
</tr>
<tr>
<td>$a$</td>
<td>~0.3123</td>
</tr>
<tr>
<td>$b$</td>
<td>0.3</td>
</tr>
<tr>
<td>$K_m$</td>
<td>6.8157</td>
</tr>
</tbody>
</table>
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6. Pavement Response Structure (1/3)

- **Main components**
  - Traffic information: axle load, axle configuration, and tire pressure
  - Structural performance analysis:
    - Equivalent Thickness Method (ETM)
    - Linear elastic analysis
      - Uses $M_R$ profile from geotechnical structure to estimate pavement response

$$H_{Eq} = H_n + \sum_{i}^{n} C_i H_i \frac{E_i(1 - \nu_n^2)}{E_n(1 - \nu_i^2)}^{1/3}$$

$$\sigma_z = q(1 - \frac{z^2}{(a^2 + z^2)^{1.5}})$$
6. Pavement Response Structure (2/3)

Flexible pavement example:

<table>
<thead>
<tr>
<th>Assumed material properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC resilient modulus ($M_{R,AC}$)</td>
<td>2500 MPa (~360 ksi)</td>
</tr>
<tr>
<td>AC Poisson ratio ($\nu_{AC}$)</td>
<td>0.35</td>
</tr>
<tr>
<td>Base Poisson ratio ($\nu_B$)</td>
<td>0.3</td>
</tr>
<tr>
<td>Subbase Poisson ratio ($\nu_{Sb}$)</td>
<td>0.3</td>
</tr>
<tr>
<td>Subgrade Poisson ratio ($\nu_{Sg}$)</td>
<td>0.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Assumed traffic information</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tire pressure</td>
<td>550 kPa (80 psi)</td>
</tr>
<tr>
<td>Wheel load</td>
<td>45 kN (10 kips)</td>
</tr>
</tbody>
</table>

Typical results from SDM

![Graph showing precipitation rate and surface deflection over time]

- System Dynamics Model
- Layered Elastic Analysis
6. Pavement Response Structure (3/3)

**Input variables**

- **Soil type**: Sandy loam
- **Effective grain size (D50)**: 0.015 (mm)
- **a_s**: 5
- **a_w**: 2
- **Residual volumetric water content**: 0.03
- **Saturated volumetric water content**: 0.3

**Hydrological structure**

- **Layer k**
- **Precipitation**
- **Evaporation**
- **Infiltration rate**
- **Surface water runoff**
- **Current GWL**
- **Layer thickness**
- **Layer porosity**

**Geotechnical structure**

- **Pavement Layer 0**
- **Layer M_d**
- **Layer M_d**
- **Layer porosity**

**Pavement response structure**

- **Vehicle class**
- **Axle configuration & tire pressure**
- **Axle load**
- **Surface deflection/peak stress/strain**
- **Pavement condition**

**Traffic Information**

- **Tire pressure**: 590 kPa (85 psi)
- **Wheel load**: 45 kN (100 psi)

**Properties**

- **AC resilient modulus (M_d)**: 2500 kPa (360 kips)
- **AC Poisson ratio**: 0.25
- **Base Poisson ratio**: 0.3
- **Subbase Poisson ratio**: 0.3
- **Subgrade Poisson ratio**: 0.4

**Simulation results**

- **Degree of saturation**
- **Resilient modulus, M_d (kPa)**
- **Surface Deflection (mm)**

- **Time (hour)**: 0 5 10 15 20 25 30 35 40 45 50 55 60
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**Task1**

**Task2**

**Task3**

**Task4**: Perform full sensitivity analysis to understand the significance of stressors, pavement components, and analysis methods/formulations on overall pavement response

**Task5**: develop a user-friendly toolkit that can be readily implemented for pavement load restriction decision process

**Task6** and **Future Phase**: Validate the toolkit using the field data/physical model testing data
Thank you!

Durham, NH
# Saturated hydraulic conductivity

<table>
<thead>
<tr>
<th>Reference</th>
<th>Hydraulic conductivity (cm/s)</th>
<th>Notation</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hazen [11]</td>
<td>( k_s = c D_{10}^2 )</td>
<td>( c = \text{constant.} )</td>
<td>( c \approx 1 ), applicable for fairly uniform sand</td>
</tr>
<tr>
<td>Chapius [12]</td>
<td>( k_s = 2.46 [D_{10}^2 \left( \frac{e^3}{(1 + e)} \right)^{0.78} )</td>
<td>( e = \text{void ratio of soil} )</td>
<td>Applicable for uniform gravel and sand and non-plastic silty sands</td>
</tr>
<tr>
<td>Mbonimpa et al. [13]</td>
<td>( k_s = c_p \frac{\gamma_w}{\mu_w} \left( \frac{e^{3+x}}{(1 + e)} \right) \frac{1}{\rho_s W_L^{2x}} )</td>
<td>( \gamma_w = \text{unit weight of water (kN/m}^3) )</td>
<td>Applicable for plastic soils, ( \gamma_w \approx 9.8 ), ( \mu_w \approx 10^{-3} ), ( \chi = 1.5 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \mu_w = \text{Water dynamic viscosity (Pa·s)} )</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \rho_s = \text{Density (kg/m}^3) \text{ of solids} )</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>( W_L = \text{Liquid limit (}) % )</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>( x = 7.7 W_L^{-0.15} - 3 )</td>
<td></td>
</tr>
</tbody>
</table>