National Center for INFRASTRUCTURE TRANSFORMATION
Led by: Prairie View A&M University

NCIT Webinar Series

On the Importance of Geotechnical Research to Support Strategic Goals of a Transportation Agency

Raul Velasquez, PhD, PE

Geomechanics & Deployment Research Engineer
MnDOT

Date: June 10, 2025

Time: 1:30 p.m. (CDT)

2023-2027 Minnesota Department of Transportation
Strategic Plan

VISION

Minnesota's multimodal transportation system maximizes the health of people, the environment and our economy

MISSION

Connect and serve all people through a safe, equitable and sustainable transportation system

VALUES

Our values guide how all MnDOT employees show up each day on behalf of Minnesotans:

Safety

Service

Equity

Sustainability

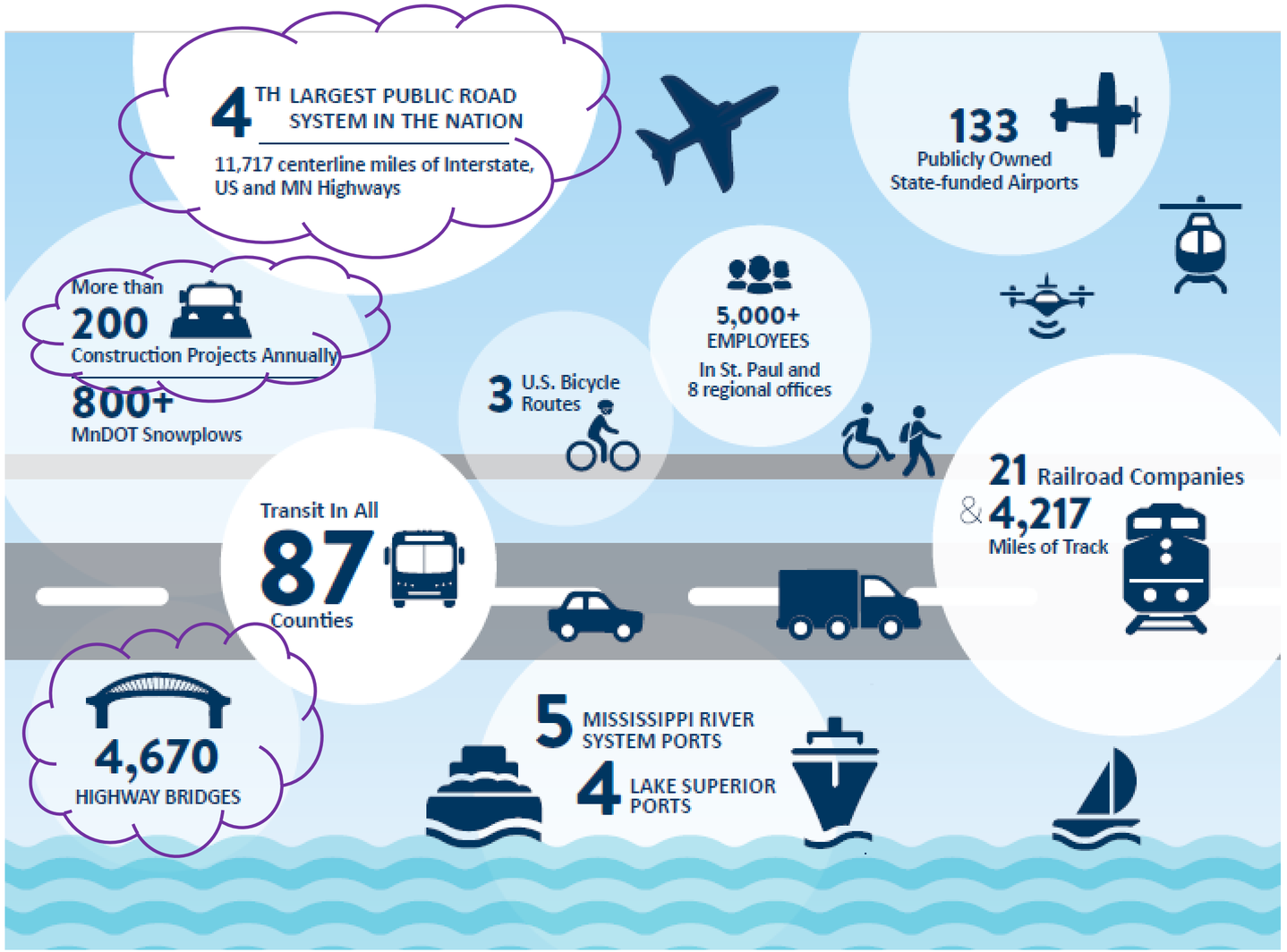
Innovation

Collaboration

https://www.dot.state.mn.us/about/strategic-plan.html

2023-2027 Minnesota Department of Transportation

Strategic Plan



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2023-2027 Minnesota Department of Transportation *Strategic Plan*

National Center for INFRASTRUCTURE TRANSFORMATION
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Goals Outline:

Implementation Principles

- Making progress on these *strategic goals* will require a *collaborative and flexible approach*
- We will leverage existing plans, committees, measures and proven strategies wherever possible to expand our capacity and increase our impact
- Where MnDOT has an established and long-standing track record, we will rethink our approach and *try innovative solutions*
- Where objectives and strategies are emerging and less defined, we will explore, *research and collaborate with our partners to find the best path forward*

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https://www.dot.state.mn.us/about/strategic-plan.html

2023-2027 Minnesota Department of Transportation *Strategic Plan*

National Center for INFRASTRUCTURE TRANSFORMATION
Led by: Prairie View A&M University

Goals Outline:

CHAMPION SUSTAINABILITY ACTIONS

Preparing for extreme weather already impacting MN transportation system

Materials and processes that reduces emissions

MAXIMIZE STEWARDSHIP OF RESOURCES

Use best practices and data-informed approaches to ensure that construction, technology and other agency projects are on-time and on-budget

Implement our asset management plan to maximize the useful life of our pavement, bridges and other critical transportation assets within available resources

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2023-2027 Minnesota Department of Transportation *Strategic Plan*

National Center for INFRASTRUCTURE TRANSFORMATION
Led by: Prairie View A&M University

Goals Outline:

MAXIMIZE STEWARDSHIP OF RESOURCES

Prepare for emerging technologies with national research partnerships, training and scalable pilot demonstrations

Accelerate, pilot and scale innovations that improve our efficiency, effectiveness and service

Encourage employee-driven innovation and continuous improvement through communities of practice and leadership support

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Examples of Geotech Research Products

Completed + Ongoing

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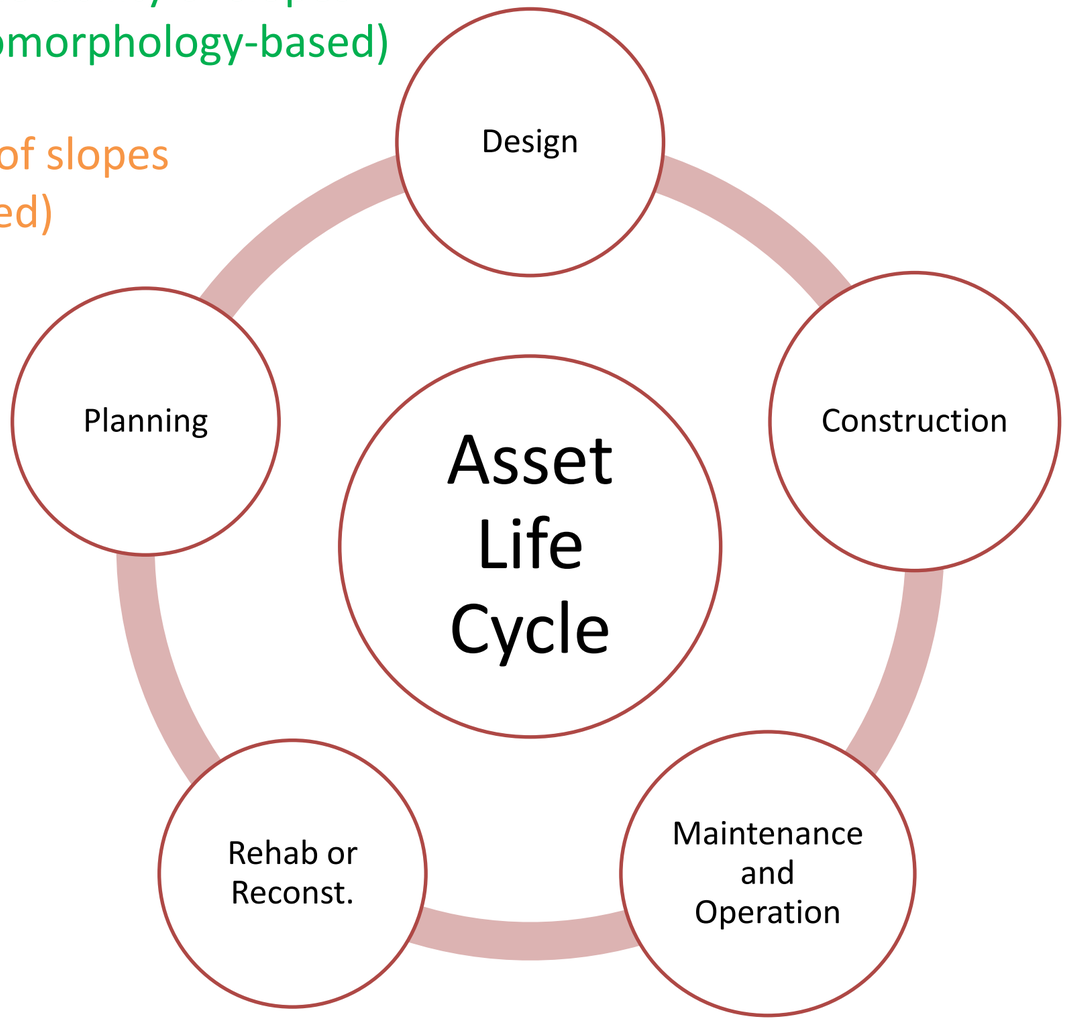
Vulnerability of slopes (geomorphology-based)

Vulnerability of slopes (geotech-based)



Light Weight Deflectometer (LWD) for QA/QC of Pavement Foundations

Pavement Foundation Uniformity (aka IC)

Pavement temperature as a surrogate of performance

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Examples of Geotech Research Products

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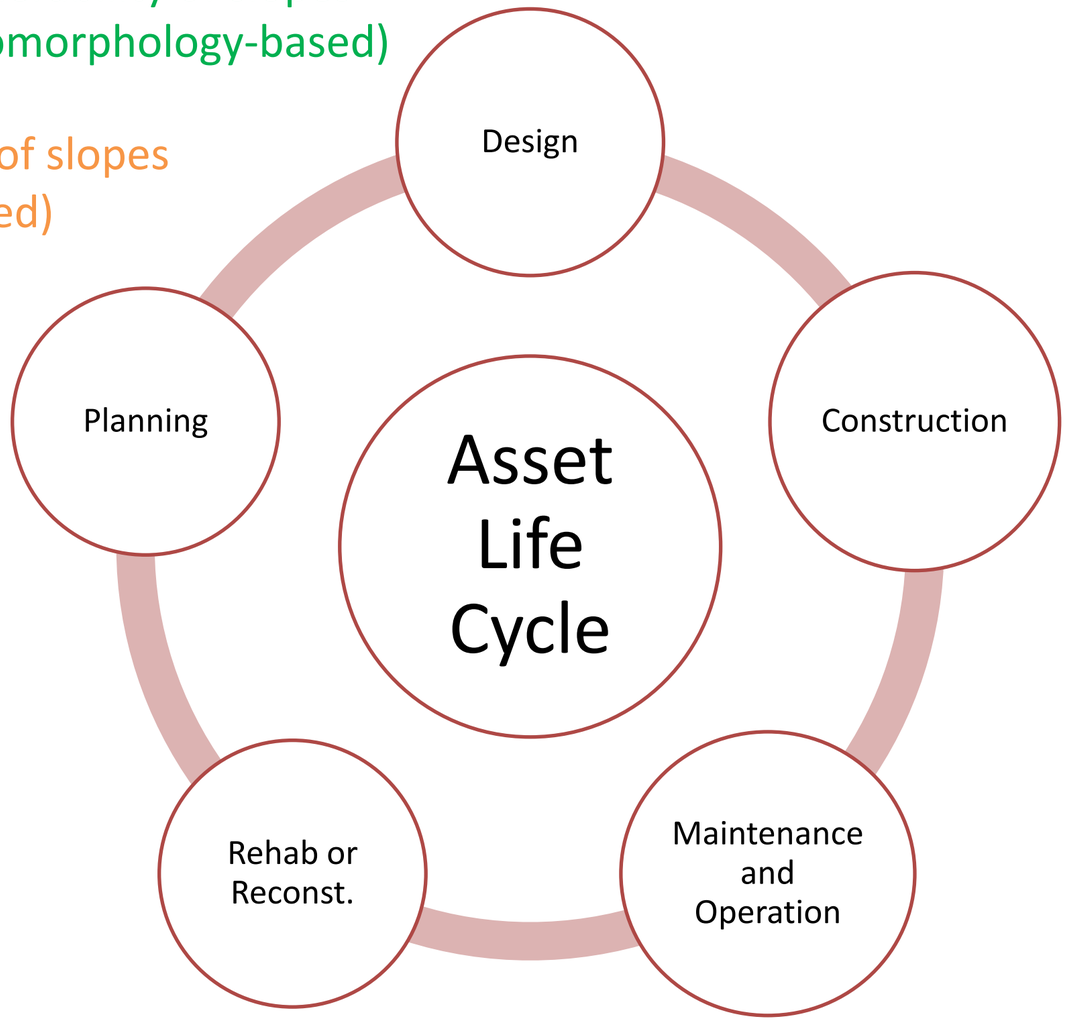

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Light Weight Deflectometer (LWD) for QA/QC of Pavement Foundations

MAXIMIZE STEWARDSHIP OF RESOURCES

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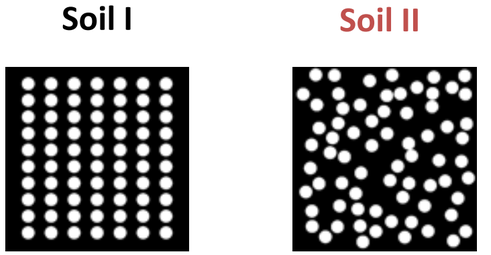
Density Does Not Determine Stiffness or Strength

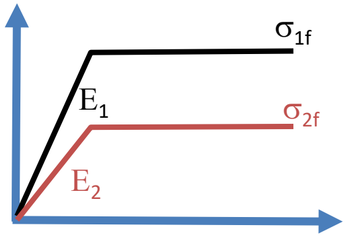


ρ_1 ρ_2

$$\rho_1 = \rho_2$$

However

$$E_1 \neq E_2 \quad \sigma_{1f} \neq \sigma_{2f}$$



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Compaction Compliance -> Options

MAXIMIZE STEWARDSHIP OF RESOURCES

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- Specified Density
  - Proctor Test
  - Moisture Test
  - Sand Cone Test
  - Nuclear Density Test
- Quality Compaction
- Penetration Index (DCP)
- Light Weight Deflectometer (LWD)
- Test Rolling

Two Methods:

- Deflection Based
- Modulus Based

DCP and LWD
Aggregate Base Target Values

Grading Number	Moisture Content	Dynamic Cone Penetrometer Target Value	Light Weight Deflectometer Target Value
	%	mm / drop	mm
3.1-3.5	5 - 7	10	0.38
	7 - 9	12	0.45
	9 - 11	16	0.60
3.6-4.0	5 - 7	10	0.38
	7 - 9	15	0.56
	9 - 11	19	0.71
4.1-4.5	5 - 7	13	0.49
	7 - 9	17	0.64
	9 - 11	21	0.79

https://www.dot.state.mn.us/materials/gradingandbase.html

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Compaction Compliance -> Options

MAXIMIZE STEWARDSHIP OF RESOURCES

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- Two Methods:
  - Deflection Based
  - Modulus Based

Specification	Material Type	Minimum Elastic Modulus [MPa]
2106	Granular	40
2106	Clay and Clay Loam	20
2211 or 2215	Base or Reclamation	50

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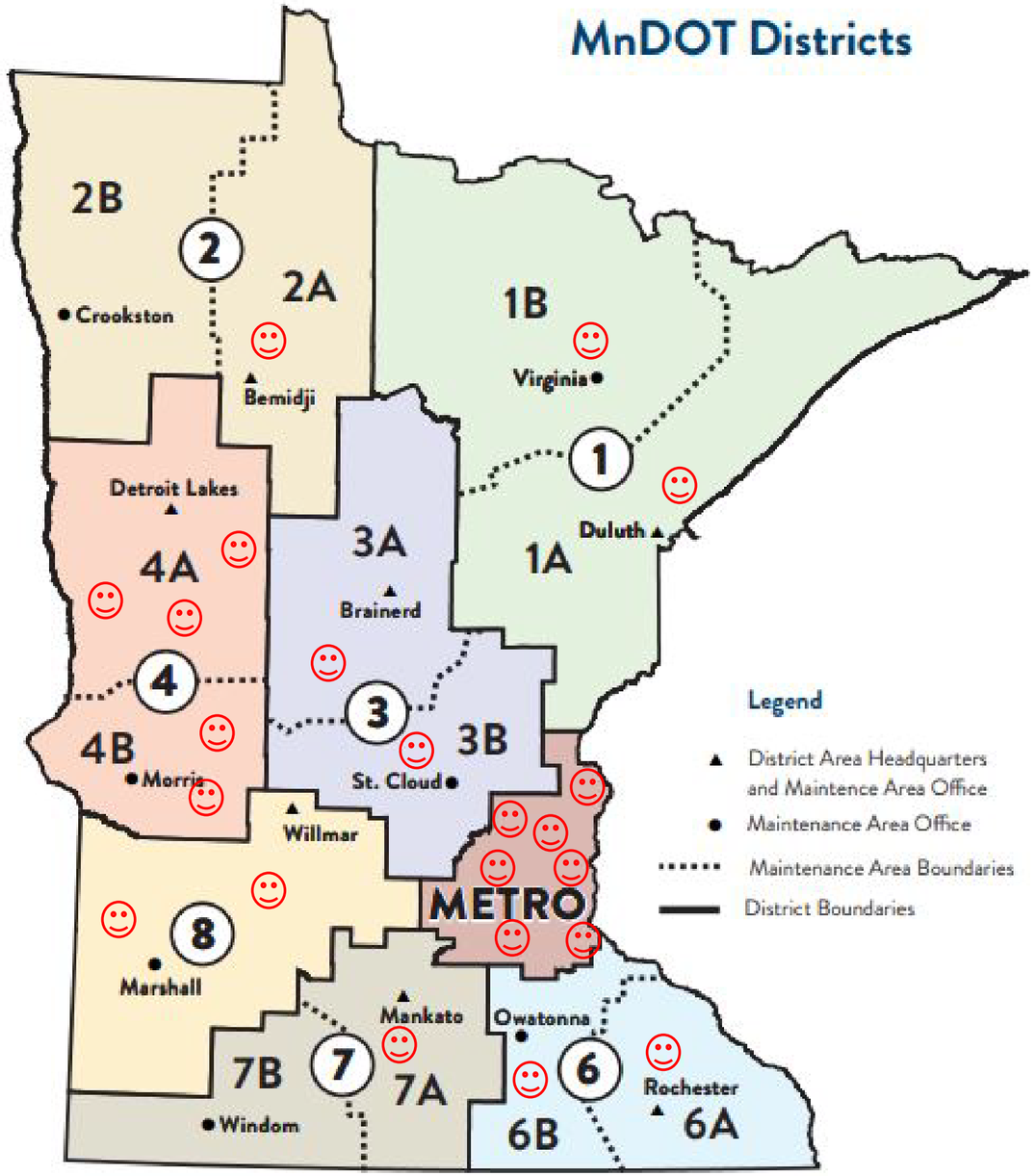
https://www.dot.state.mn.us/materials/gradingandbase.html

LWD Usage



Testing Constraints

- LWD cannot be used when:
  - Embankment thicknesses are less than 1 foot
  - Base or reclamation thicknesses are less than 4 inches
  - When testing within 3 feet of the water table
- Perform test after compaction
- Test when the air temperature is from 36 to 120 degrees Fahrenheit
- Ensure soil is not frozen

Light Weight Deflectometer (LWD) for QA/QC of Pavement Foundations

MAXIMIZE STEWARDSHIP OF RESOURCES

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- Avoid disconnect between Design, Specifications and Construction QC/QA
- Importance of fundamental engineering properties of materials such as stiffness and strength
  - ME based design procedures rely on E and σ_f not density
- Performance improved with more effective mechanistic QA/QC
- Quantify alternative materials and innovative construction practices
- Reward good construction practices

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Examples of Geotech Research Products

Completed + Ongoing

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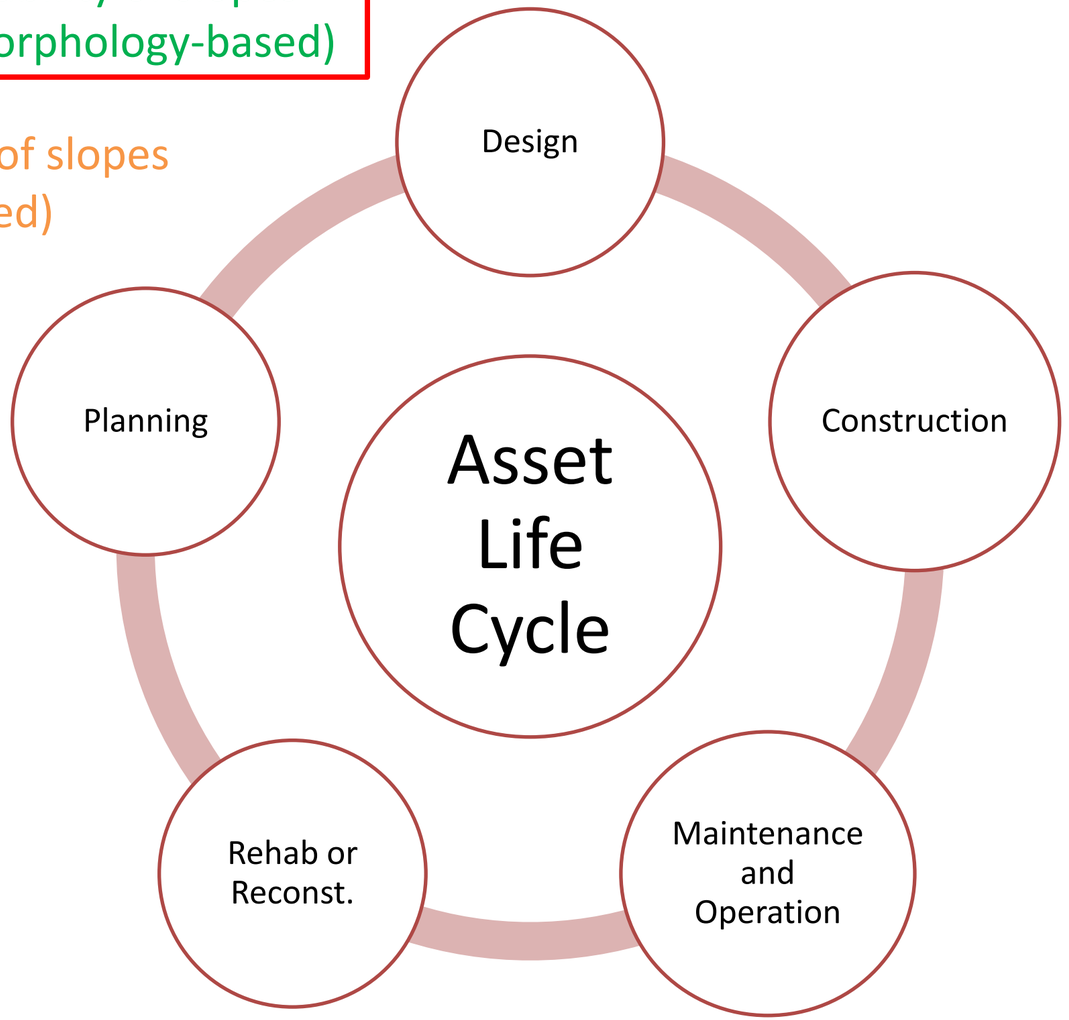

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MAXIMIZE STEWARDSHIP OF RESOURCES

CHAMPION SUSTAINABILITY ACTIONS

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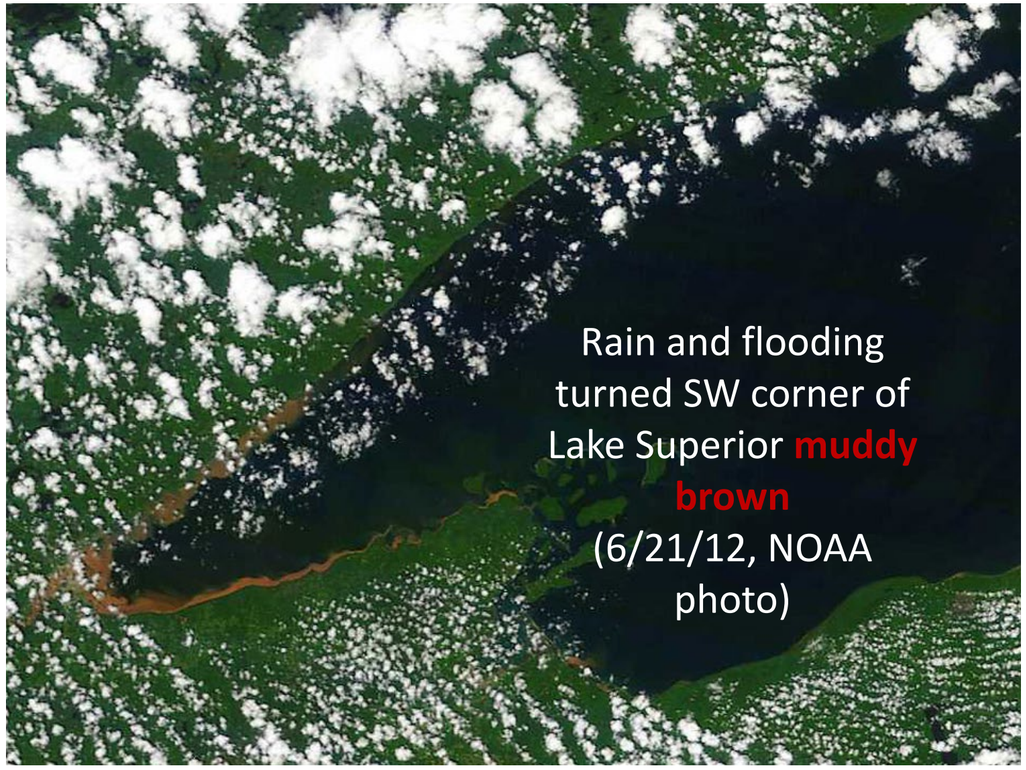
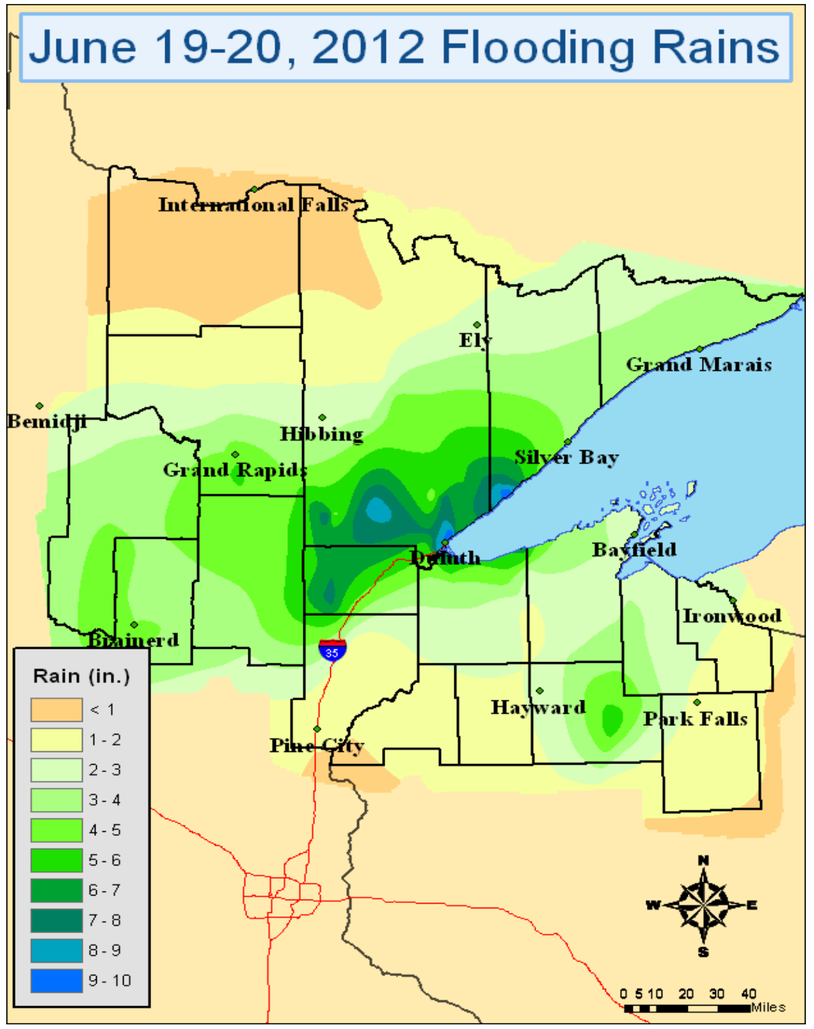
Rainy season in June 2012 in Minnesota caused slope failures and major damage in MN Trunk Highway (~ $50 million dollars in damage)





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Vulnerability of slopes (geomorphology-based)

MAXIMIZE STEWARDSHIP OF RESOURCES

CHAMPION SUSTAINABILITY ACTIONS

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- **26** Road Closures on Trunk Highway System
- Major team effort to bring system back:
  - MnDOT, DNR, DPS, Local Law Enforcement, FHWA, Consultants, Contractors.
- MnDOT Main Damage Areas:
  - TH-210 in Jay Cooke
  - TH-210 in Thomson
  - TH-23 in Fond du Lac
  - TH-2 from Proctor to I-35

Vulnerability of slopes (geomorphology-based)

MAXIMIZE STEWARDSHIP OF RESOURCES

CHAMPION SUSTAINABILITY ACTIONS

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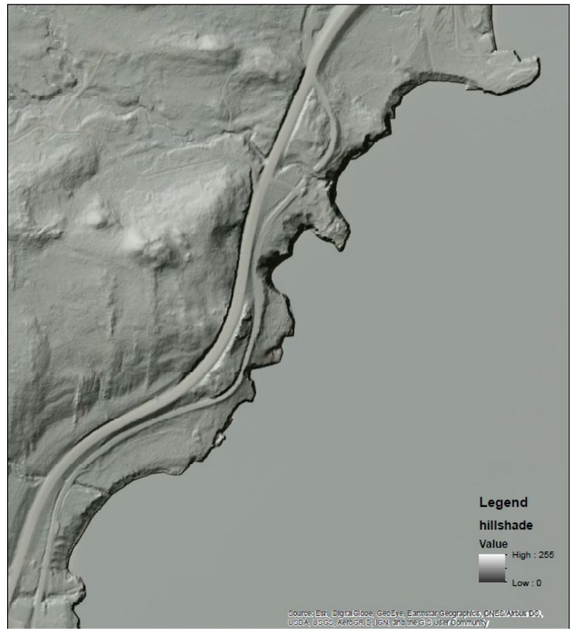
- *Assist engineers to proactively identify and mitigate slope risk along interstate highways*
  - Help during **project scoping** to **long range planning**
  - Enhance risk-based **asset management** decision making

Model assist in proactive identification of slope failures like deep-seated slide in TH-67

Geographic Information Systems (GIS) model that uses:

- **Geomorphology** of site among other key parameters to provide a *vulnerability rating score*
- **Geographic Weighted Regression (GWR)** to account for local variation of key parameters and minimized bias and subjectivity



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Vulnerability of slopes (geomorphology-based)

MAXIMIZE STEWARDSHIP OF RESOURCES

CHAMPION SUSTAINABILITY ACTIONS

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Model Development

1. Selection of preliminary input parameters (vulnerability factors) and interaction terms based on geomorphology and geology of region
2. Checking vulnerability rating using preliminary input parameters and historical slope failures (sensitivity analysis)
3. Selecting final input parameters (statistically significant)
4. Field verification of model
5. Further adjustment (if required)

Vulnerability Rating Score is computed with:

$$p = \frac{e^z}{1 + e^z}$$

$$z = \beta_o + \beta_1 X_1 + \cdots + \beta_n X_n$$

p= probability of slope failure (0 < p <1)

X_n=input parameters (independent variables)

β_n=regression coefficients from GWR

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Vulnerability of slopes (geomorphology-based)

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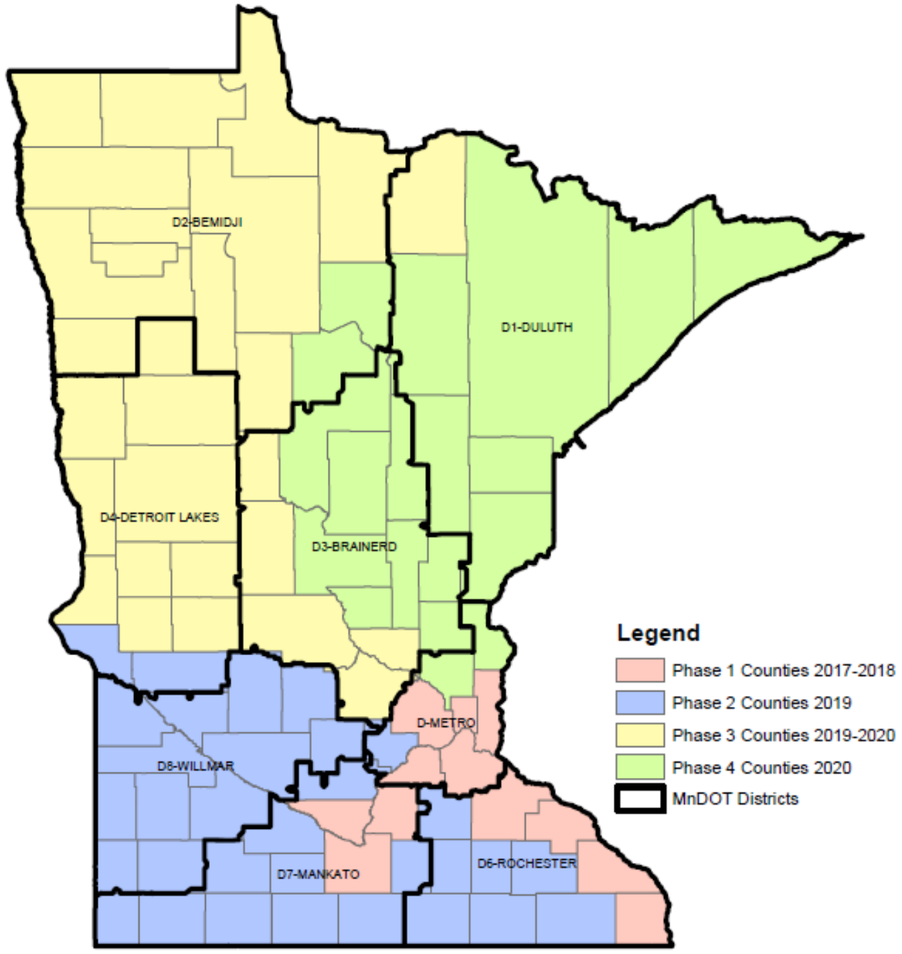
Model Development

- **Phase 1** - includes steep terrain and bedrock exposures
- **Phase 2** - contains steep slopes along river tributaries formed by catastrophic drainage of Glacial Lake Minnesota
- **Phase 3** - low relief and gradual slopes formed in bed of Glacial Lake Agassiz and glacially eroded and deposited landforms
- **Phase 4** - small mountain ranges with steep slopes and exposed bedrock and glacial till deposits that form gently rolling terrain



Final Input Parameters

- **Phase 1**
  - Slope angle
  - Terrain curvature
  - Distance to streams
  - Distance to bedrock outcrops
- **Phase 2**
  - Slope angle
  - Terrain curvature
  - Incision potential
  - Local relief
- **Phase 3**
  - Slope angle
  - Terrain curvature
  - Water table depth
- **Phase 4**
  - Slope angle
  - Slope orientation
  - Local relief
  - Bedrock proximity
  - Elevation

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Vulnerability of slopes (geomorphology-based)

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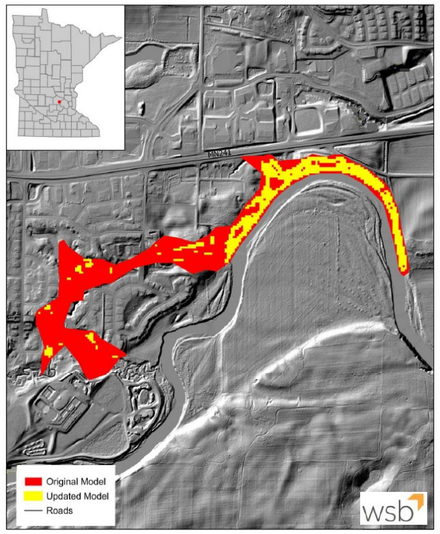
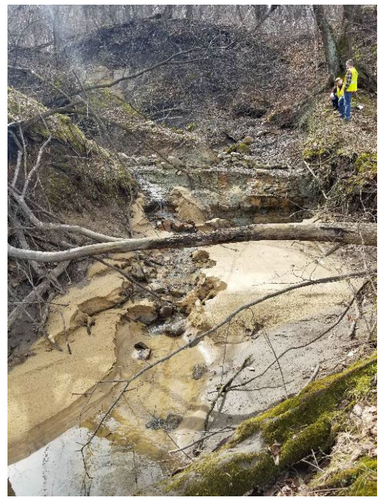
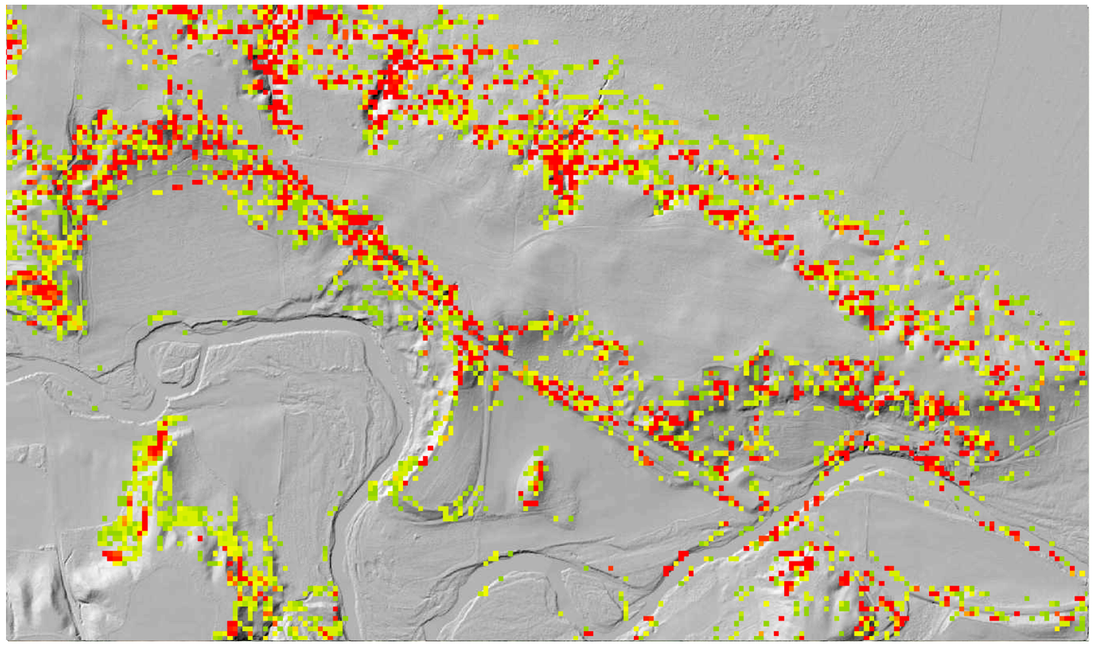
Field Verification





- Validation of final input parameters and vulnerability rating score
- Selection of sites with different geomorphology, geology, and hydrology

Example



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MAXIMIZE STEWARDSHIP OF RESOURCES

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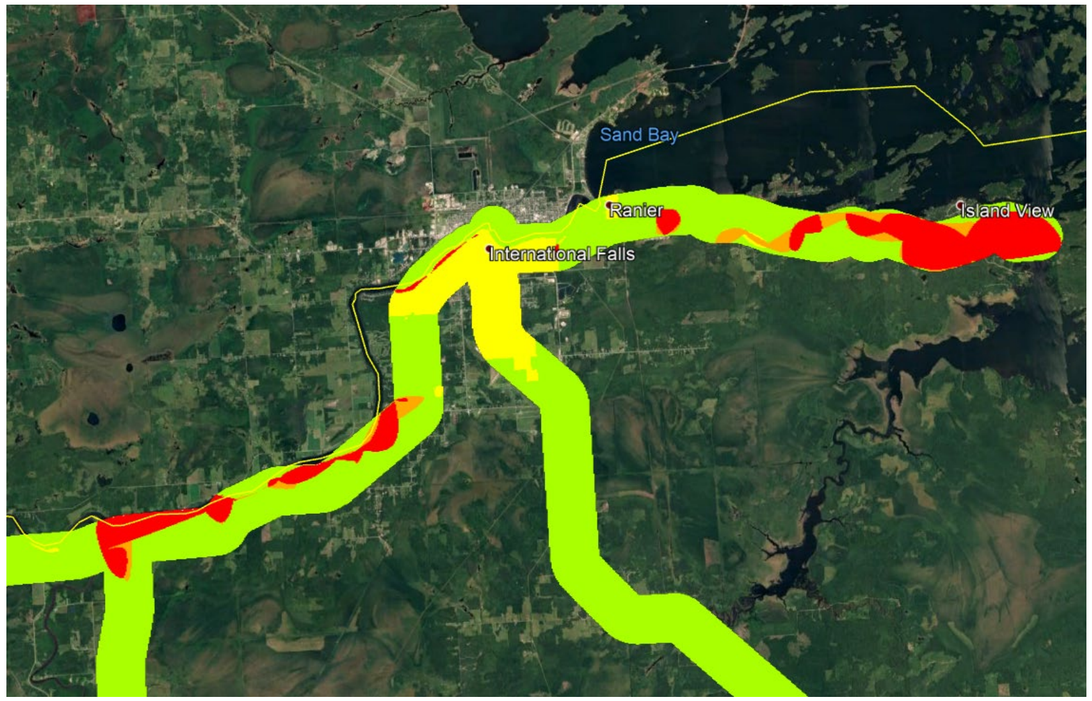
Preliminary Risk Ranking

				Consequence		
				Intersects Trunk Highways	Within 500 feet of Trunk Highways	More than 500 feet of Trunk Highways
				Within Metro or Incorporated Town	Rural	
	Slope Stability	Rational		Critical (5)	Serious (3)	Marginal (2)
LIKELIHOOD	Low	Slope is likely already experiencing mass failure or has the highest risk of failure.	Likely (4)	20 Site Visit / Action Recommended	12 Further Evaluation	8 Monitoring
	Medium	Surface erosion and other pre-cursors for catastrophic failure.	Possible (3)	15 Further Evaluation	9 Monitoring	6 No Action Recommended
	High	Slope has been repaired, recovered, or shows no signs of imminent future.	Unlikely (2)	10 Monitoring	6 No Action Recommended	4 No Action Recommended

Risk = Likelihood (model output) × Consequence (effect on infrastructure)



- Risk matrix used to create **Preliminary Management Areas**
- Preliminary Management Areas => *delineated areas in GIS with similar risk ranking*

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Vulnerability of slopes (geomorphology-based)

MAXIMIZE STEWARDSHIP OF RESOURCES

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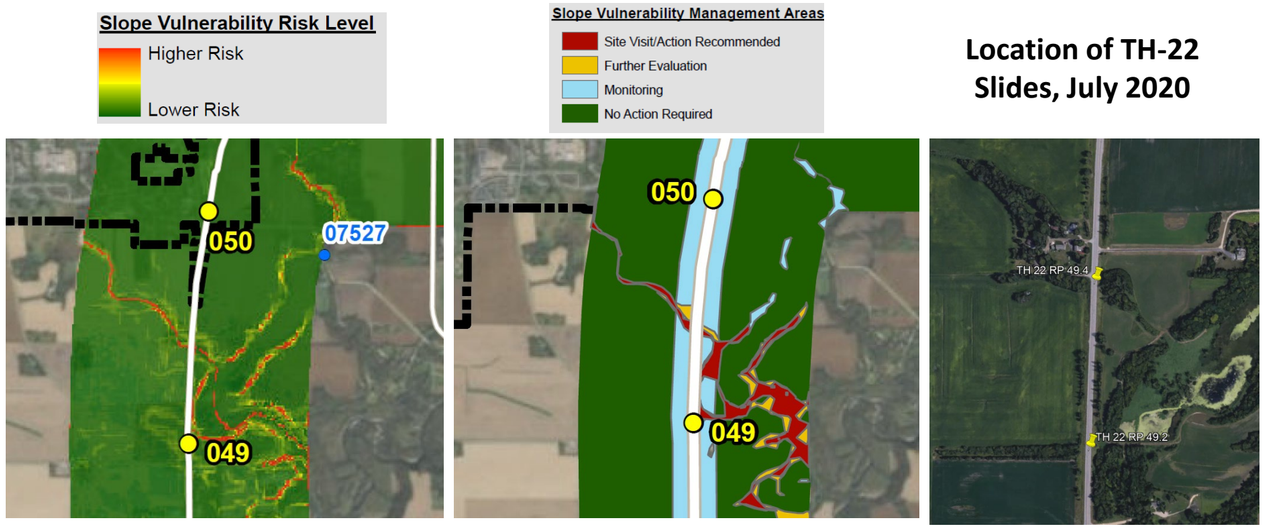
Verification of Model



Location of TH-22 Slides, July 2020

- GIS model helps identify, map and categorize slopes vulnerable to failure with potential to affect MnDOT highways
- Assist in risk evaluation during project development
- Model is data-driven (minimizes bias)
- Time efficient approach that can cover large geographic areas
- Can be used in Geotechnical Asset Management (GAM)

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Examples of Geotech Research Products

Completed + Ongoing

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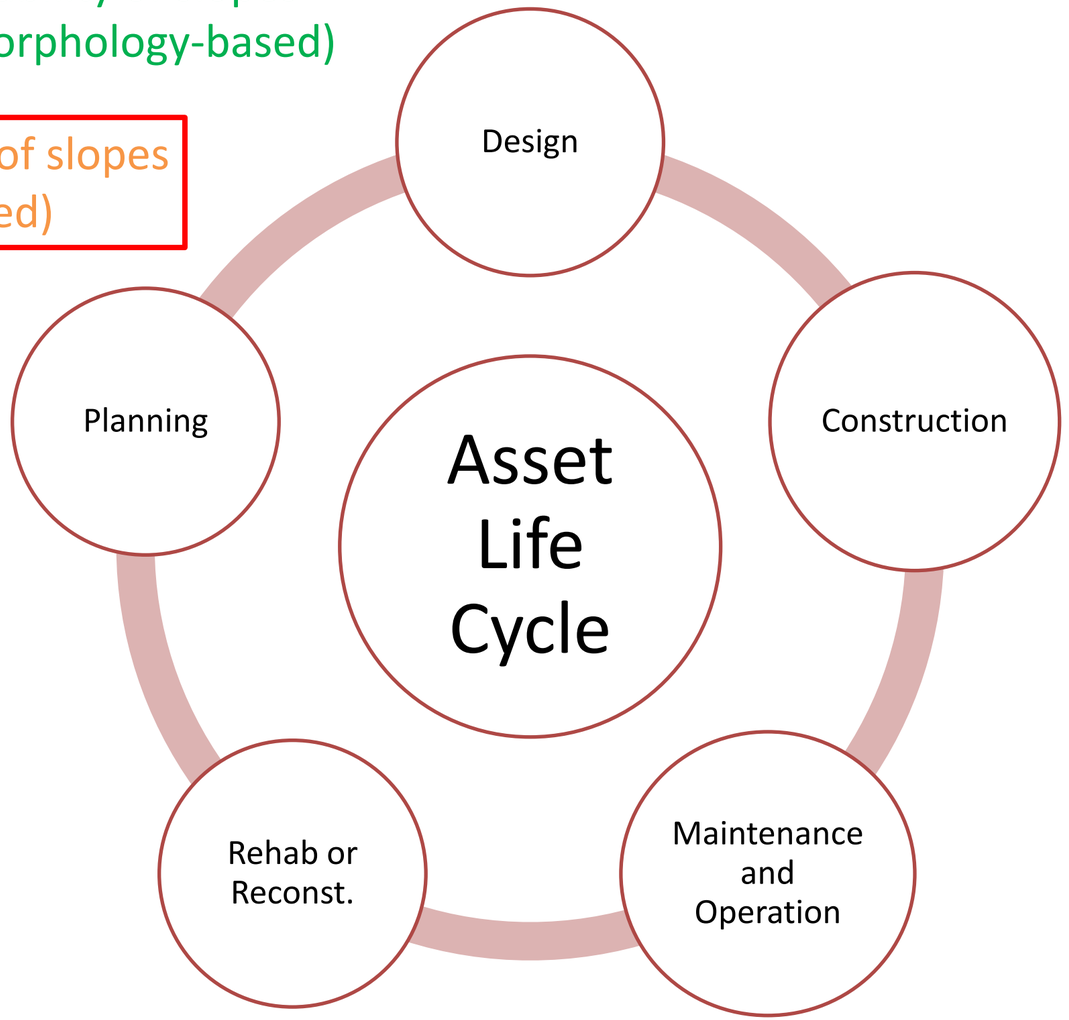

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MAXIMIZE STEWARDSHIP OF RESOURCES

CHAMPION SUSTAINABILITY ACTIONS

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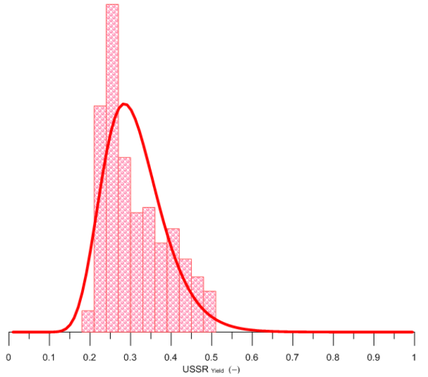
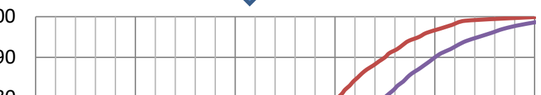
Motivation

1. Address recommendations and gaps from previous studies:
    - MnDOT Slope Vulnerability Phase I-IV
2. Help with implementation of advanced geotechnical tools such as 2D and 3D modeling software for slope stability (e.g., PLAXIS 3D)
3. Assess value of advanced remote sensing technologies such as UAVs for geotechnical applications
4. Improve quantification of risk via powerful numerical methods (commonly available)
5. Help with Geotechnical Asset Management (GAM) efforts
6. Internal Staff Development



Monte-Carlo + Geotech simulation



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Vulnerability of slopes (geotech-based)

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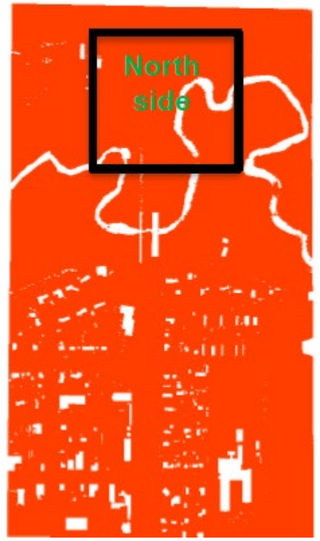
Climax, MN



Number of points: 155,702,365

Cropped: North side

Number of points: 15,241,847

Face count: 200,000

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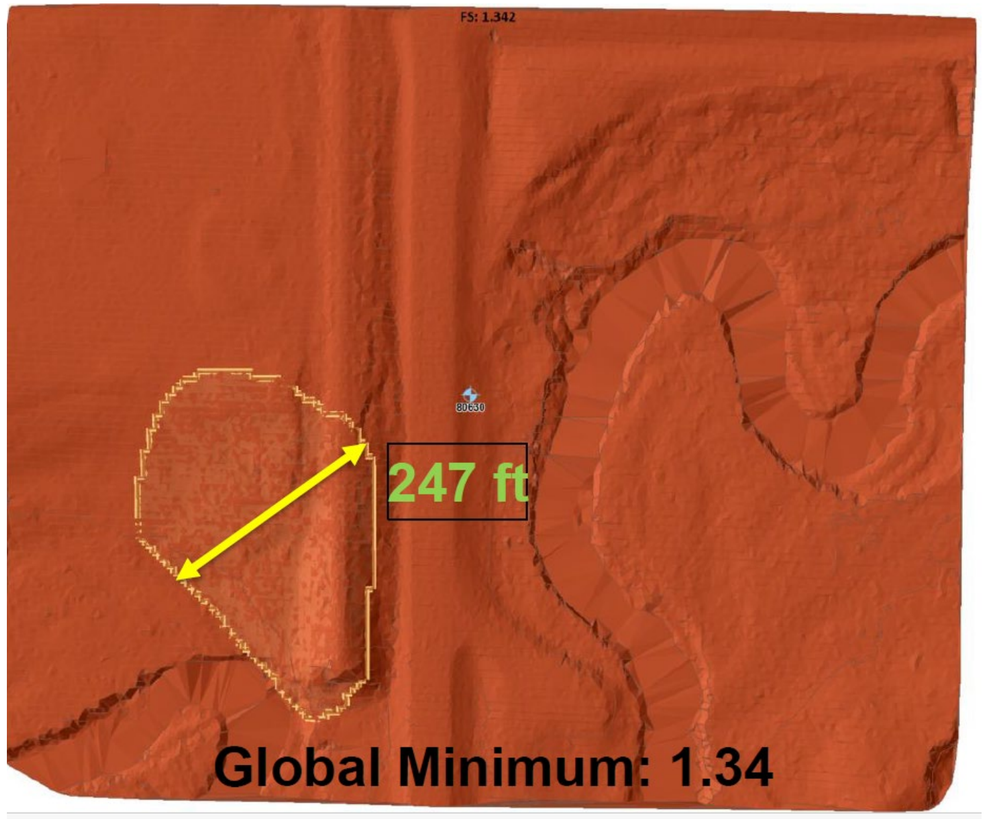
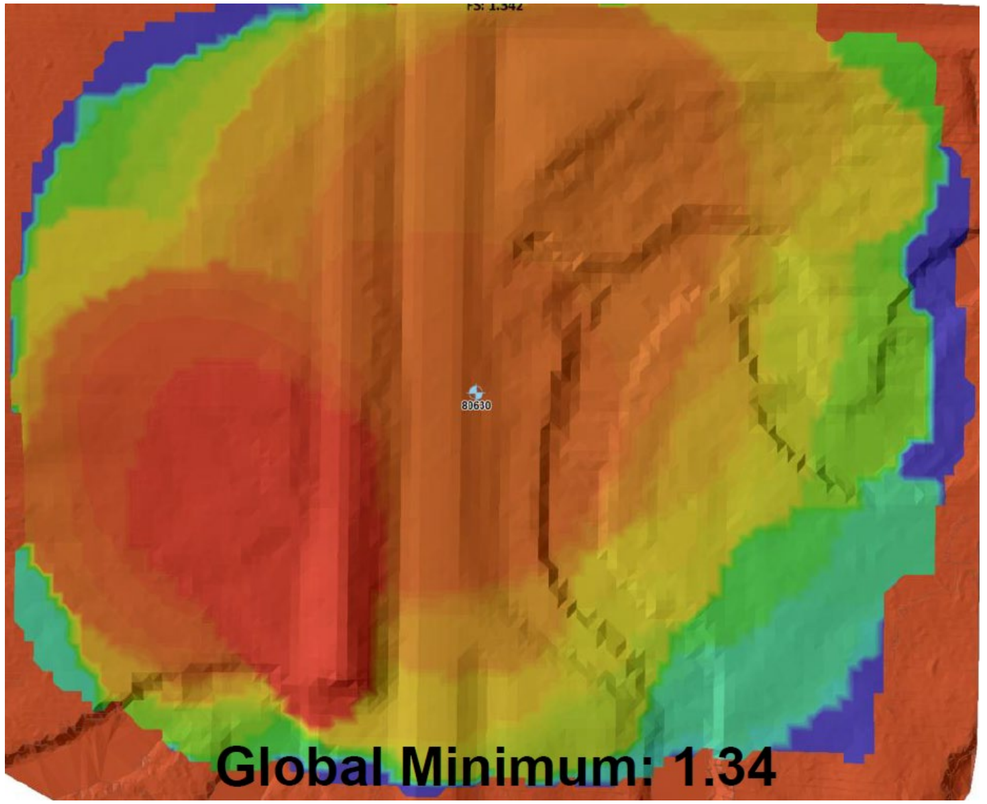
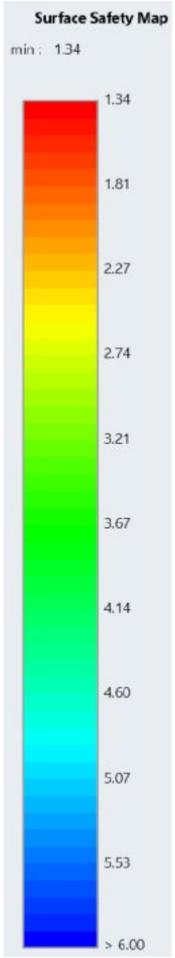
Climax, MN







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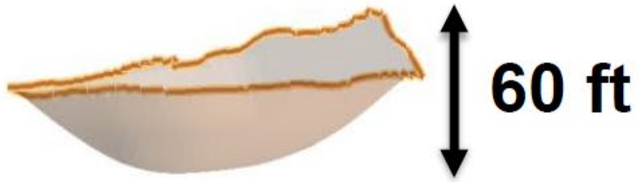
Climax, MN



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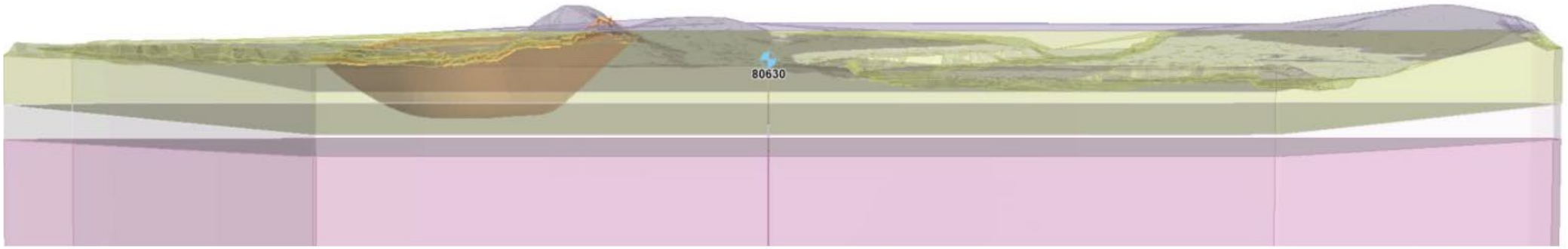

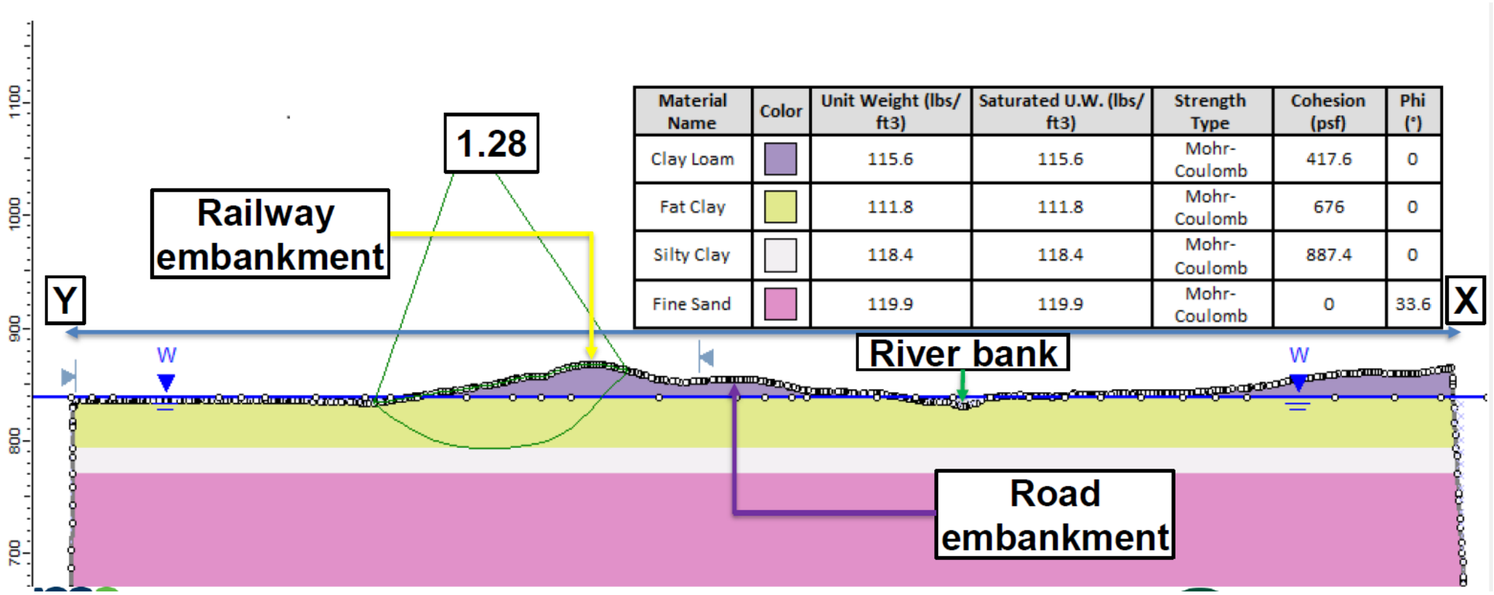

Material Name	Color	Unit Weight (lbs/ft3)	Saturated U.W. (lbs/ft3)	Strength Type	Cohesion (psf)	Phi (°)
Clay Loam		115.6	115.6	Mohr-Coulomb	417.6	0
Fat Clay		111.8	111.8	Mohr-Coulomb	676	0
Silty Clay		118.4	118.4	Mohr-Coulomb	887.4	0
Fine Sand		119.9	119.9	Mohr-Coulomb	0	33.6

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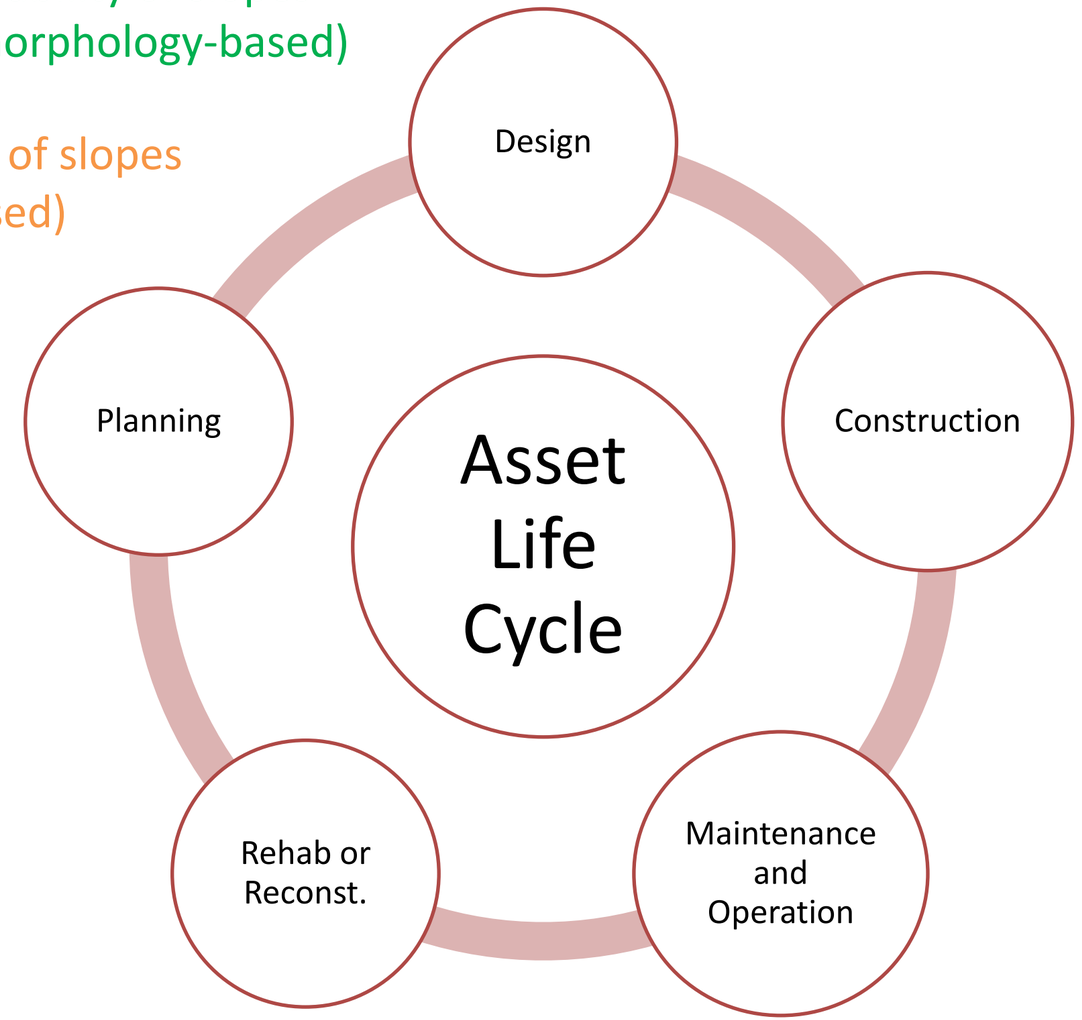

Light Weight Deflectometer (LWD) for QA/QC of Pavement Foundations

Pavement Foundation Uniformity (aka IC)

Pavement temperature as a surrogate of performance

DEPARTMENT OF TRANSPORTATION

Pavement Foundation Uniformity

MAXIMIZE STEWARDSHIP OF RESOURCES

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~15,000+ Sensors Installed

Temperature
~ 1 billion total values

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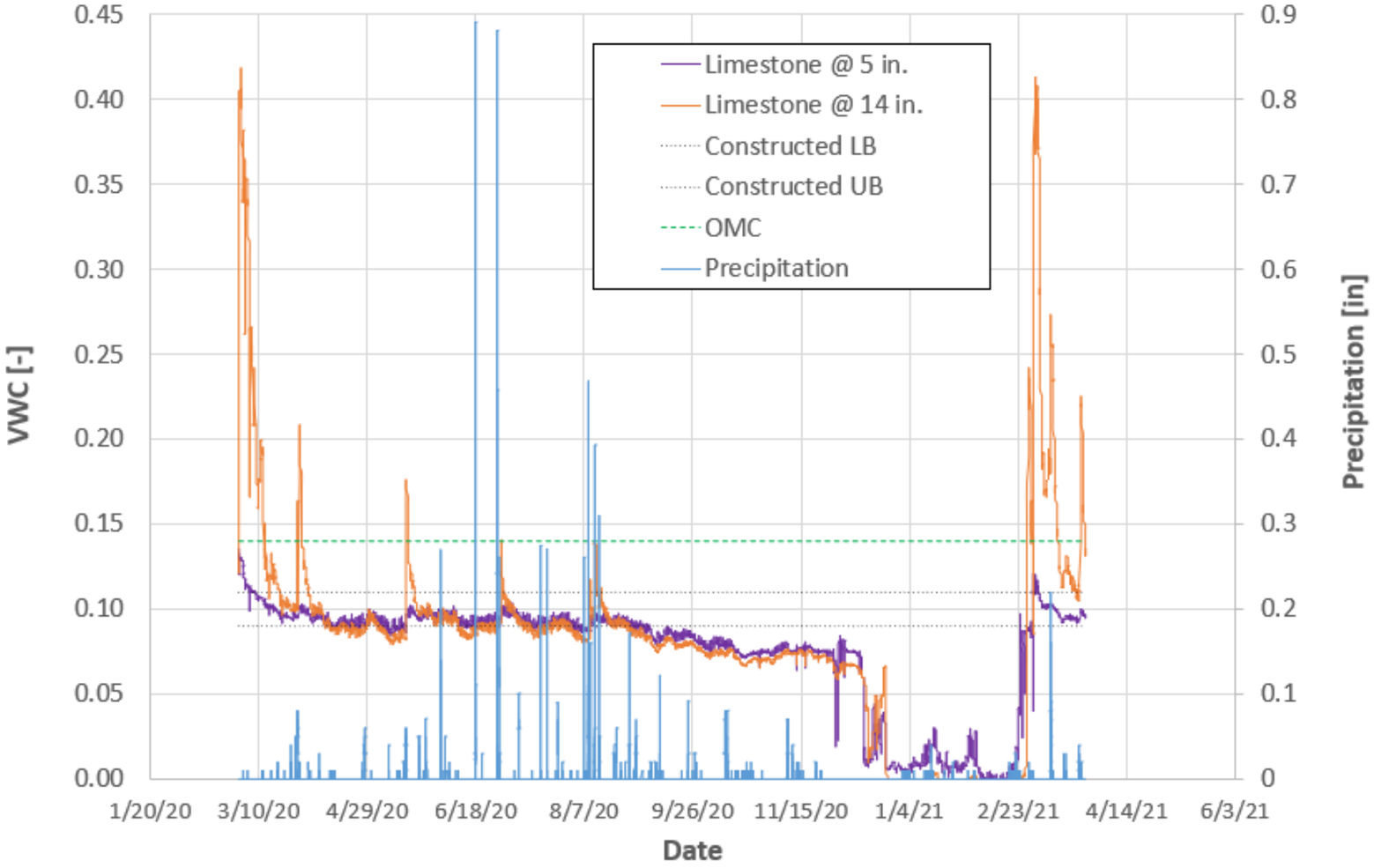
Example Moisture Monitoring @ MnROAD (Cell 127)



Pavement Foundation Uniformity

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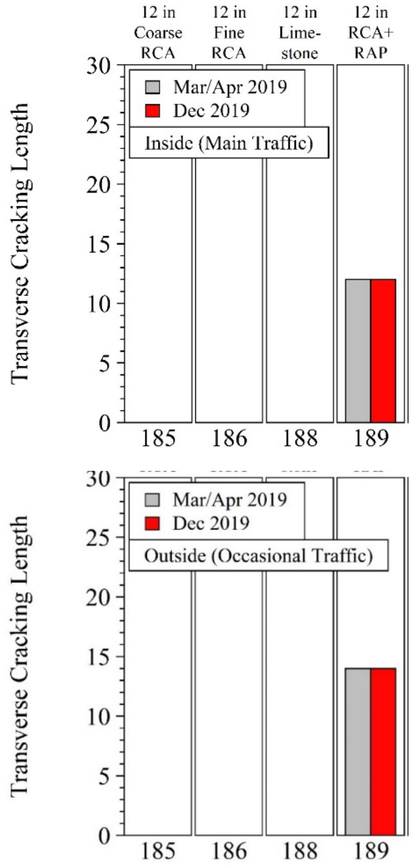
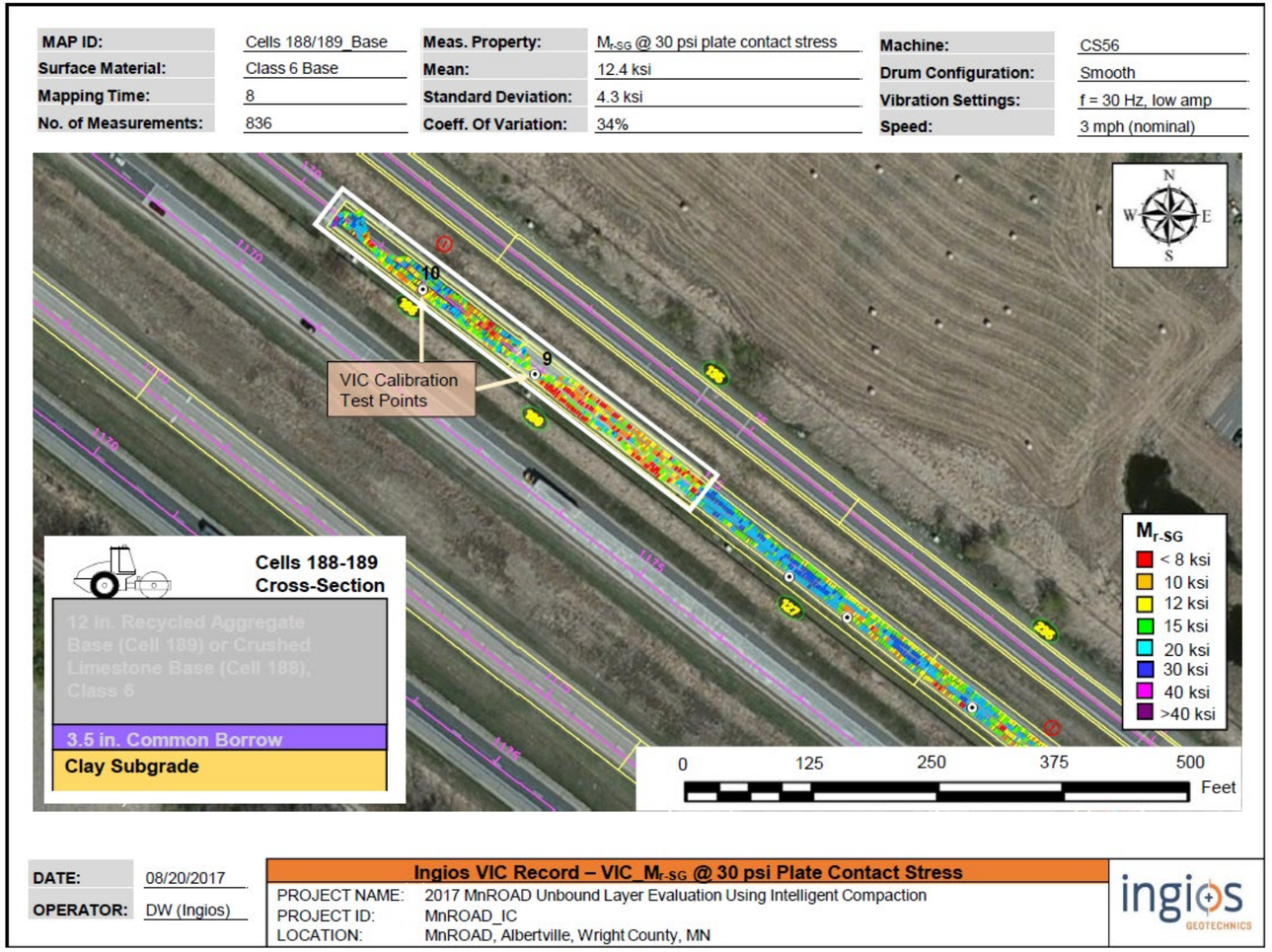
Led by: Prairie View A&M University





White and Vennapusa (2017)

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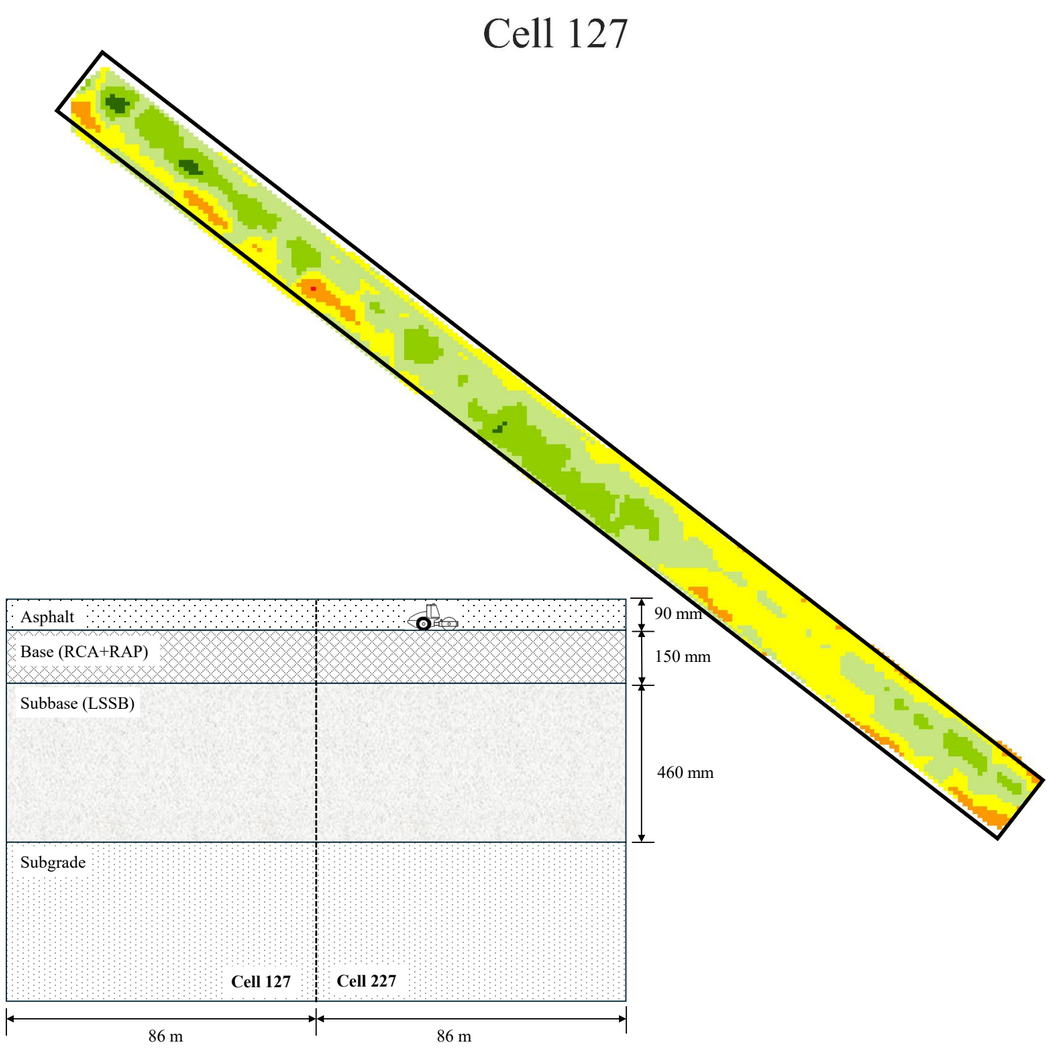

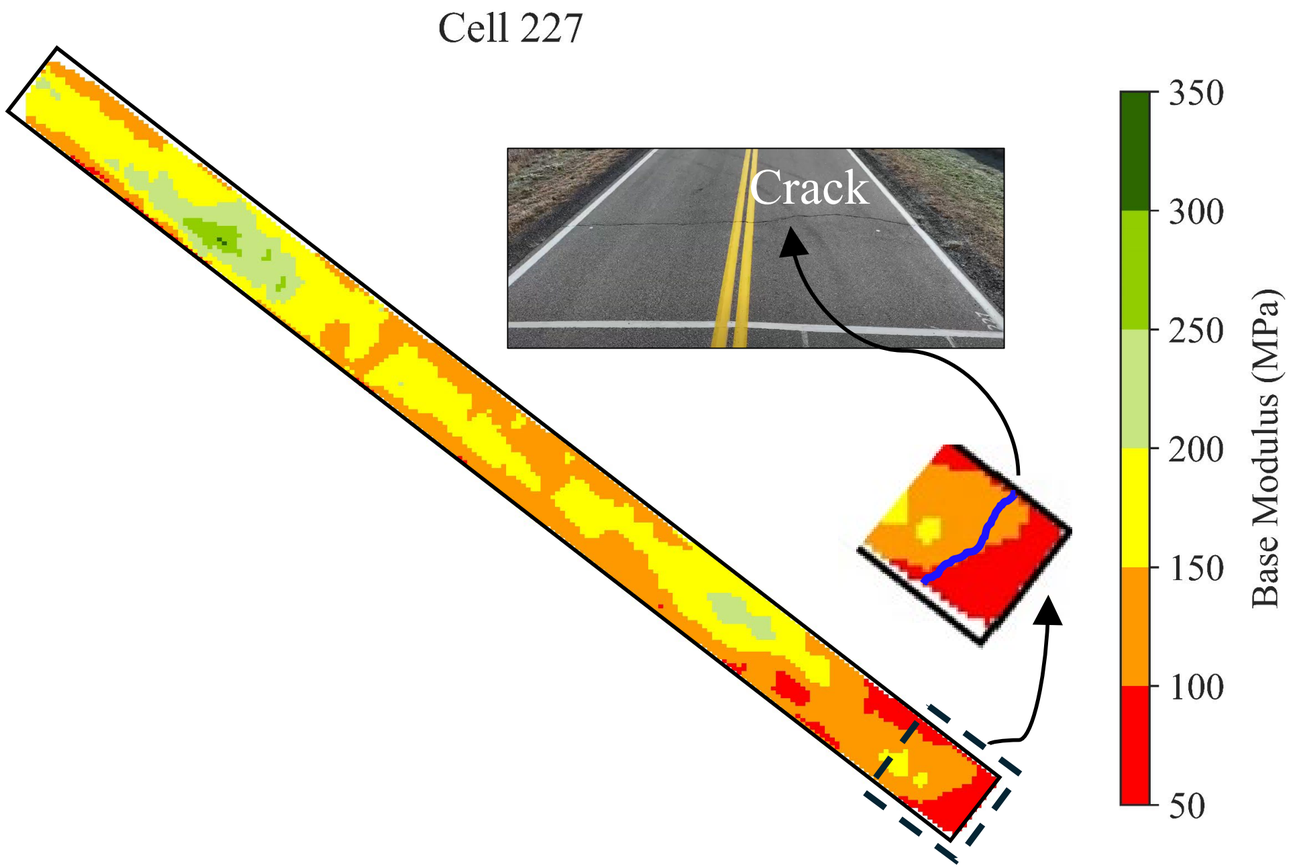

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*Sadiq, M., Velasquez, R., Aydin, C., Cetin, B., Izevbekhai, B. (2025), Influence of Initial Stiffness and Foundation Uniformity on Pavement Performance, IJPE

Pavement Foundation Uniformity

MAXIMIZE STEWARDSHIP OF RESOURCES

National Center for INFRASTRUCTURE TRANSFORMATION
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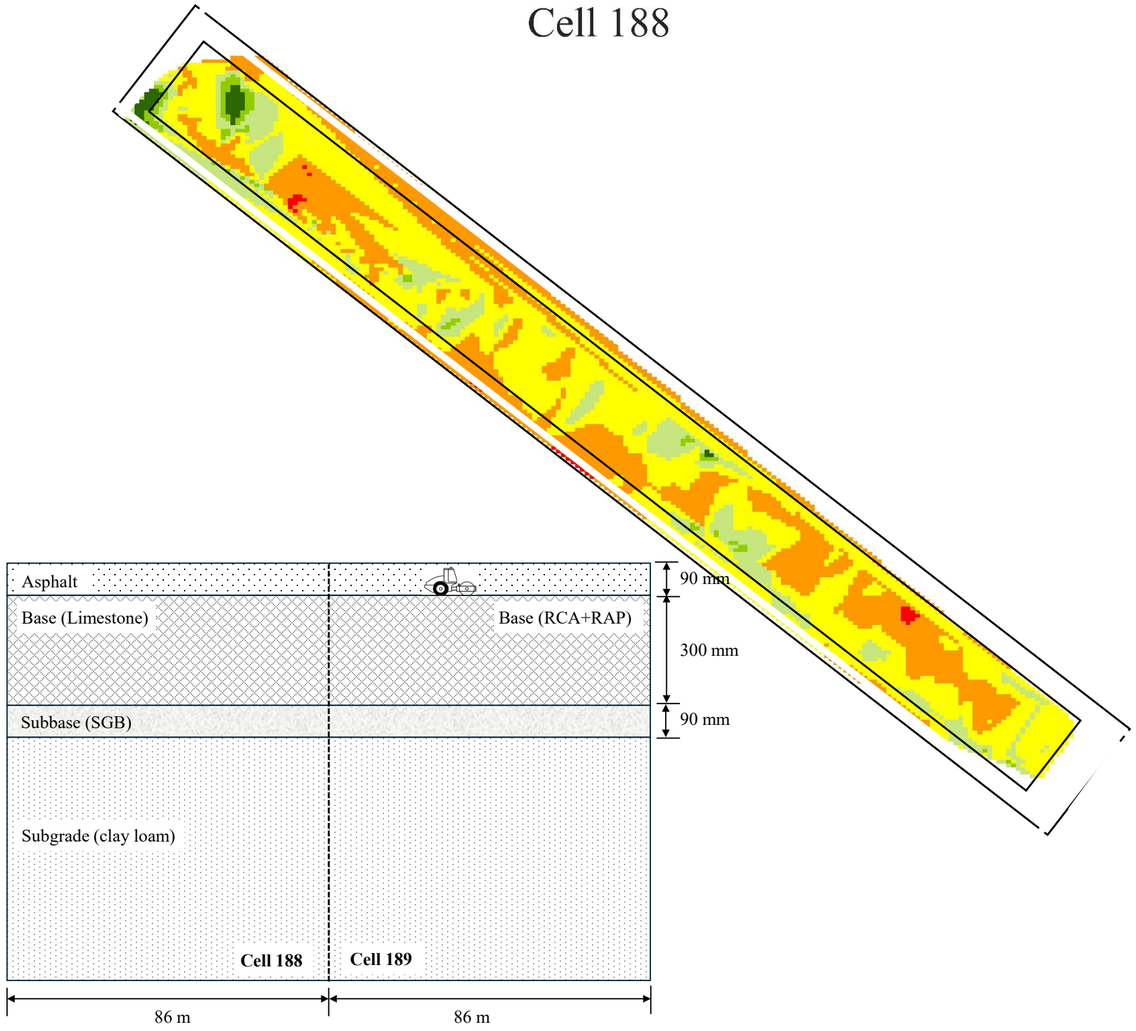

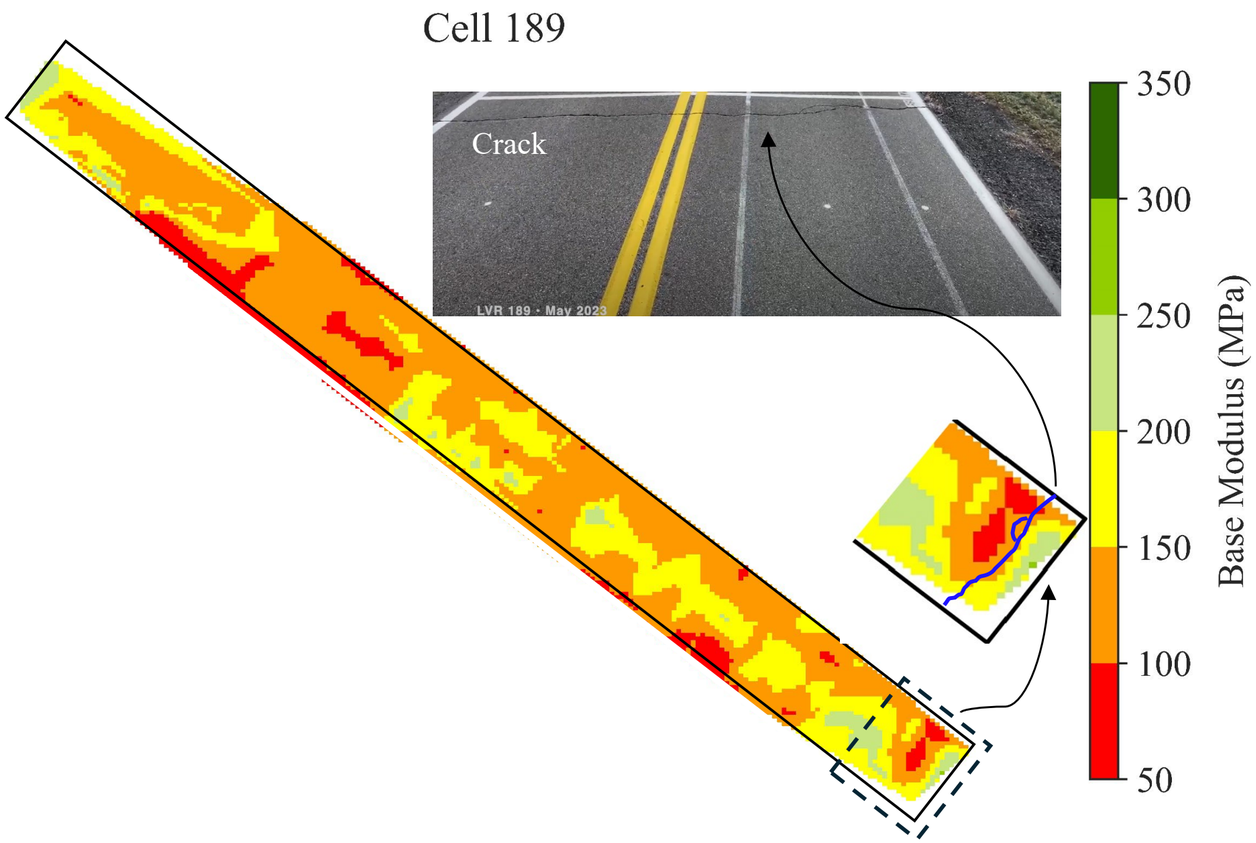

DEPARTMENT OF TRANSPORTATION

*Sadiq, M., Velasquez, R., Aydin, C., Cetin, B., Izevbekhai, B. (2025), Influence of Initial Stiffness and Foundation Uniformity on Pavement Performance, IJPE

Examples of Geotech Research Products

Completed + Ongoing

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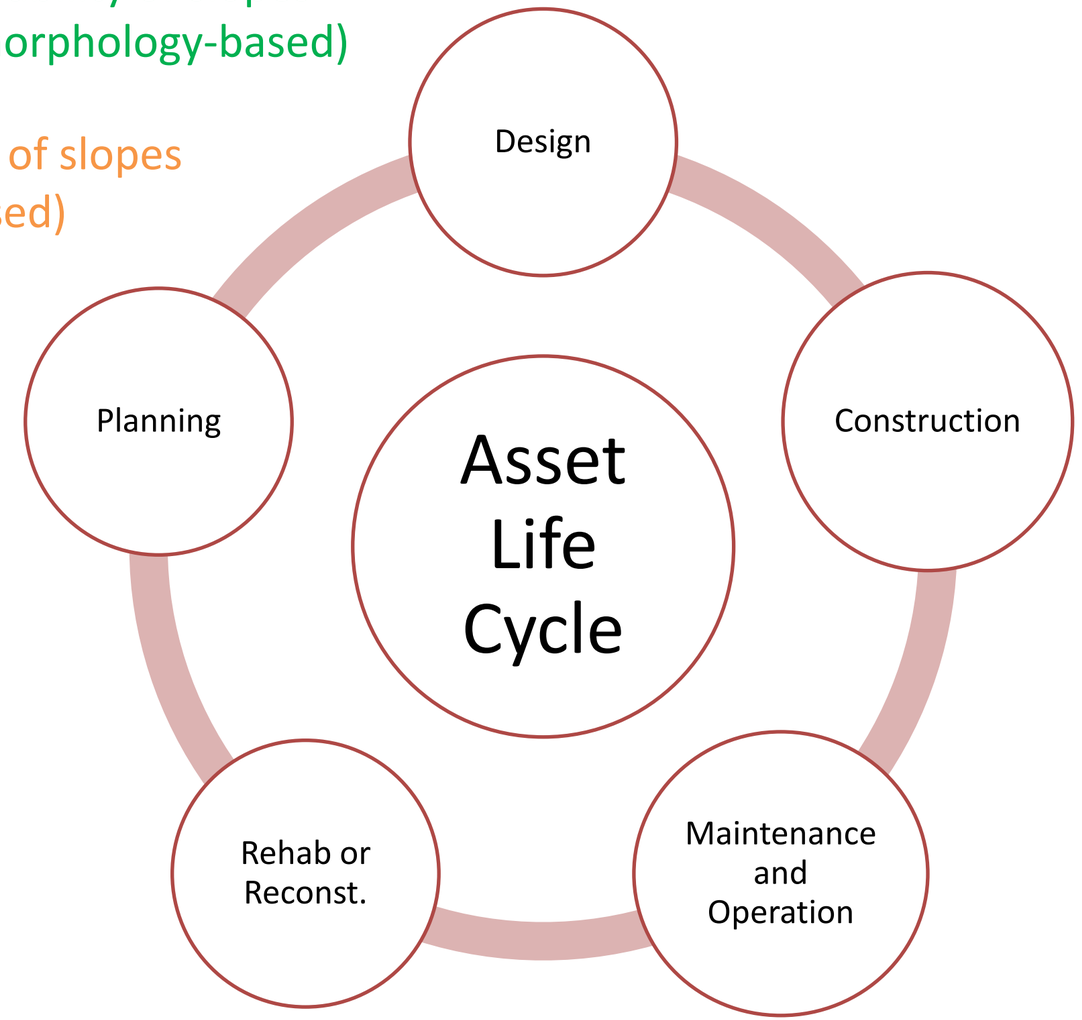
Vulnerability of slopes (geomorphology-based)

Vulnerability of slopes (geotech-based)



Light Weight Deflectometer (LWD) for QA/QC of Pavement Foundations

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Pavement temperature as a surrogate of performance

DEPARTMENT OF TRANSPORTATION

Pavement temperature as a surrogate of performance

MAXIMIZE STEWARDSHIP OF RESOURCES

CHAMPION SUSTAINABILITY ACTIONS

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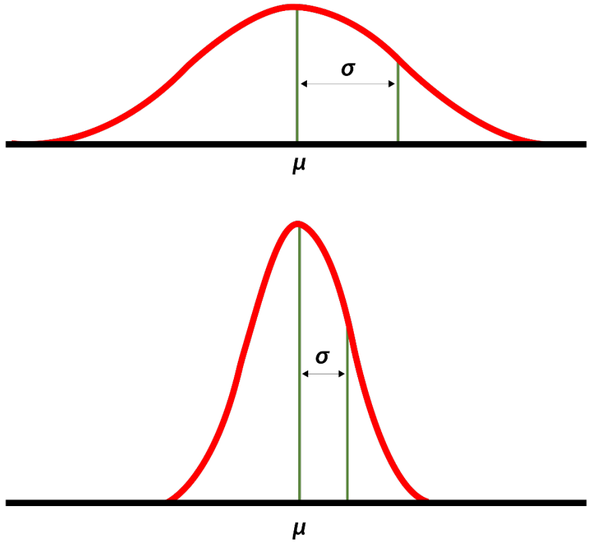
Processing Data with Descriptive Statistics:



Mean
Max
Min
Median
Variance
Standard Deviation
Kurtosis
Skewness
Range

DEPARTMENT OF TRANSPORTATION

Pavement temperature as a surrogate of performance

MAXIMIZE STEWARDSHIP OF RESOURCES

CHAMPION SUSTAINABILITY ACTIONS

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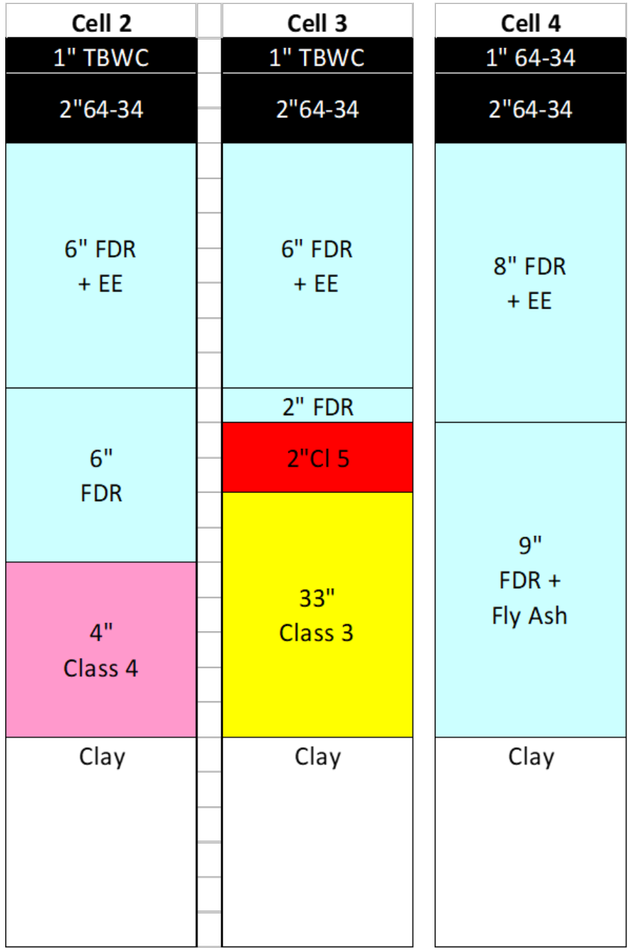
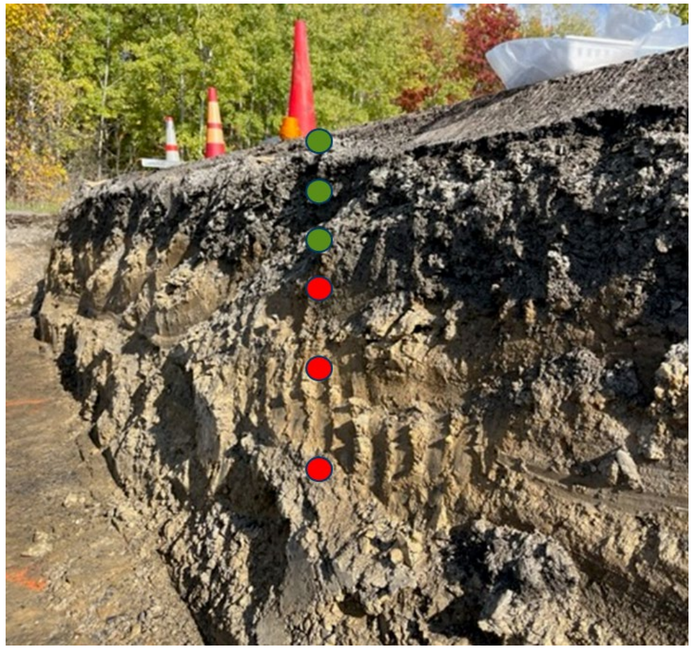
- Collected data from 3 flexible pavement test sections
  - Built on different foundations such as aggregate, Full Depth Reclamation (FDR) and Stabilized Full Depth Reclamation (SFDR)
  - Test section 2 and 3 have proper drainage vs Test section 4 that is directly on top of clay layer





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Pavement temperature as a surrogate of performance

MAXIMIZE STEWARDSHIP OF RESOURCES

CHAMPION SUSTAINABILITY ACTIONS

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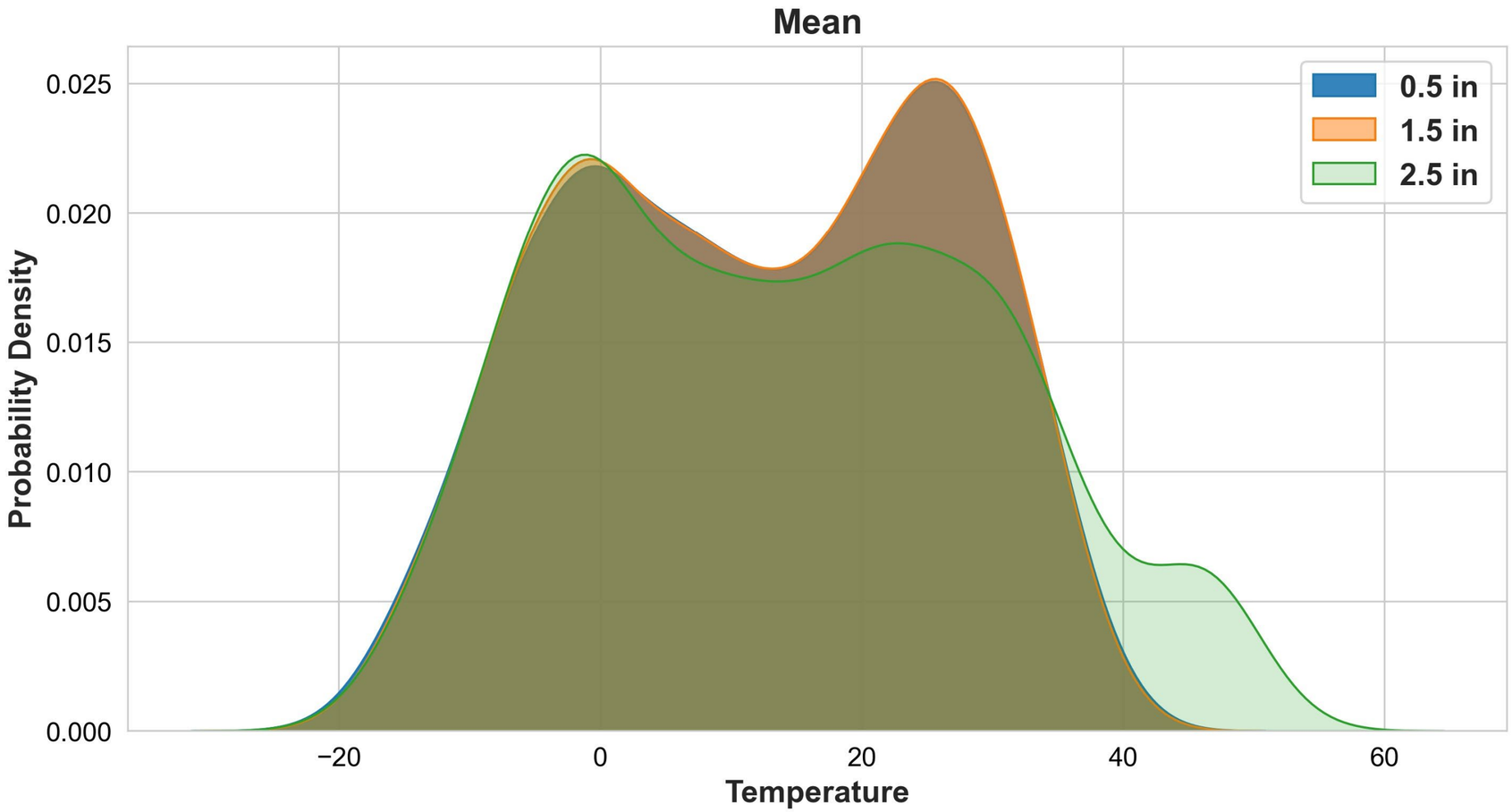
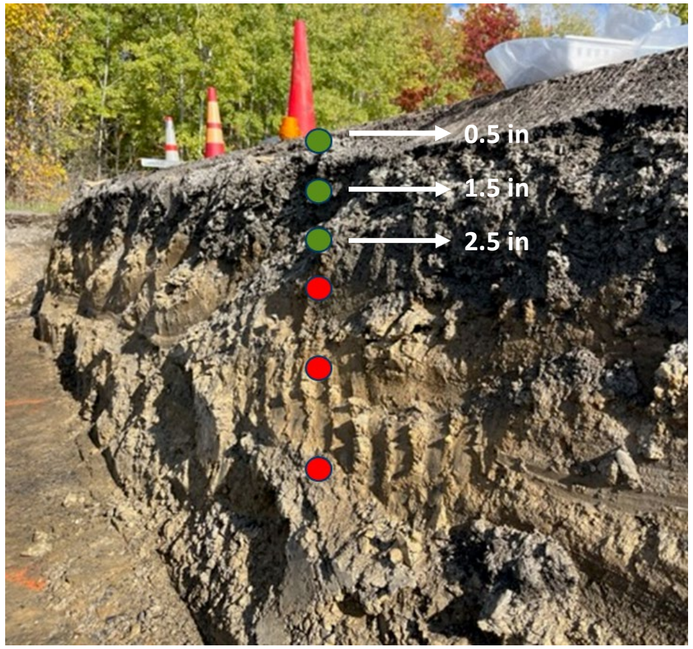
Cell 4





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Pavement temperature as a surrogate of performance

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CHAMPION SUSTAINABILITY ACTIONS

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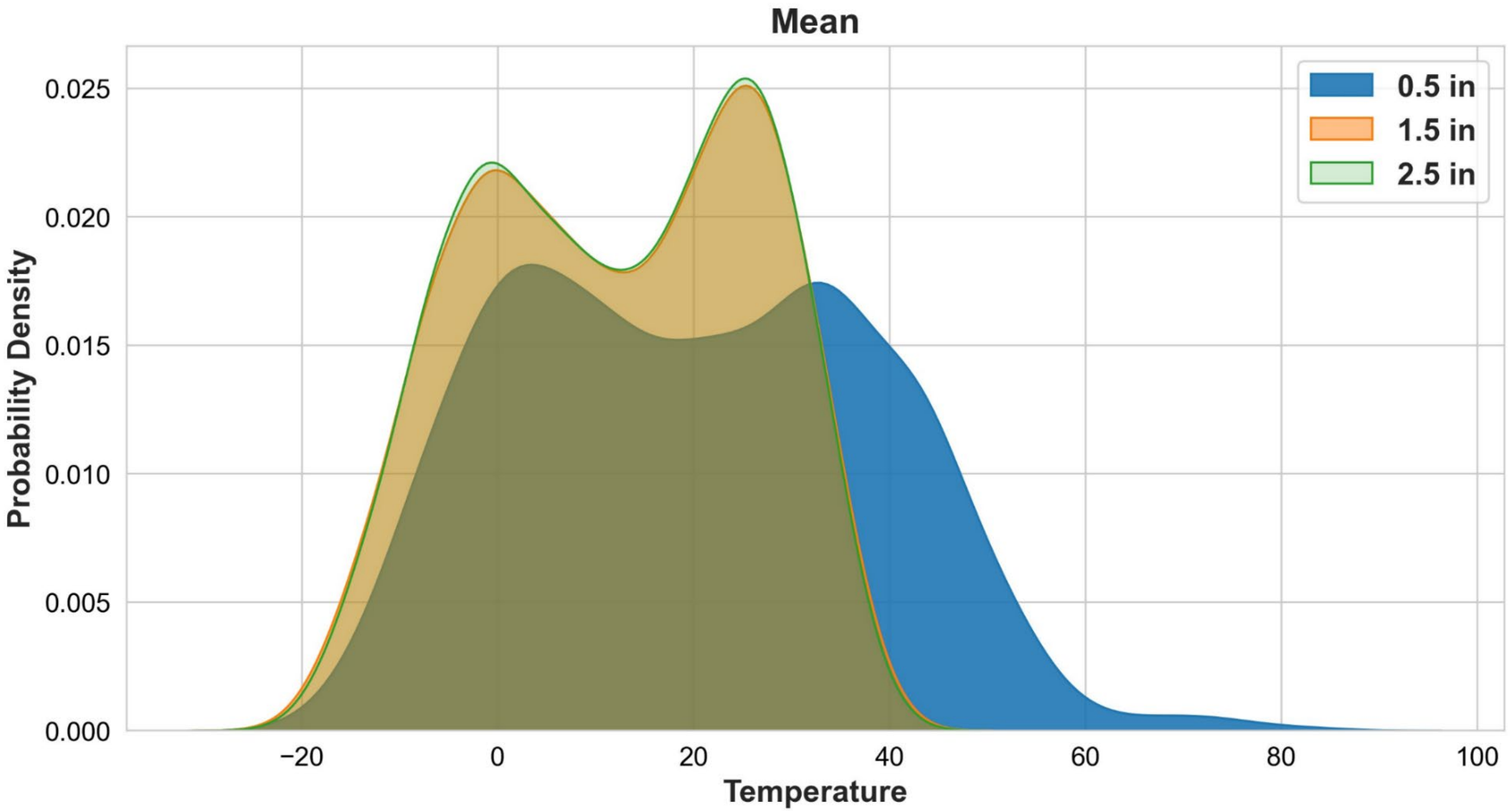
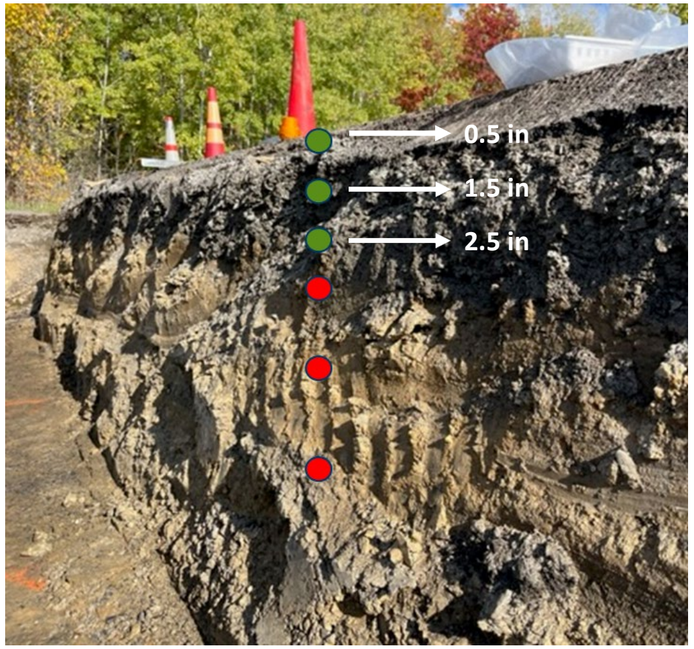
Cell 3





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Pavement temperature as a surrogate of performance

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CHAMPION SUSTAINABILITY ACTIONS

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Pavement – Test Sections 2 and 3

Pavement – Test Section 4

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Pavement temperature as a surrogate of performance

MAXIMIZE STEWARDSHIP OF RESOURCES

CHAMPION SUSTAINABILITY ACTIONS

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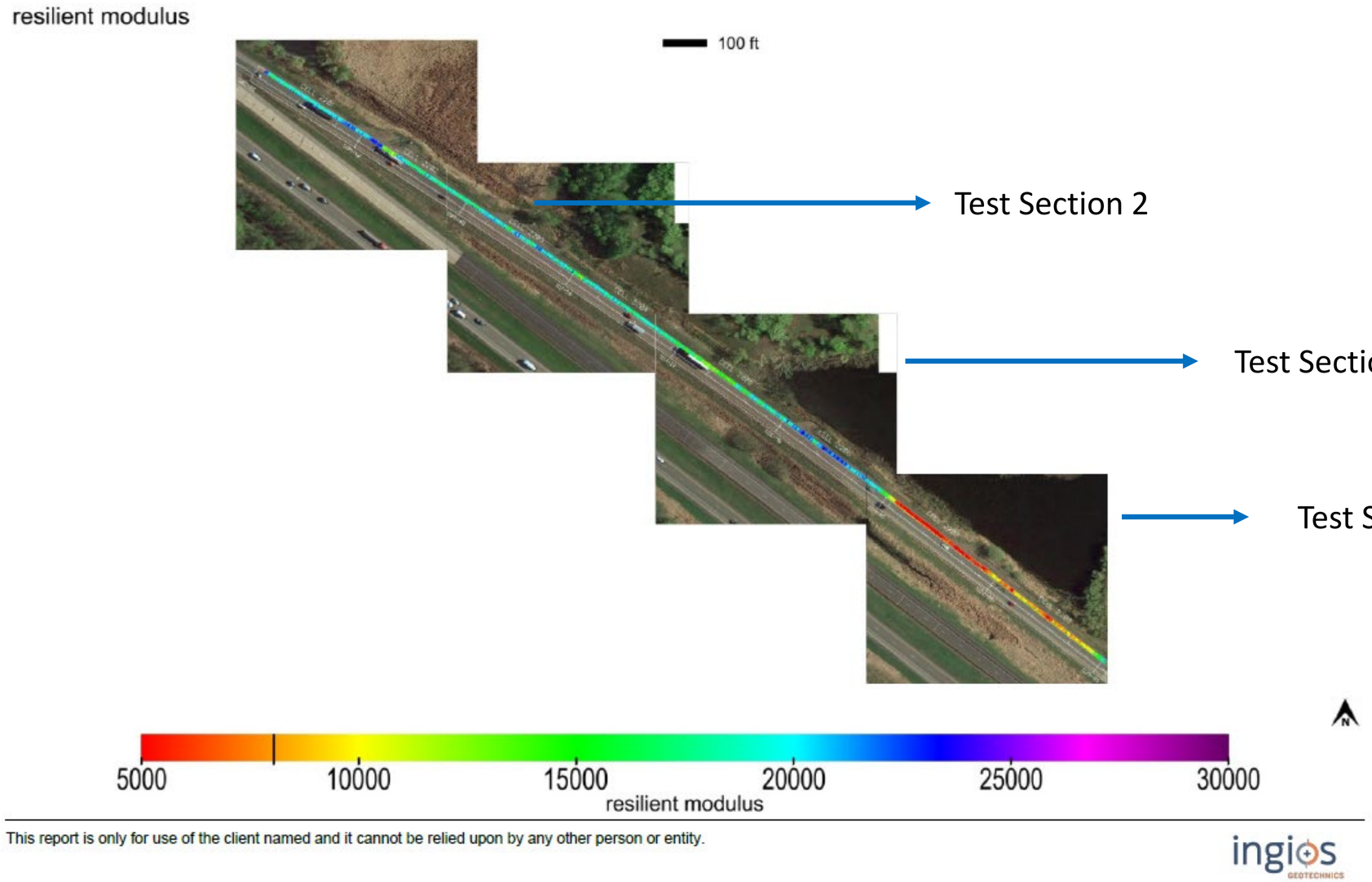

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Pavement temperature as a surrogate of performance

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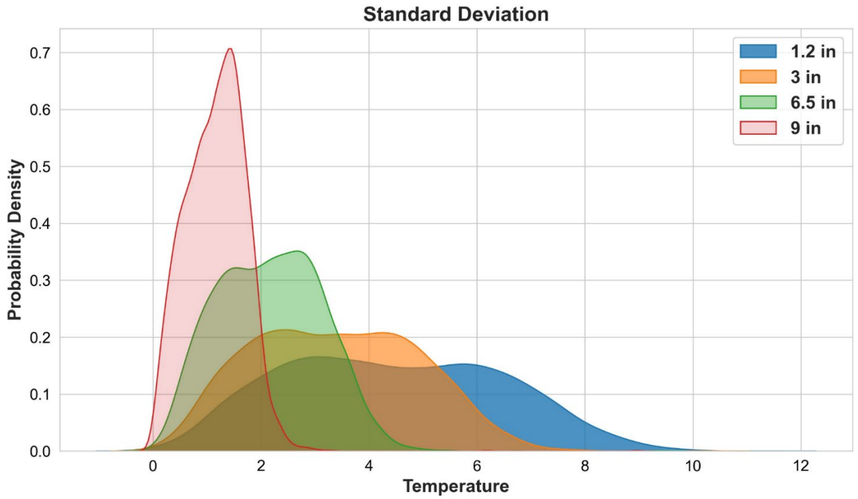

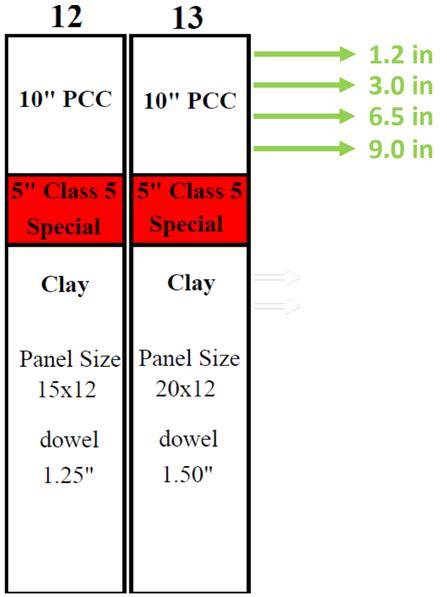

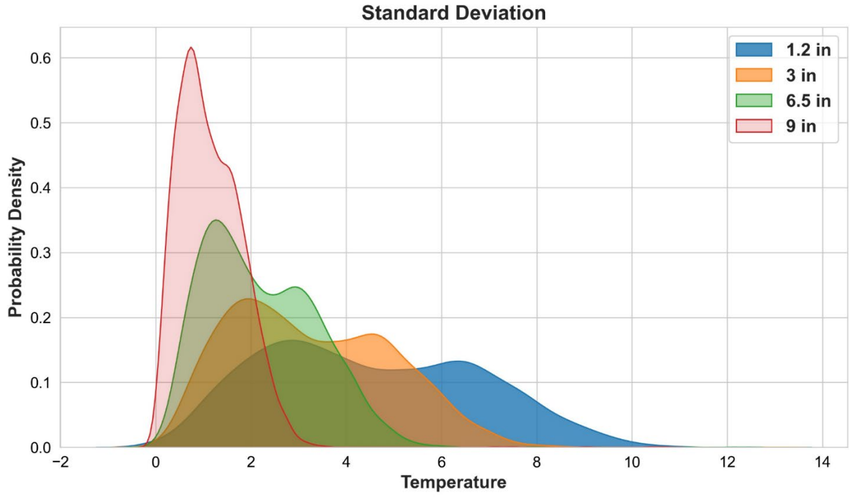

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Pavement temperature as a surrogate of performance

MAXIMIZE STEWARDSHIP OF RESOURCES

CHAMPION SUSTAINABILITY ACTIONS

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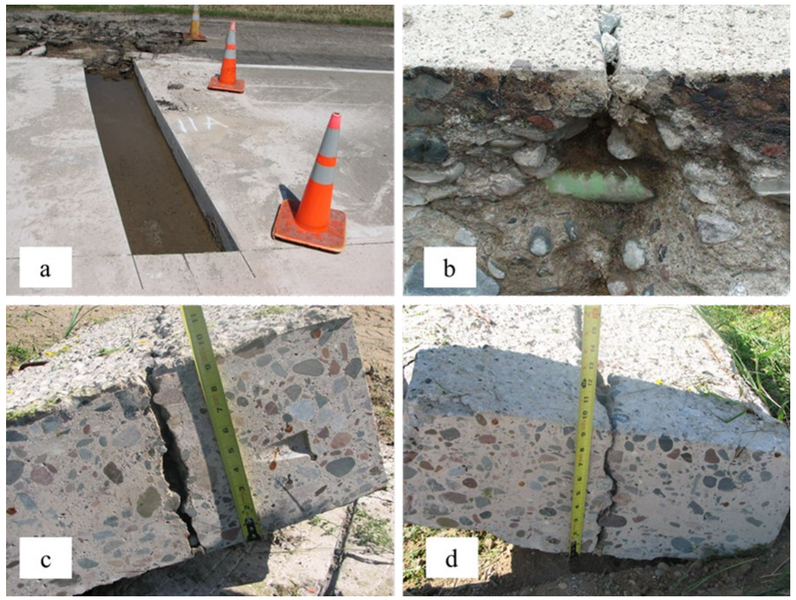
Good Pavement – Test Section 12

Distressed Pavement – Test Section 13



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Pavement temperature as a surrogate of performance

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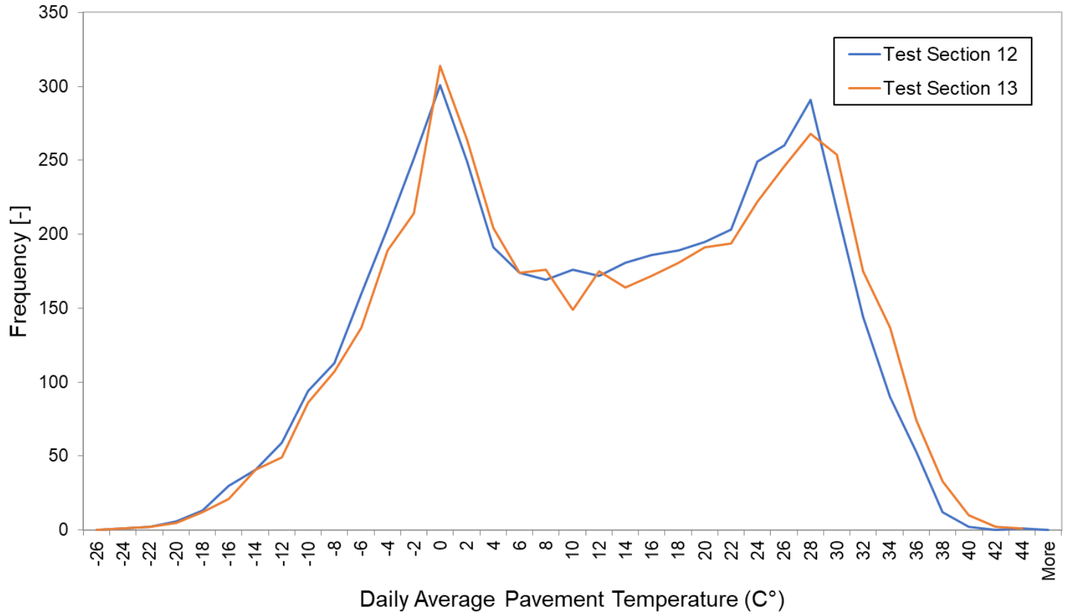

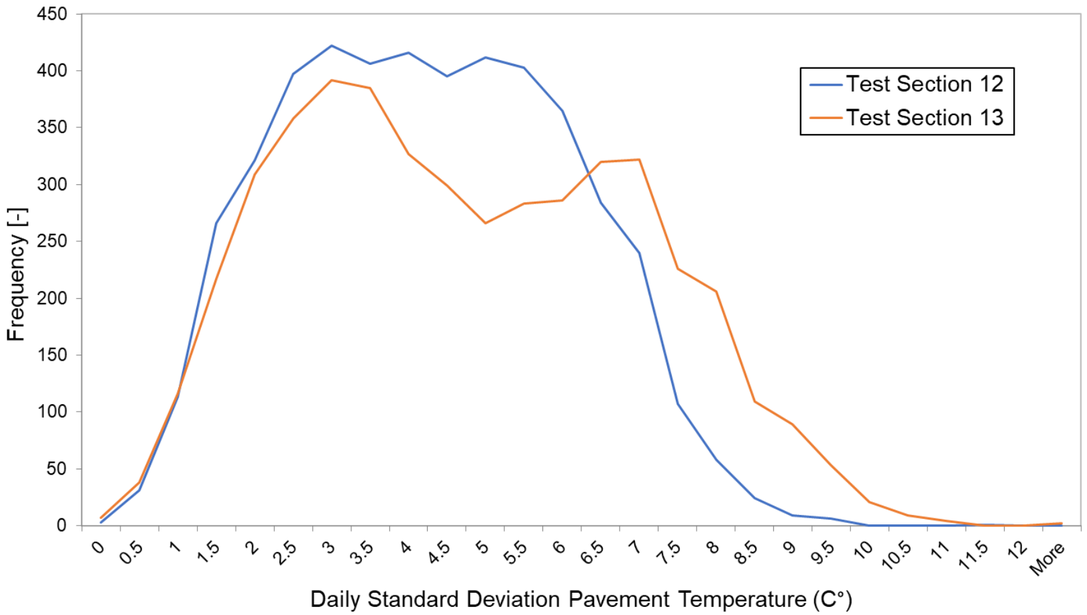

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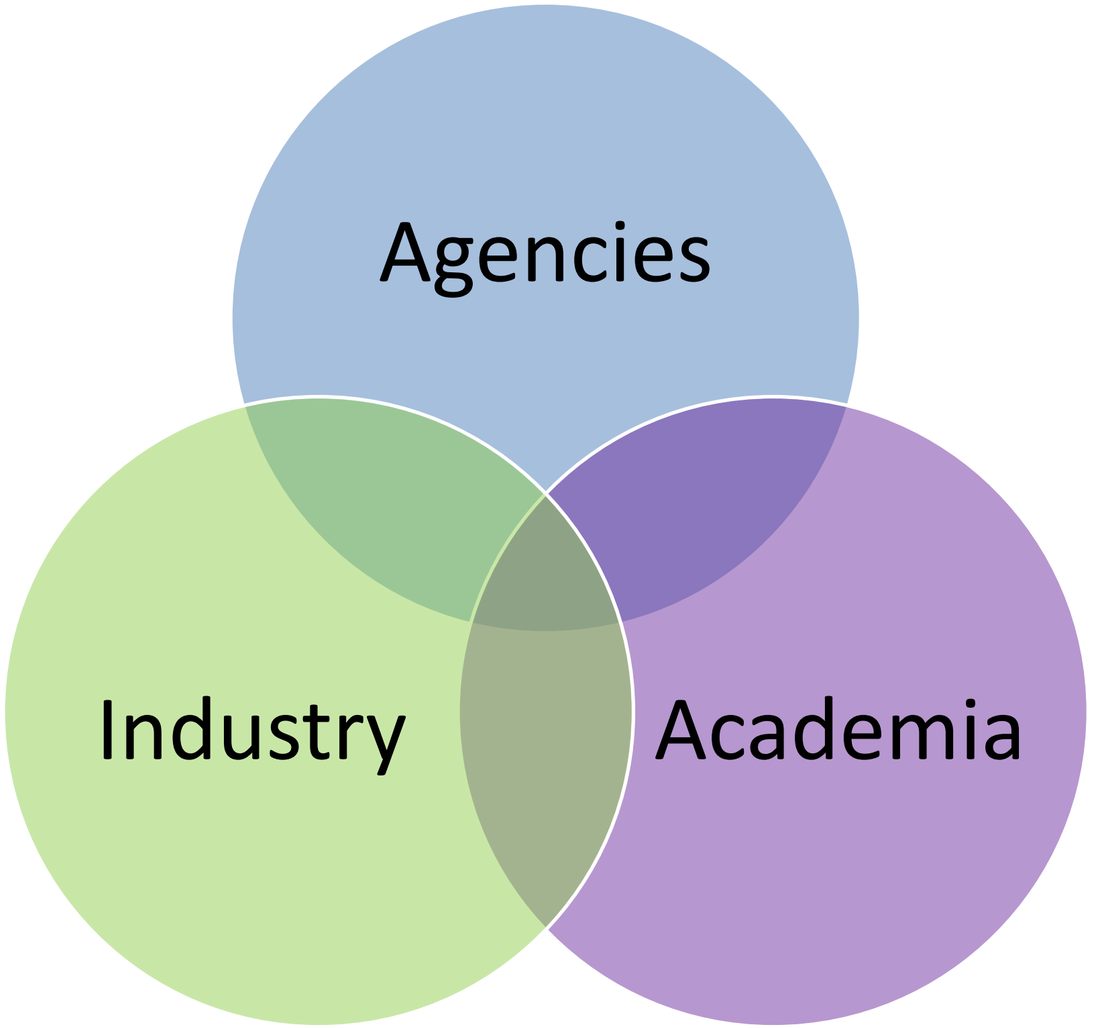
Lessons Learned for Implementation of Geotech Research



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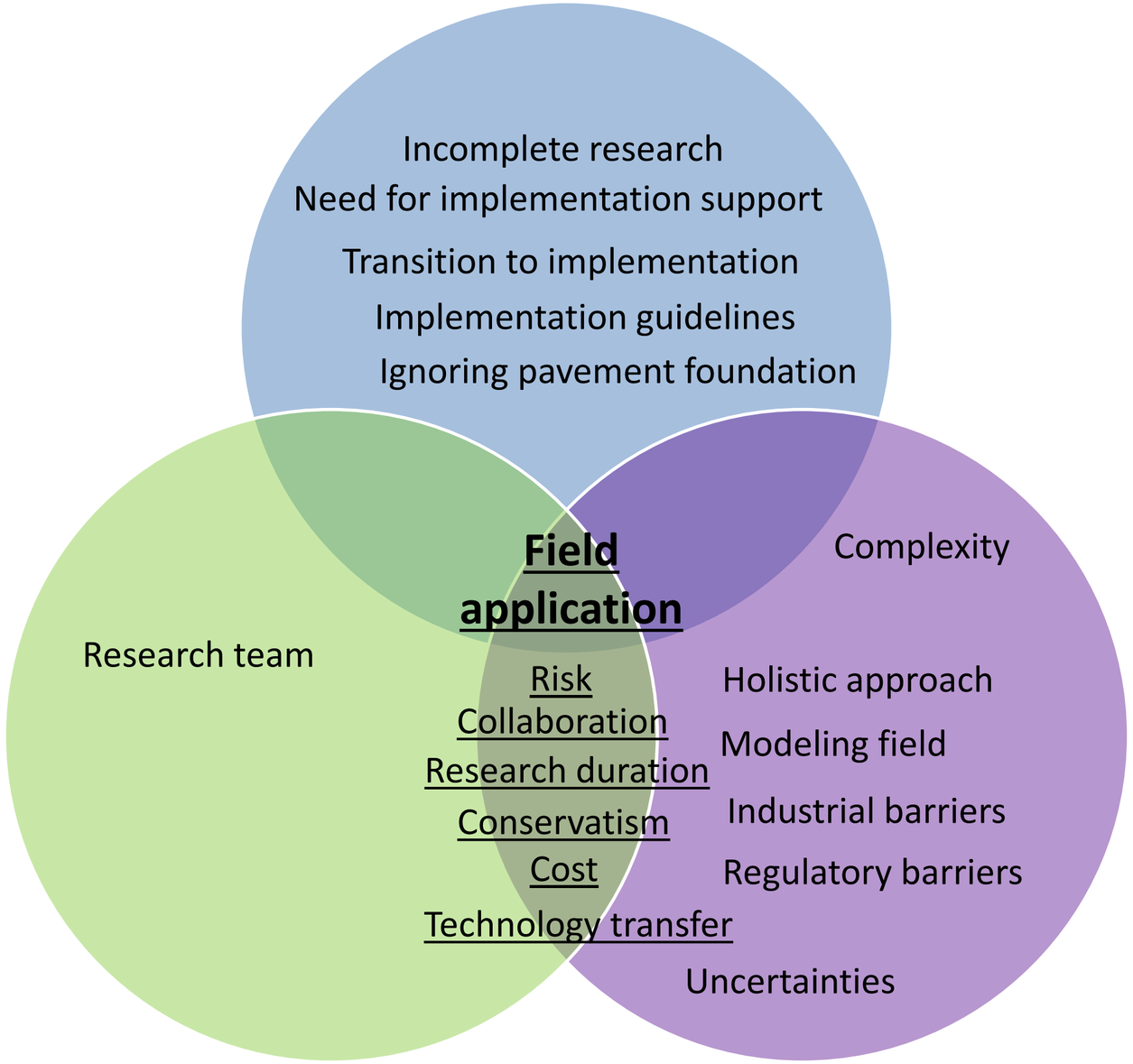
Industry
Academia

Barriers for Geotechnical Research *Implementation*



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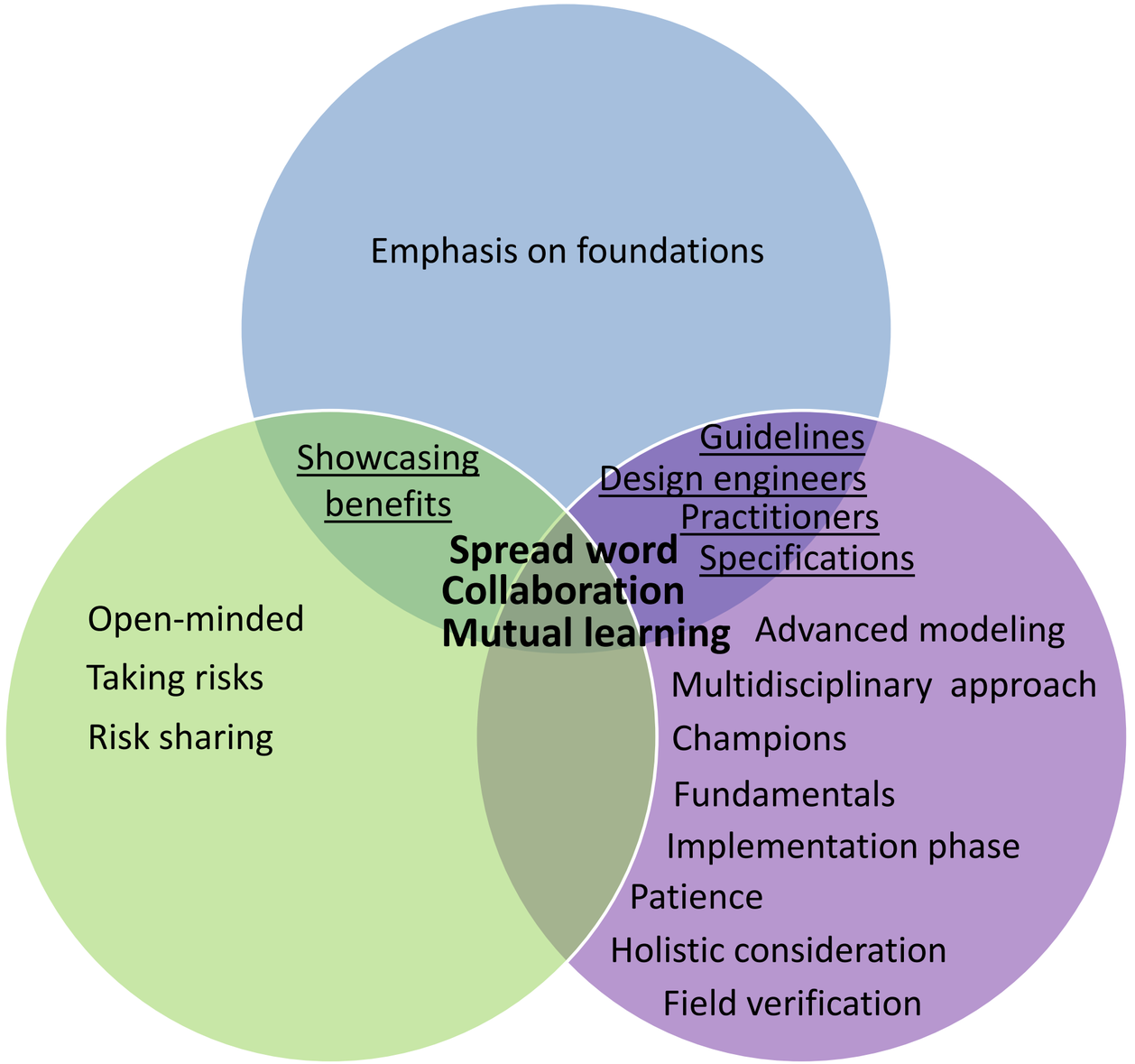
Solutions to Remove Barriers for Implementation



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Additional Thoughts on Implementation

- Proper credit in Design stage
- Practioner bias towards an established/standard solution
- Short-term fixes of assets in transportation network
- Siloing between functional groups

Acknowledgments

- Office of Materials and Road Research (OMRR) Leadership and Staff, MnDOT
  - Research Section Staff @ OMRR, MnDOT
- Retired and former MnDOT Staff
- MnROAD Operations
- National Road Research Alliance (NRRA)
- WSB (slope vulnerability geomorphology-based)
- MSU (slope vulnerability geotech-based)
- Ingios and UTEP (IC @ MnROAD)

Any Questions?

National Center for INFRASTRUCTURE TRANSFORMATION
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Thank You!

Raul Velasquez, PhD, PE

Geomechanics & Deployment Research Engineer
MnDOT