Advanced Road Profile Analysis-Fundamental Calculus

PURDUE ROAD SCHOOL
INDIANA, 2014

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Soil & Materials Engineers, Inc.
Plymouth, MI Office
AASHO Profilometer

Profile data was “written” onto a paper roll

N.A.S.-N.R.C Publication 1061, “The AASHO Road Test”, 1962
AASHO Profilometer

Device measures a continuous SLOPE profile

SLOPE VARIANCE found strongly correlated to expert panel

N.A.S.-N.R.C Publication 1061, “The AASHO Road Test”, 1962
AASHO data analyzed using Electric-Analog Chart Recorder

N.A.S.-N.R.C Publication 1061, “The AASHO Road Test”, 1962
Figure 10. Average annual frost penetration, in inches.
MEPDG ➔ SHRP/LTPP Data

Test Site Locations

Over 1,800 profiles analyzed

GPS3 and GPS4 Sites
HIGH-SPEED PROFILER

Accelerometer
Distance Measurement
Computer

Special Vehicle

50 mph

Height Sensor

For most LTPP Data:
*1 Elevation measurement per inch, raw data.
*Elevation reported every 6” (Avg. of surrounding 12, 1” samples)
* 6” Data also has 300-ft Long Wavelength Reduction Filter
PAVEMENT ELEVATION PROFILE:
Uniformly Spaced Point Elevations

LWP
RWP
Most Common “Roughness Index”

Profile $z = f(x)$

$IRI = \frac{1}{L} \int_0^L |\dot{z}_s - \dot{z}_u| \, dt$

$IRI$ Units = $L/L \rightarrow$ Suspension Movement per Mile
GPS3 Fault Model: No Dowels

$\textbf{MEPDG} \rightarrow \textbf{IRI and Faulting}$

- $r^2 = 0.93$
- Std Error = 15.7
- Error Plot:

![Error Plot Diagram](image_url)

- Measured Faulting
- Predicted Faulting

- Measured Faulting, mm/152m
- Predicted Faulting, mm/152m
- Pavement Age, years

- Graph shows the comparison between measured and predicted faulting over pavement age.
### INPUT DATA

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
<th>Case 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slab Curvature, ft² x 1000</td>
<td>0.1</td>
<td>0.15</td>
<td>0.2</td>
<td>0.25</td>
<td>0.3</td>
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<tr>
<td>PCC thickness, in.</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>11</td>
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<tr>
<td>PCC E-modulus, psi</td>
<td>4700000</td>
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<tr>
<td>PCC Split Tensile, psi</td>
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<td>600</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>Joint spacing, ft</td>
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<td>20</td>
<td>20</td>
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<td>Subgrade Overburden, psf</td>
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<td>220</td>
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<tr>
<td>Subgrade w%</td>
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<tr>
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<td>Days with precip/yr</td>
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<td>151</td>
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<tr>
<td>Days &lt; 32 degF/yr</td>
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<td>Days &gt; 90 degF/yr</td>
<td>5</td>
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<tr>
<td>Initial KEASL/yr</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td>300</td>
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<tr>
<td>Traffic Growth Rate, %/yr</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
</tr>
</tbody>
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### Aggregate Interlock Only-No Dowels

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PAVEMENT STRESS ANALYSIS:
Soil-Structure Interaction Engineering

3-D Analyses:

\[ M_x = \frac{Eh^3}{12(1 - \mu^2)} \frac{\partial^2 z}{\partial x^2} \]

2-D Analyses:

\[ M = EI \frac{d^2 z}{dx^2} \]
PAVEMENT STRESS ANALYSIS: Soil-Structure Interaction Engineering

3-D Analyses:
SLAB/BEAM CURVATURE

\[ M_x = \frac{Eh^3}{12(1 - \mu^2)} \frac{\partial^2 z}{\partial x^2} \]

2-D Analyses:

\[ M = EI \frac{d^2 z}{dx^2} \]
PAVEMENT PROFILE:
A 2-D Slice through a 3-D Solution

LWP

RWP
Profile Elevation, $z = f(x)$

Major Lesson #1 → Continuity
Function \( z = f(x) \)

Discontinuities

No Fault

Fault

Pavements are \( \Rightarrow \) “Piecewise Continuous Functions”

with Fuzz (texture, measurement error...)

Function $z = f(x)$

Points of Inflection
Function $z = f(x)$
Function \( z = f(x) \)

**SLOPE** = “rise/run” = \( \frac{dz}{dx} \)

First Derivative
$1/\kappa = R$, Radius of Curvature

**Curvature** of $f(x) = \kappa \approx \frac{d^2 z}{dx^2} \approx \frac{1}{R}$
Example Profile, $z = f(x)$

Profile Date: June 19, 1992
Profile Time: 15:51:44

* “Thermally” Curved-Down at this time of day?
* High Level of “Locked-In” Up-Warp and Faulting.
BREAKING DOWN PROFILE DATA

Finite Difference Methods are Ideal For Constant Interval Profile Data

\[
\frac{dz}{dx} = \text{slope}_n = \frac{z_{n+i} - z_n}{x_{n+i} - x_n}
\]

\[
\frac{d^2z}{dx^2} = \text{curvature}_n = \frac{\text{slope}_{n+i} - \text{slope}_n}{x_{n+i} - x_n}
\]
**Discrete Slope**

-0.04
-0.03
-0.02
-0.01
0
0.01

Distance, m
Slope, l/l

**Discrete Curvature**

-0.3
-0.2
-0.1
0.1
0.2
0.3

Distance, m
Curvature, 1/m x1000

**Elevation**

-15
-10
-5
0
5
10
15

Distance, m
Elevation, mm

**LWP**

**RWP**

**Upward Translation = “Rocking”**

**Initial Shape. Patterns Grow**
Consider Profile as a Matrix

**Raw Profile**

\[
\begin{pmatrix}
X_1 & L_1 & R_1 \\
X_2 & L_2 & R_2 \\
X_3 & L_3 & R_3 \\
\vdots & \vdots & \vdots \\
X_n & L_n & R_n \\
\end{pmatrix}
\]
Split Profile into 2 Sub-Matrices

Raw Profile

\[
\begin{pmatrix}
X_1 & L_1 & R_1 \\
X_2 & L_2 & R_2 \\
X_3 & L_3 & R_3 \\
\vdots & \vdots & \vdots \\
X_n & L_n & R_n
\end{pmatrix}
\]

Discontinuities

\[
\begin{pmatrix}
\text{Discontinuities}
\end{pmatrix}
\]

Continuous Segments

\[
\begin{pmatrix}
\text{Continuous Segments}
\end{pmatrix}
\]
Faulting Evaluation

Discontinuities

= 

Continuous Segments
Slab Curvature, Waves, Tilt, and Texture Evaluation
Analysis of Discontinuities

Typical Faulting distress

2/8/2000
Typical Faulting distress
Fault Size, $H$

Travel Direction

Structural Discontinuity in the Road Surface Layer

Fault Size, $H$
How much suspension movement will occur when the IRI quarter Car goes over the Fault of Size H?
Fault Size, $H$

Travel Direction

Transient Responses with Exponential/Linear decay, A function of damping/friction

about 20 m per cycle

about 2 m per cycle
How much suspension movement will occur when the IRI quarter Car goes over the Fault of Size H?

Current MEPDG Design Guide, $\text{IRI}_H = 1.5 \, H$
How much suspension movement will occur when the IRI quarter Car goes over the Fault of Size $H$?

Current MEPDG Design Guide, $\text{IRI}_H = 1.5 \ H$

Results of My Study, $\text{IRI}_H = 1.75 \ H$
<table>
<thead>
<tr>
<th>500-ft Summary Statistics</th>
<th>LWP</th>
<th>RWP</th>
</tr>
</thead>
<tbody>
<tr>
<td># Imperfections detected</td>
<td>34</td>
<td>33</td>
</tr>
<tr>
<td>Average Size, mm</td>
<td>8.8</td>
<td>11.1</td>
</tr>
<tr>
<td>Maximum Size, mm</td>
<td>14.2</td>
<td>16.7</td>
</tr>
<tr>
<td>Minimum Size, mm</td>
<td>2.4</td>
<td>4.4</td>
</tr>
<tr>
<td>Total Imperfections, mm</td>
<td>298.7</td>
<td>367.8</td>
</tr>
<tr>
<td>Total Imperfections, m/km</td>
<td>1.96</td>
<td>2.41</td>
</tr>
<tr>
<td>Calculated IRI, m/km</td>
<td>4.42</td>
<td>5.43</td>
</tr>
</tbody>
</table>
The Primary Cause of IRI - Faults

Faulting vs. Roughness for GPS3 Profiles

IRI(faults) = 1.762(TotalFaults) + 1.104

\[ R^2 = 0.83 \]

IRI(faults) = 1.762(TotalFaults) + 1.104

\[ R^2 = 0.83 \]
WHAT CAN WE UNDERSTAND FROM FIRST-DERIVATIVE ANALYSIS

Subgrade - Clay, Silt, Sand, Gravel, Muck, Peat…

Base

Subbase

Subgrade - Clay, Silt, Sand, Gravel, Muck, Peat…
JOINTED CONCRETE PAVEMENT UNDER-SLAB EROSION - pumping
Traffic Direction

Site 553009  7/13/94  7:48:52 PM

Slab Shapes

Elevation, inches

Distance, feet

Faulted joints

Erosion (drop)  Deposition (Lift)

Slabs

Traffic Direction
Traffic Direction

Sediment Transport

Slab Shapes

Erosion (drop) - Deposition (Lift)

Faulted joints

Site 553009  7/13/94  7:48:52 PM

Distance, feet

Traffic Direction
Tilting Data

Elevation

Size of Imperfection

Discrete Slope

Tilting Data

Discrete Curvature

Curvature Properties

Slab Region
6-in Interval Slope Distribution

LWP and RWP shown

All-Data Slope Magnitude

# Observations

Distance, feet

Slope

LWP and RWP shown

6-in Interval Slope Distribution

All-Data Slope Magnitude
6-in Interval Slope Distribution

LWP and RWP shown

Faults
6-in Interval Slope Distribution

LWP and RWP shown

Wisconsin 19'-18'-13'-14' Slab Pattern
6-in Interval Slope Distribution

LWP and RWP shown

All-Data Slope Magnitude Level Tilted
6-in Interval Slope

Slab Slope Data

Std. Dev. = f(texture, warp, bumps…)

All-Data Slope Magnitude

Distance, feet

Slope

553009 19-Jun-92 15:51:44

0
20
40
60
80
100
120
140
160
180
200

-0.025 -0.02 -0.015 -0.01 -0.005 0 0.005 0.01

-0.04
-0.03
-0.02
-0.01
0
0.01
0 50 100 150 200 250 300 350 400 450 500

Distance, feet

Slope
6-in Interval Slope

All Data Slope Magnitude

Joint/Flaw Elimination

Continuous Slabs-Only Slope Magnitude
6-in Interval Slope

**NEW PAVEMENT**

### All-Data

<table>
<thead>
<tr>
<th>Slope Magnitude</th>
<th># Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.025</td>
<td>0</td>
</tr>
<tr>
<td>-0.02</td>
<td>50</td>
</tr>
<tr>
<td>-0.015</td>
<td>100</td>
</tr>
<tr>
<td>-0.01</td>
<td>150</td>
</tr>
<tr>
<td>-0.005</td>
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<td>0</td>
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<td>0.005</td>
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<tr>
<td>0.01</td>
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<tr>
<td>0.015</td>
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### Slabs-Only

<table>
<thead>
<tr>
<th>Slope Magnitude</th>
<th># Observations</th>
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<tbody>
<tr>
<td>-0.025</td>
<td>0</td>
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<td>-0.02</td>
<td>50</td>
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<tr>
<td>-0.015</td>
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<td>-0.01</td>
<td>150</td>
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<td>0.005</td>
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<tr>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>0.015</td>
<td></td>
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</table>
INITIATION OF FAULTING

NEW

6-in Interval Slope

All-Data Slope Magnitude

Slabs-Only Slope Magnitude
6-in Interval Slope

# Observations

Slope Magnitude

FAULTING\((t)\)

NEW

All-Data Slope Magnitude

Slabs-Only Slope Magnitude
6-in Interval Slope

**All-Data** Slope Magnitude

- **ROCKING**
  - $t$

- **FAULTING**
  - $t$

### NEW Slabs

- **SLABS ONLY**
  - Without FAULTS

- **Slabs-Only** Slope Magnitude
6-in Interval Slope

**All-Data** Slope Magnitude

**SLABS ONLY** Without FAULTS

- **FAULTING**
- **NEW**
- **ROCKING**
6-in Interval Slope

**AVERAGE SLAB SLOPE INDEX**

**All-Data** Slope Magnitude

**SLABS ONLY Without FAULTS**

**Slabs-Only** Slope Magnitude
The "mean" slab

Average Fault Spacing, $L$

$L/2$

$RI$

$H = \frac{1}{2}$(Rocking Fault Size)$

Average Per Slab Volume $\approx \frac{1}{2}(L/2)(H)(\text{Lane Width})$

Per Mile Volume Index $= (\text{Per Slab Volume}) \times 5280/L$

RI = Slab Rocking Index, reported in inches per 10 feet

Rocking Fault Size $= RI(L)/10$

Pumped

The "mean" slab

Average Fault Spacing, $L$

10'

Rocking Deformation
### SLABS ONLY

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<thead>
<tr>
<th></th>
<th>LWP</th>
<th>RWP</th>
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<tr>
<td>maximum slope</td>
<td>0.0067</td>
<td>0.0068</td>
</tr>
<tr>
<td>minimum slope</td>
<td>-0.0057</td>
<td>-0.0045</td>
</tr>
<tr>
<td>average slope</td>
<td>0.0011</td>
<td>0.0014</td>
</tr>
<tr>
<td>slope stdev</td>
<td>0.0022</td>
<td>0.0022</td>
</tr>
<tr>
<td>median slope</td>
<td>0.0013</td>
<td>0.0015</td>
</tr>
<tr>
<td>slope trimmed mean (remove outer 40%)</td>
<td>0.0012</td>
<td>0.0015</td>
</tr>
</tbody>
</table>

### Slab Rocking Index-inches per 10-ft = 0.142 0.182

### Average Joint/Crack Spacing, feet = 15.2 15.2

### Average Fault Size from Rocking Index, mm = 5.48 7.00

### Average Fault Size from Profile Data, mm = 5.28 6.85

### Volume Pumped, cubic feet per mile per 12-ft lane = 142 182

### Average, cubic feet per mile per 12-ft lane = 162
Generally Constant Rate per ESAL

GPS3 Test Group

Cumulative Volume Pumped, cubic feet per mile

Pavement Age, yr

Cumulative KESAL

Volume per Kilo-ESAL, cubic inches per mile

Pavement Age, yr
For LTPP Site 55-3009

18,900 ESAL per lb-pumped per Slab
WHAT CAN WE UNDERSTAND FROM SECOND-DERIVATIVE ANALYSIS

Subgrade - Clay, Silt, Sand, Gravel, Muck, Peat…

Subbase
JOINTED CONCRETE PAVEMENT CURLING AND WARPING

Subgrade - Clay, Silt, Sand, Gravel, Muck, Peat...

Base

Subbase

Trapped Water
\[ z = f(x) \]

\[ \frac{dz}{dx} \]

\[ \frac{d^2z}{dx^2} \]
What is the Curvature of This?

GPS3 55-3009

“Structurally Continuous”
CURLED & WARPED SLAB

Includes: Macro/Mega Texture, Slab Creep, Warp, Curl, Abrasion, Wheel-Path Location, Sensor Accuracy, Inertial Plane, Possible Plastic Hinges (pre-hair-line cracking)………many..
STRING-LINE METHOD
- Generally under-estimates $\kappa$
- Wont quantify variability

\[ \kappa_{\text{stringline}} = \frac{2(\delta)}{(L/2)^2} \]
Mean Value Theorem for “Continuous” Slab Functions from Calculus

Curvature \( \kappa \approx \frac{d^2 z}{dx^2} = z'' \)

\[ K_{\text{mean}} = \frac{\int_0^L z''(x)dx}{L} = \frac{z'(L) - z'(0)}{L} \]
\[ K_{\text{mean}} = \frac{\int_0^L z''(x) \, dx}{L} = \frac{z'(L) - z'(0)}{L} \]
All Have Same Average Curvature
But Different Statistics: std. deviation, median, max., min…..

\[ SINE\text{-}WAVE\ PERTUBATION \]

Slope = -0.00235

Slope = +0.00372

\[ \mathcal{K}_{mean} = \frac{\int_0^L z'''(x) \, dx}{L} = \frac{z'(L) - z'(0)}{L} \]
Average Curvature Over These Spans = Zero!

\[ \kappa_{AVG} \] CONCEPT NOT VALID!

- Free Rotation at Hinges, \( \kappa = \) undefined, infinity or zero
- Vertical Offsets = Faults, \( \kappa = \) undefined, not connected
- \( \kappa \) through Fault equal and opposite to Actual Avg Slab \( \kappa \)
**BEST-FIT POLYNOMIALS**

- End slopes vary and can be way off
- Wont quantify variability

\[ z = f(x) \]

\[ K_{mean} = \frac{\int_0^L z''(x)\,dx}{L} = \frac{z'(L) - z'(0)}{L} \]
Westergaard’s Infinite Strip Shape Function
BCI- For Discrete Profile Data

\[ z' = \frac{dz}{dx} = \text{slope}_n = \frac{z_{n+i} - z_n}{x_{n+i} - x_n} \]

\[ z'' = \frac{d^2z}{dx^2} \approx \text{curvature}_n = \frac{\text{slope}_{n+i} - \text{slope}_n}{x_{n+i} - x_n} \]
BCI Method for Single Slabs

End Slope Samples = Average
Std. Deviation = Variation of $\kappa$

34 Curvature Samples per Wheel Path
BCI Method for Single Slabs

End Slope Samples

Distance, feet

Elevation, feet

$2$-ft ArCS

32 Curvature Samples per Wheel Path
BCI Method for Single Slabs

End Slope Samples

30 Curvature Samples per Wheel Path
BCI Method for Single Slabs

End Slope Samples

4-ft Arcs

28 Curvature Samples per Wheel Path
BCI Method for Single Slabs

End Slope Samples

Distance, feet

Elevation, feet

5-ft Arcs

26 Curvature Samples per Wheel Path
End Slope Samples

24 Curvature Samples per Wheel Path
BCI Method for Single Slabs

End Slope Samples

Distance, feet

Elevation, feet

7-ft Arcs

22 Curvature Samples per Wheel Path
End Slope Samples
• 0.5 to 4 feet from ends
• 16 End Slopes per Slab
• 8 Curvature Strings per Slab
  • 392 Arc Samples

BCI Method for Single Slab Segments

8-Ft Arcs

20 Curvature Samples per Wheel Path
GPS3 Site 55-3009 has 33 Slabs in 500 feet
Let's Compare The Methods

Slope = -0.00235

Slope = +0.00372
\[ \kappa \approx \frac{d^2 z}{dx^2} = z'' \]
GPS3 Site 55-3009 has 33 Slabs in 500 feet
For GPS3 Site 55-3009

Avg \( \kappa \approx 0.5/1000 \text{ ft}^{-1} \)

\( \kappa = 1/R, \ R = 2000 \text{ ft} \)
Mean Trend $\approx$ 3 Deg F per inch Gradient
Warp Variation is Huge, down or up

$50\% = +/- 0.067$
$80\% = +/- 0.121$
$90\% = +/- 0.166$
$95\% = +/- 0.206$
Average of Cluster = Warp
Variation of Cluster = Curl

50% = +/- 0.067
80% = +/- 0.121
90% = +/- 0.166
95% = +/- 0.206
“Generalized Analysis of Variation of Slope and Curvature for Discrete Data”

“Moving Arcs & Slopes”

1. “Moving” 1-ft to 8-ft long arcs are calculated along each continuous segment at 0.5 ft intervals

2. Avg., Std. Dev., Median, Count, Std Error…. for each Arc Length Class
55-3009  Classic Real Faults with Fine Texture
For PCC and AC Pavements

\[ IRI_{\text{Total}} = IRI_{\text{Faults}} + IRI_{\text{Warp}} + IRI_{\text{Texture}} + IRI_{\text{Waves}} \]
The Primary Cause of IRI- Faults

Faulting vs. Roughness for GPS3 Profiles

IRI(faults) = 1.762(TotalFaults) + 1.104

$R^2 = 0.83$

IRI(faults) = 1.762(TotalFaults) + 1.104

$R^2 = 0.83$
Avg. Slab Curvature vs. IRI

IRI rises above the Lower Boundary as Faulting/Deformation Develops

Lower Boundary for GPS3 Data

\[0.0948x^3 - 0.4585x^2 + 1.5966x\]

\[x = \text{Average Profile Curvature (24")}, \ 1/m \times 1000\]
Sensitivity Analysis for the IRI Regression Model

Faulting
- None
- Low
- High
- Very Curved

Avg. Slab Curvature
- Flat
- Very Curved

Stdev Curvature
- Low
- High

All Parameters
- All Low
- All High

"Average" LTPP GPS3 Profile

IRI, m/km
For PCC and AC Pavements

\[ IRI_{\text{Total}} = IRI_{\text{Faults}} + IRI_{\text{Warp}} + IRI_{\text{Texture}} + IRI_{\text{Waves}} \]

\[ IRI_{\text{Texture}}, \text{m/km} = 0.065(6\sigma \text{ Texture Band Size, mm}) \]

2mm (very fine texture) < 6\sigma < 10 mm (very coarse texture)
0.2 mm Sample Interval

0.5 mm Laser Footprint Diameter

No use having really short spacing with big footprint, low resolution,.....
Discussions or Questions

Michigan’s State Fossil: Mastodon

\[ M = EI \frac{d^2 z}{dx^2} \]