SPR-4230: Alternative Quality Assurance Methods for Compacted Subgrade

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Presentation Layout

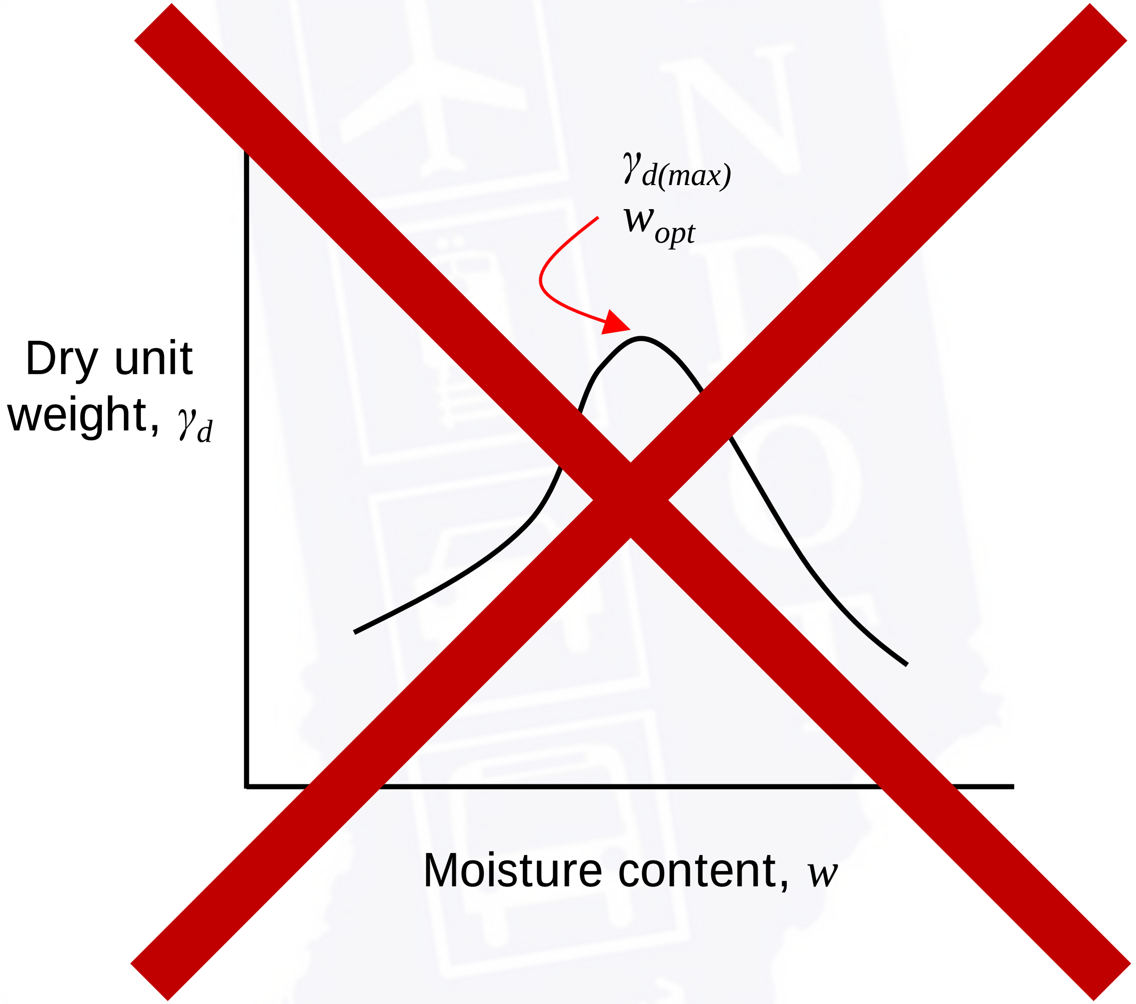
- Project background
- Research approach
- Research Findings to Date
  - Laboratory Testing
  - Field Testing
- Summary
- Future Work

Performance-Based Specifications

- Type of quality assurance specification
  - Quality assurance = owner/owner’s representative (i.e., INDOT)
  - Quality control = contractor
- Describes desired level(s) of engineering property(s)
  - Predictor(s) of performance
  - Appear in primary prediction relationship(s)

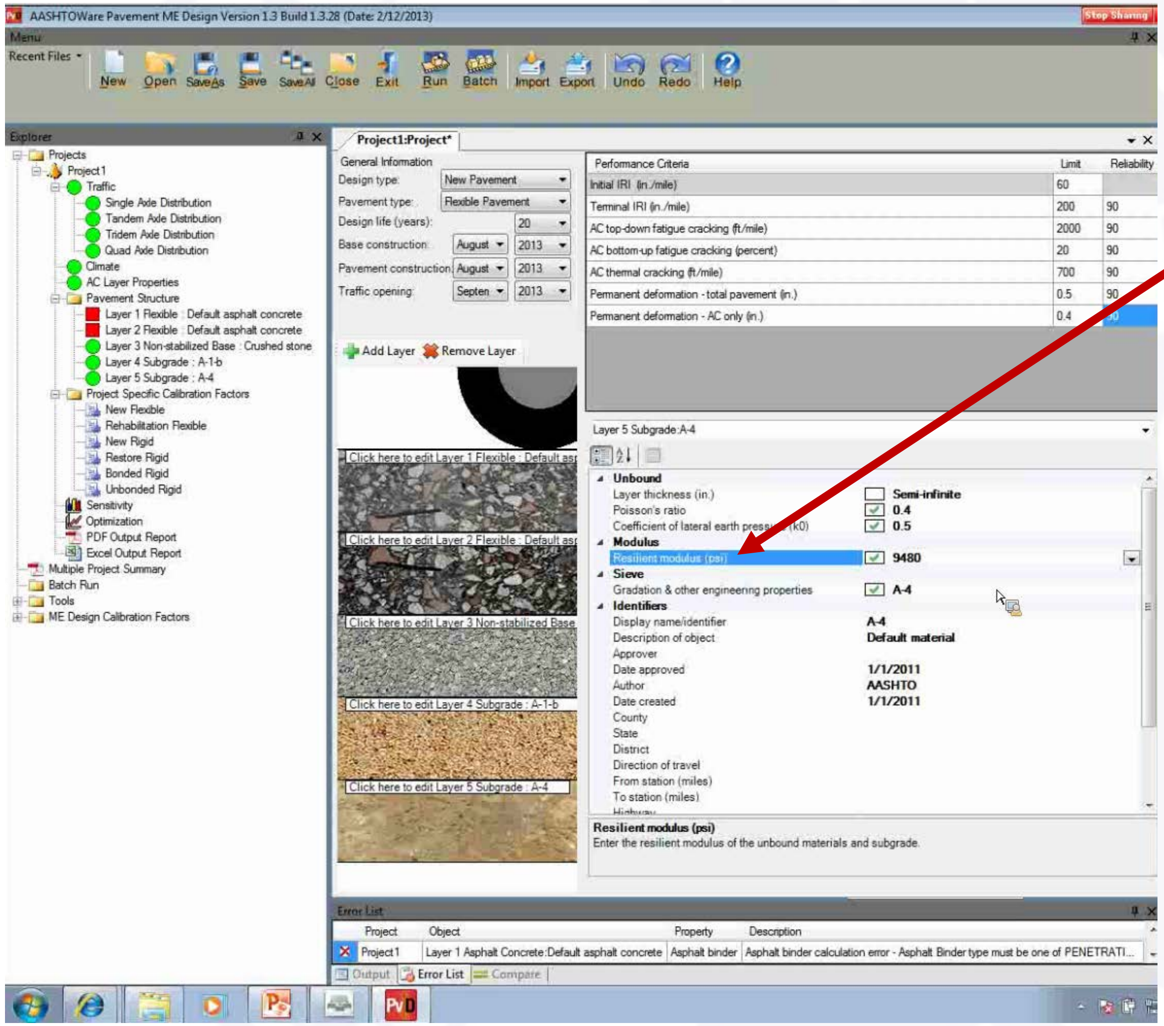
Doyle, G. (2003). *Major Types of Transportation Construction Specifications: A Guideline to Understanding Their Evolution and Application.* AASHTO Highway Subcommittee on Construction, Quality Construction Task Force. Washington, D.C.: American Association of State Highway and Transportation Officials.

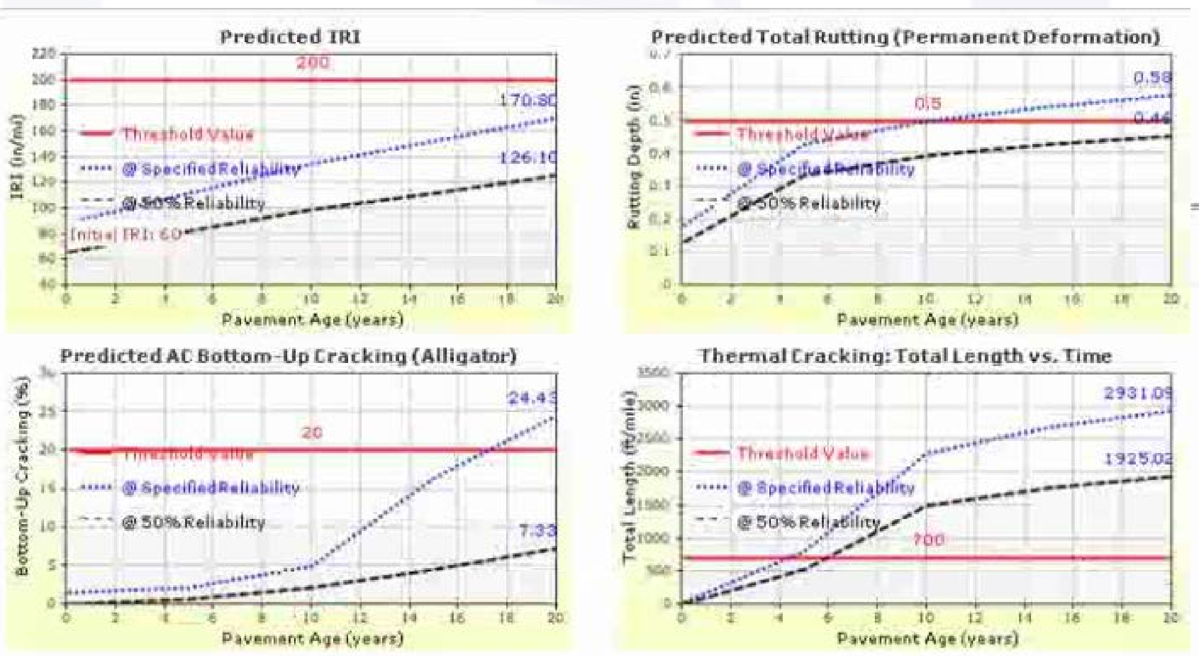
Traditional Subgrade Quality Assurance



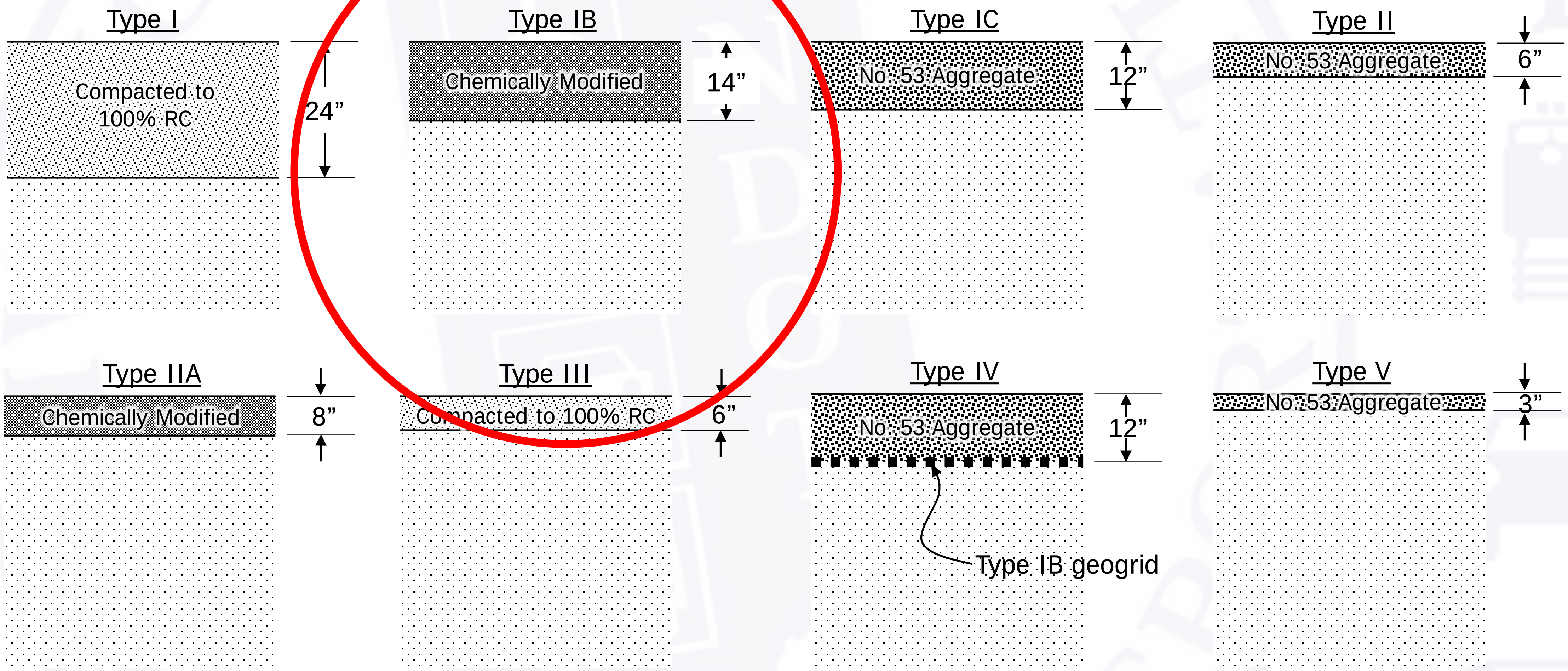
Although soil strength and stiffness tends to increase with increasing dry unit weight (density), density/dry unit weight cannot be used to directly predict performance

A More Appropriate Performance Property





INDOT Allowed Subgrade Treatment Types



Goal of SPR-4230

Specified chemically modified subgrade resilient modulus used in design

→

In situ quality assurance testing

Light weight deflectometer (LWD)

- Rapid
- Easy to use
- Provides stiffness meaurement

→

Confirm specified chemically modified subgrade resilient modulus during construction

Light Weight Deflectometer (LWD)

10 kg drop weight imparting 1,589 lbf maximum force

Accelerometer measuring peak deflection

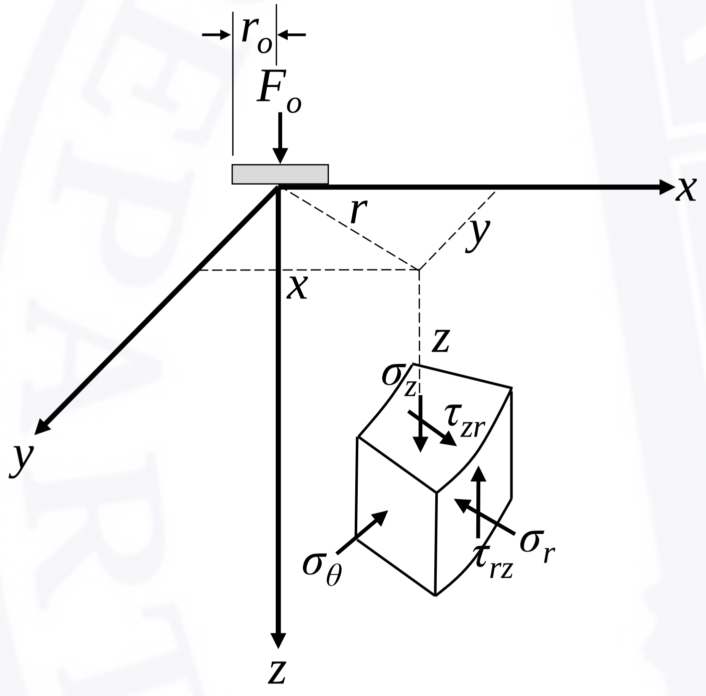
≈28-⅜ in. drop height

Data collector

Loading plate (11.81 in. diameter)

LWD Elastic Modulus Backcalculation

Boussinesq's solution:



In Situ Stresses:

$$\sigma_z = f(F_o, r, z) \quad \sigma_r = f(F_o, r, z) \quad \sigma_\theta = f(F_o, r, z)$$

In Situ Vertical Strain:

$$\varepsilon_z = \frac{1}{E}[\sigma_z - \nu(\sigma_\theta + \sigma_r)]$$

ν is Poisson's ratio
(0.2 to 0.4 typical)

Vertical Deflection at Surface:

$$\delta_z = \int_0^\infty \varepsilon_z dz$$

$$\delta_z = \frac{F_o(1-\nu^2)k}{\pi r_o E}$$

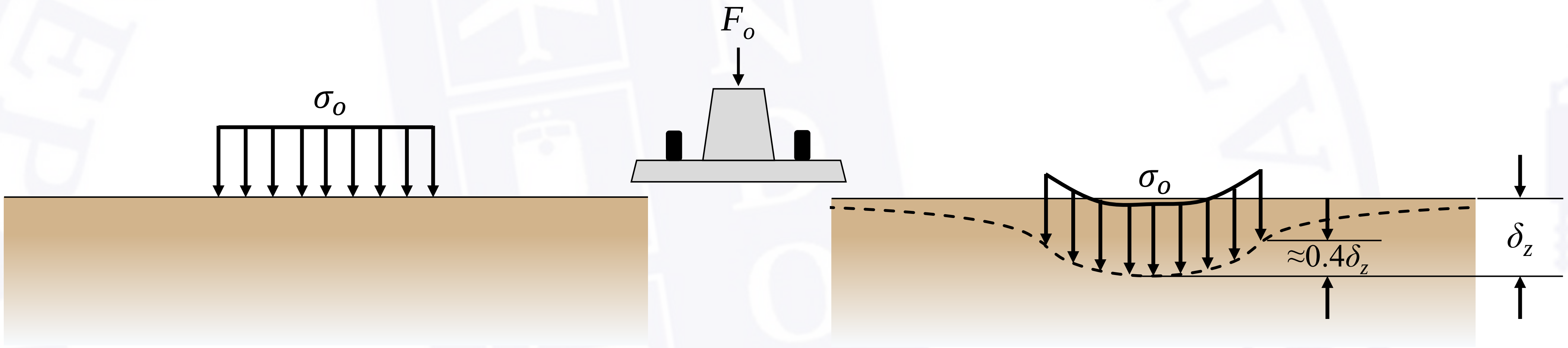
k is applied stress shape factor

$$E_{LWD} = \frac{F_o(1-\nu^2)k}{\pi r_o \delta_z}$$

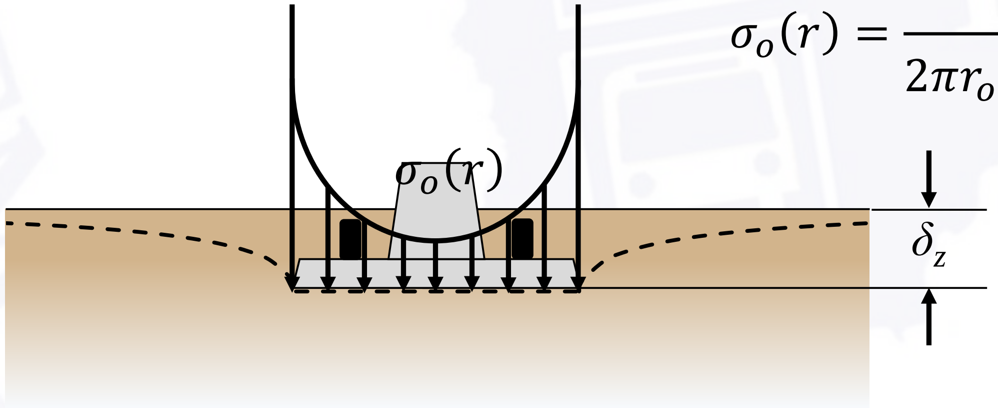
E is elastic Modulus
F_o is applied force
r_o is loading plate radius
ν is Poisson's ratio
k is applied stress shape factor
δ_z is surface deflection

Applied Stress Shape Factor (k)

Is stress applied uniformly? **Probably not (loading plate is too stiff)**



Stress applied over an **inverse-parabolic stress distribution** is a better assumption

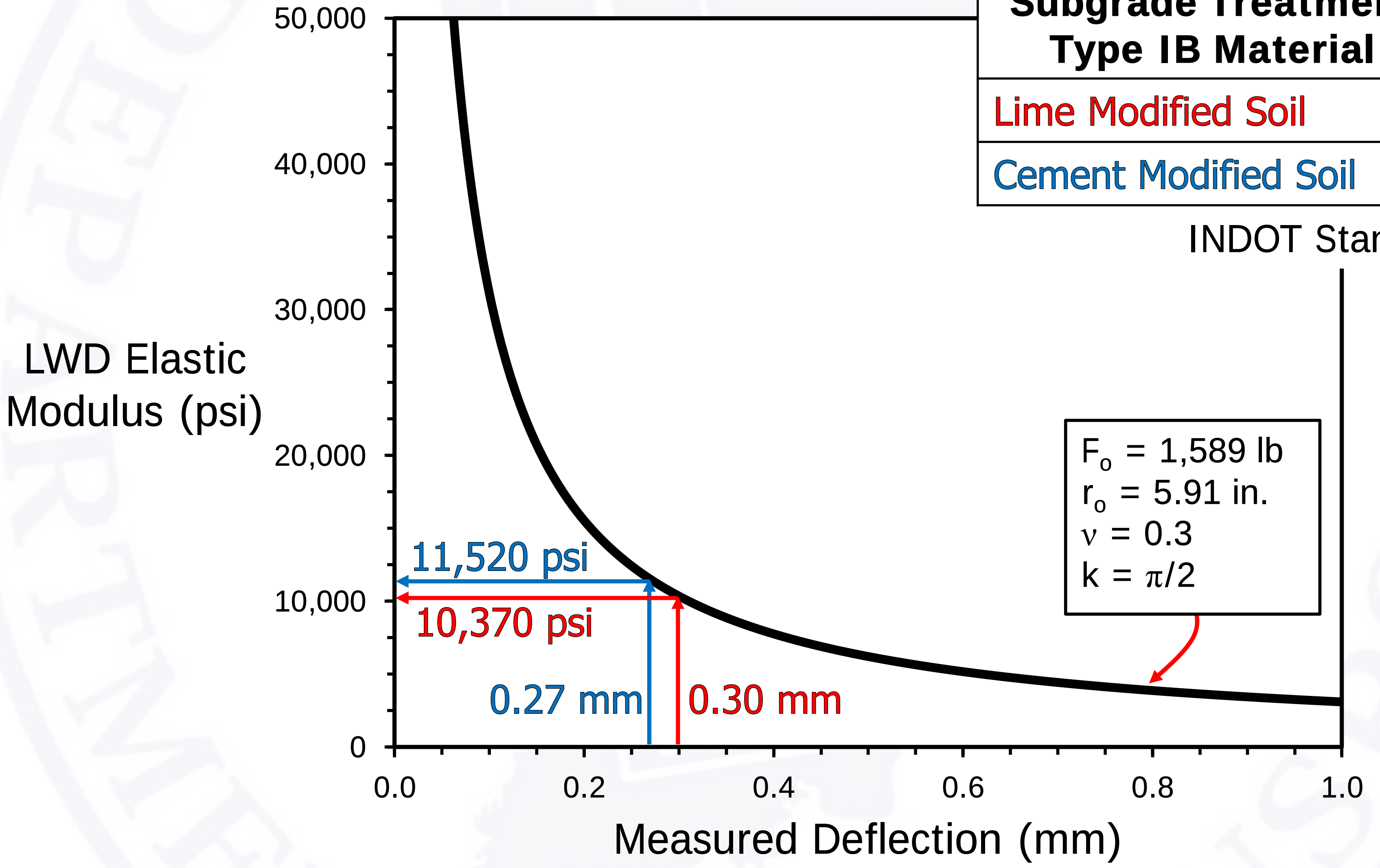


$$\sigma_o(r) = \frac{F_o}{2\pi r_o \sqrt{r_o^2 - r^2}}$$

$$E_{LWD} = \frac{F_o(1-\nu^2)k}{\pi r_o \delta_z}$$

$$k = \frac{\pi}{2}$$

LWD Elastic Modulus



Subgrade Treatment Type IB Material	Maximum Allowable Deflection (mm)
Lime Modified Soil	0.30
Cement Modified Soil	0.27

INDOT Standard Specification No. 203.24

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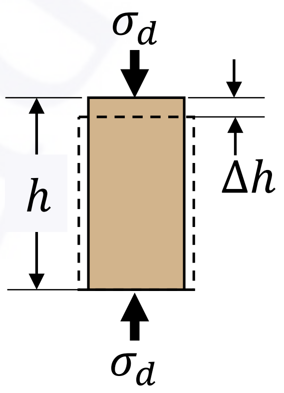
LWD Elastic Modulus ≠ Resilient Modulus (Strain)



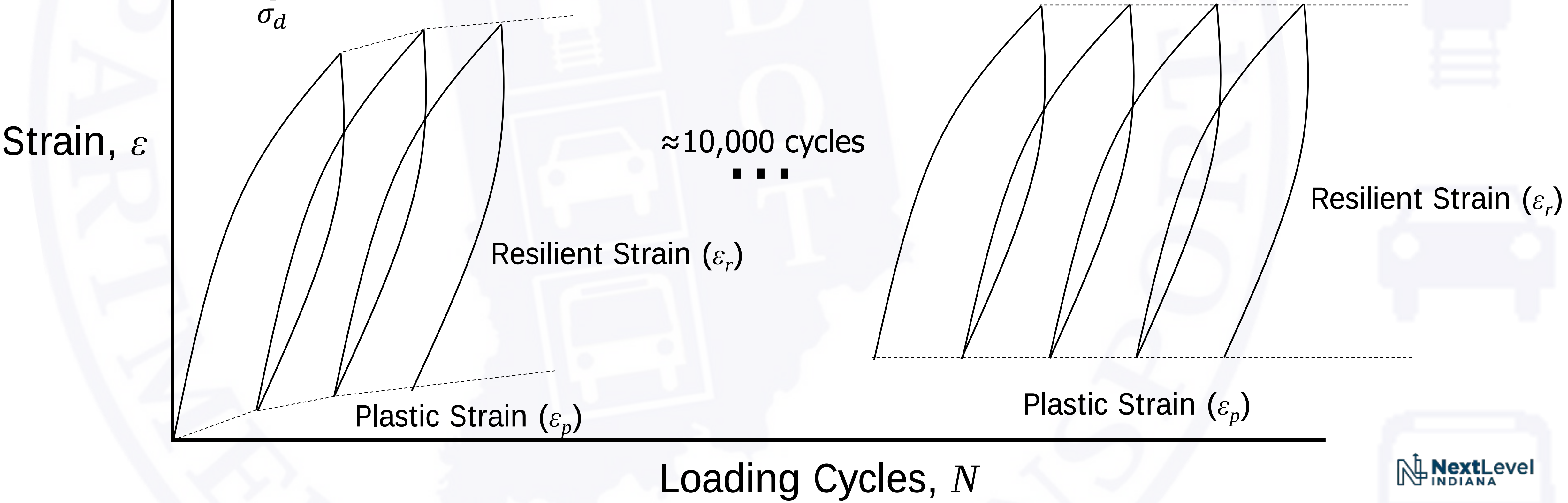
$$\varepsilon = \frac{\Delta h}{h}$$

$$\varepsilon = \varepsilon_p + \varepsilon_r$$

$$E = \frac{\sigma_d}{\varepsilon} = \frac{\sigma_d}{\varepsilon_p + \varepsilon_r}$$

$$\lim_{N\to\infty} \varepsilon_p = 0$$

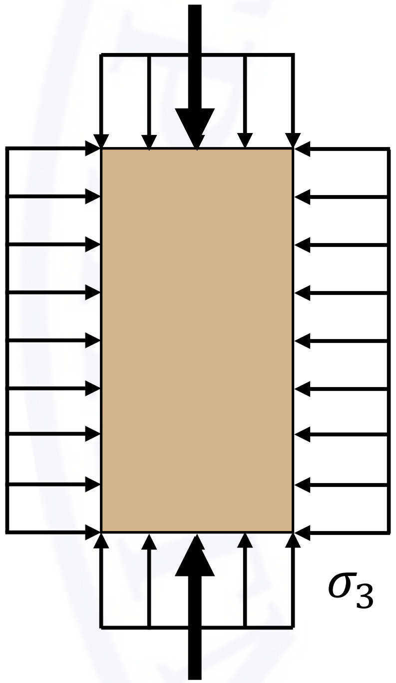
$$\lim_{N\to\infty} E = \frac{\sigma_d}{\varepsilon_r} = M_r$$



LWD Elastic Modulus ≠ Resilient Modulus (Stress)

AASHTO T 307
(Resilient Modulus Lab Test)

$\sigma_d = 6$ psi



$\sigma_3 = 2$ psi

$\sigma_2 = \sigma_3 = 2$ psi
$\sigma_1 = 8$ psi

$$M_r = k_1 p_a \left(\frac{\theta}{p_a}\right)^{k_2} \left(\frac{\tau_{oct}}{p_a} + 1\right)^{k_3}$$

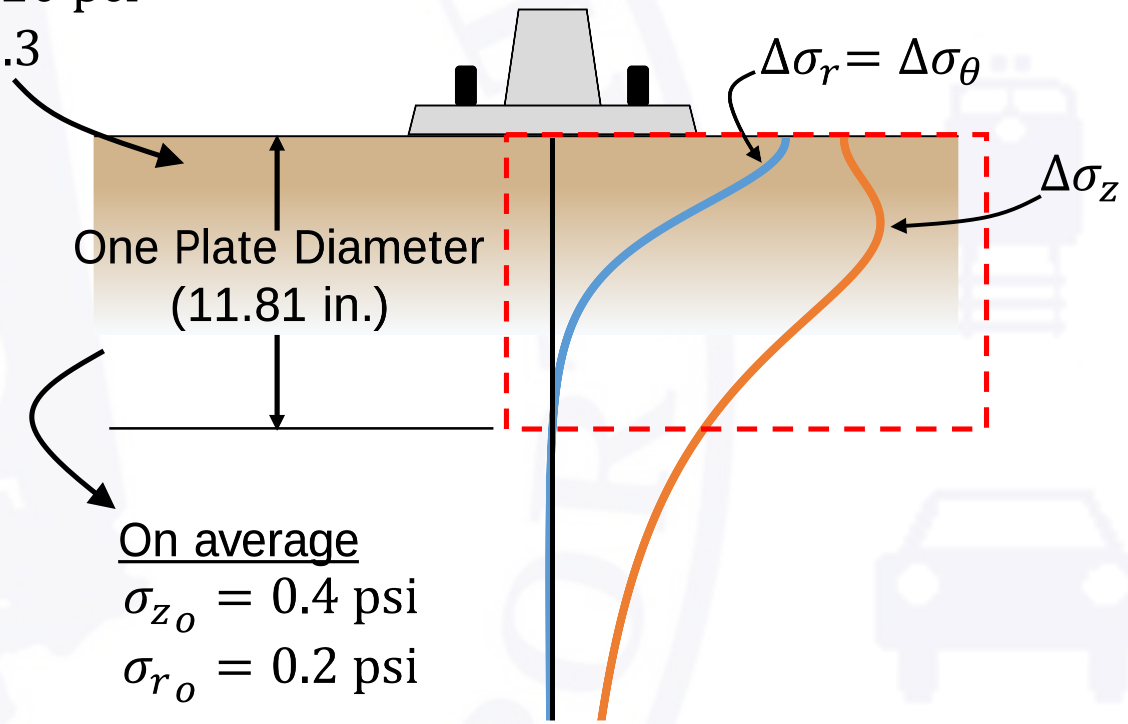
$$\theta = \sigma_1 + \sigma_2 + \sigma_3$$

$$\tau_{oct} = \frac{1}{3}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2}$$

θ is bulk stress
τ_{oct} is octahedral shear stress
p_a is atmospheric pressure
k_1, k_2, k_3 are material constants

Light Weight Deflectometer

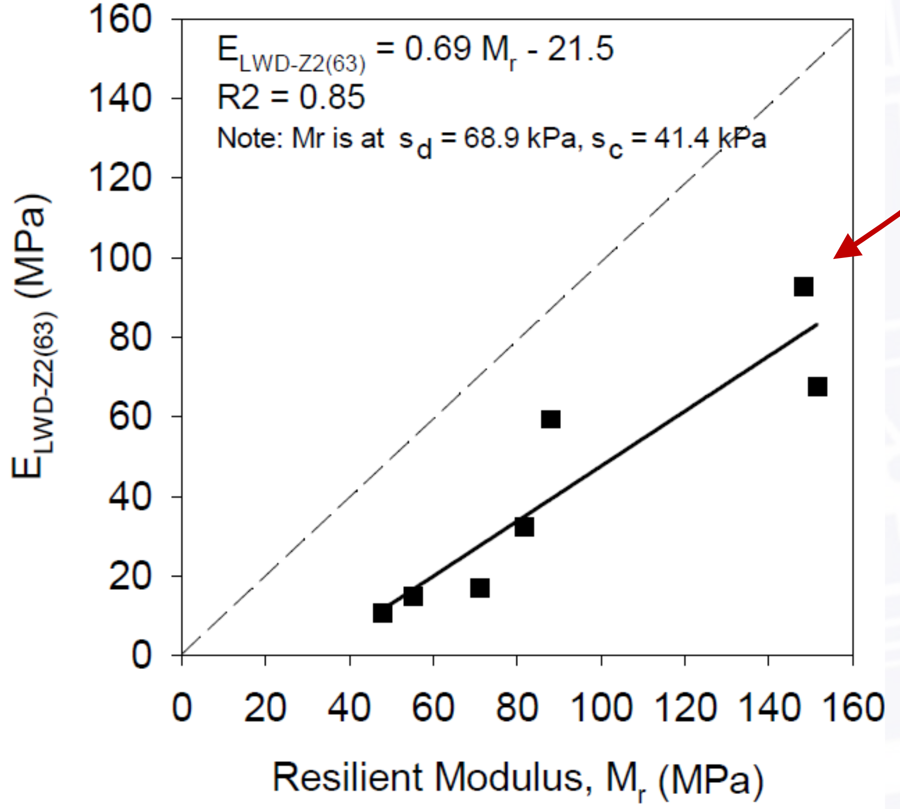
$\gamma = 120$ pcf
$\nu = 0.3$



<u>On average</u>
$\sigma_{z_o} = 0.4$ psi
$\sigma_{r_o} = 0.2$ psi
$\Delta\sigma_z = 6.5$ psi
$\Delta\sigma_r = 1.9$ psi
$\sigma_{z_f} = 6.9$ psi
$\sigma_{r_f} = 2.1$ psi

$\sigma_2 = \sigma_3 = 2.1$ psi
$\sigma_1 = 9.0$ psi

Previously Established E_{LWD} and M_r Correlations



D. J. White, M. Thompson, and P. Vennapusa, "Field validation of intelligent compaction monitoring technology for unbound materials," Final Report MN/RC-2007-10, Minnesota DOT, St. Paul, Minn, USA, 2007.

Untreated
A-4 and
A-7-5 subgrades

$$M_r = k_1 p_a \left(\frac{\theta}{p_a}\right)^{k_2} \left(\frac{\tau_{oct}}{p_a} + 1\right)^{k_3}$$

$$k_i = C_1 + C_2\left(\frac{\sigma}{\delta}\right) \qquad i = 1, 2, 3$$

	C_1	C_2
k_1	480	1040
k_2	1.0	–0.9
k_3	–3.7	2.8

S. H. Mousavi, A. G. Gabr, and R. H. Borden, "Subgrade resilient modulus prediction using light-weight deflectometer data," Canadian Geotechnical Journal, 54(3), 2017.

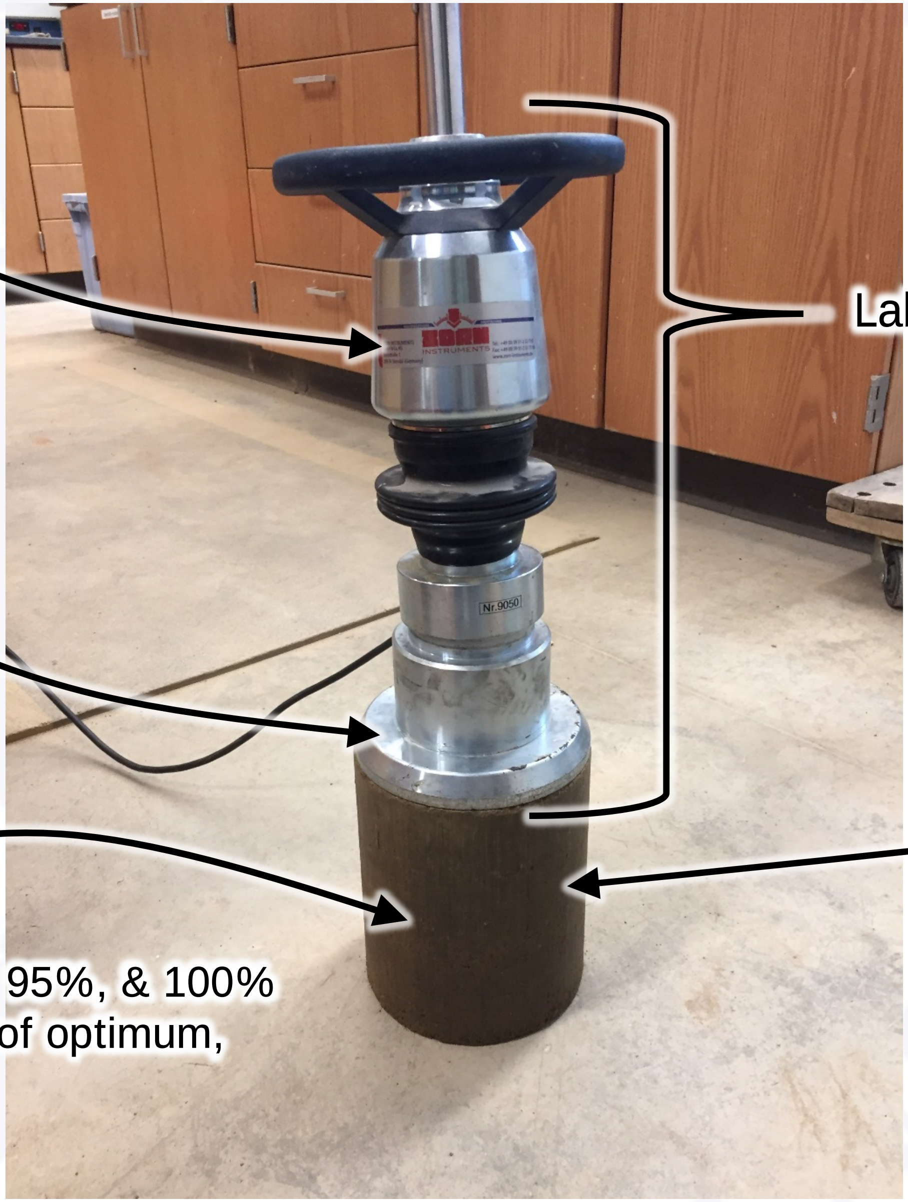
This Study's E_{LWD} and M_r Correlation

5 kg drop weight imparting up to 871 lbf maximum force

Laboratory LWD

Loading plate (5.91 in. diameter)

CBR-sized sample (7 in. high, 6 in. diameter)



A-6 subgrade

- Nominal 4% cement content
- Nominal relative compactions of 90%, 95%, & 100%
- Nominal moisture contents of 2% dry of optimum, optimum, & wet of optimum

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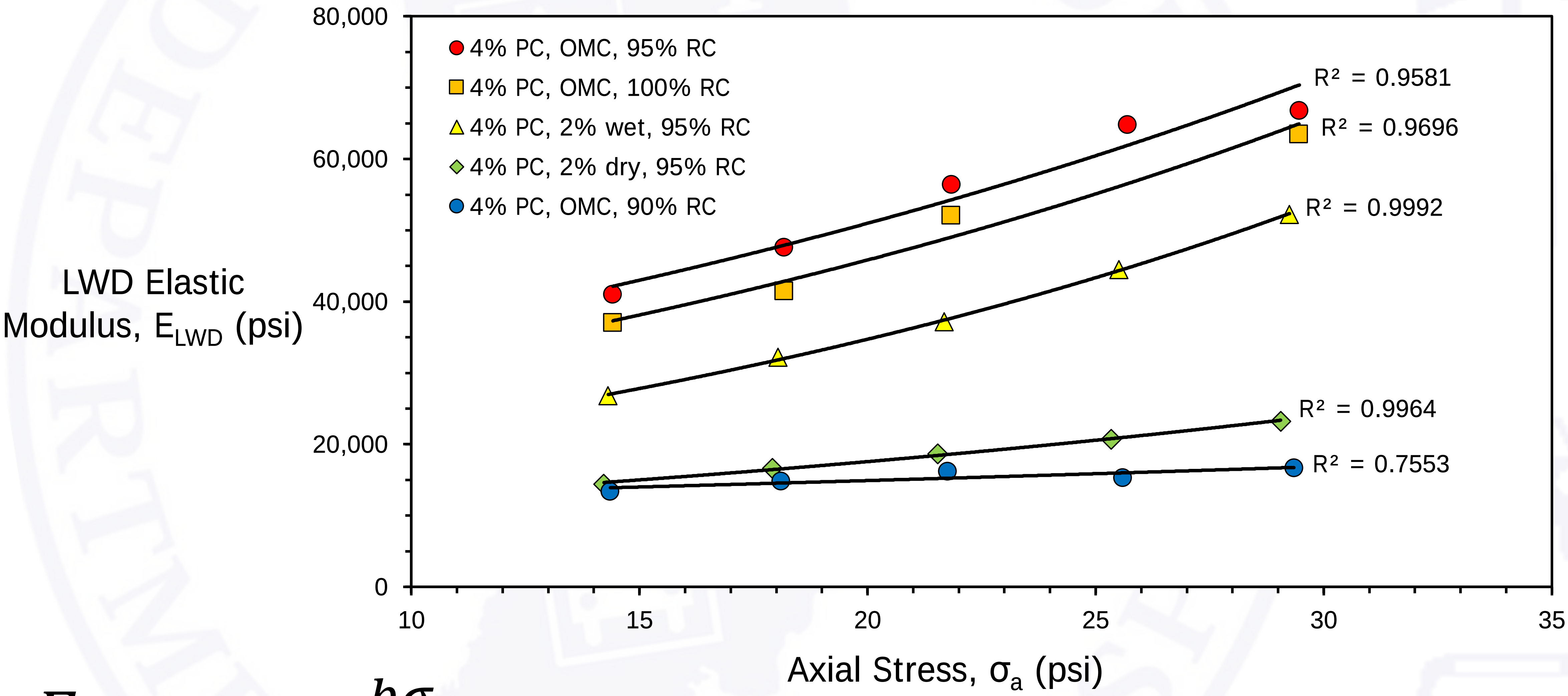
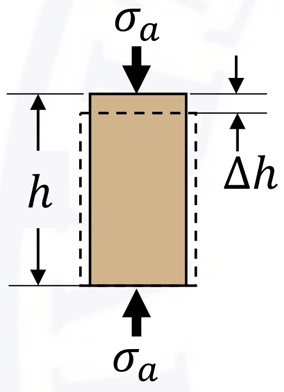
Relationship Between E_{LWD} and Axial Stress (σ_a)



$$E_{LWD} = ae^{b\sigma_a}$$

Predicting In Situ E_{LWD}

In the lab...



$$\varepsilon_{LWD} = \frac{\Delta h}{h}$$

$$E_{LWD} = ae^{b\sigma_a}$$

$$\sigma_a = (\varepsilon_{LWD})(E_{LWD})$$

$$E_{LWD} = a\exp[b(\varepsilon_{LWD})(E_{LWD})]$$

In the field...

$$\varepsilon_{LWD} = \frac{1}{E_{LWD}}[\sigma_z - \nu(\sigma_r + \sigma_\theta)]$$

$$(\varepsilon_{LWD})(E_{LWD}) = \sigma_z - \nu(\sigma_r + \sigma_\theta)$$

For symmetric loading...

$$\sigma_r = \sigma_\theta$$

$$(\varepsilon_{LWD})(E_{LWD}) = \sigma_z - 2\nu\sigma_r$$

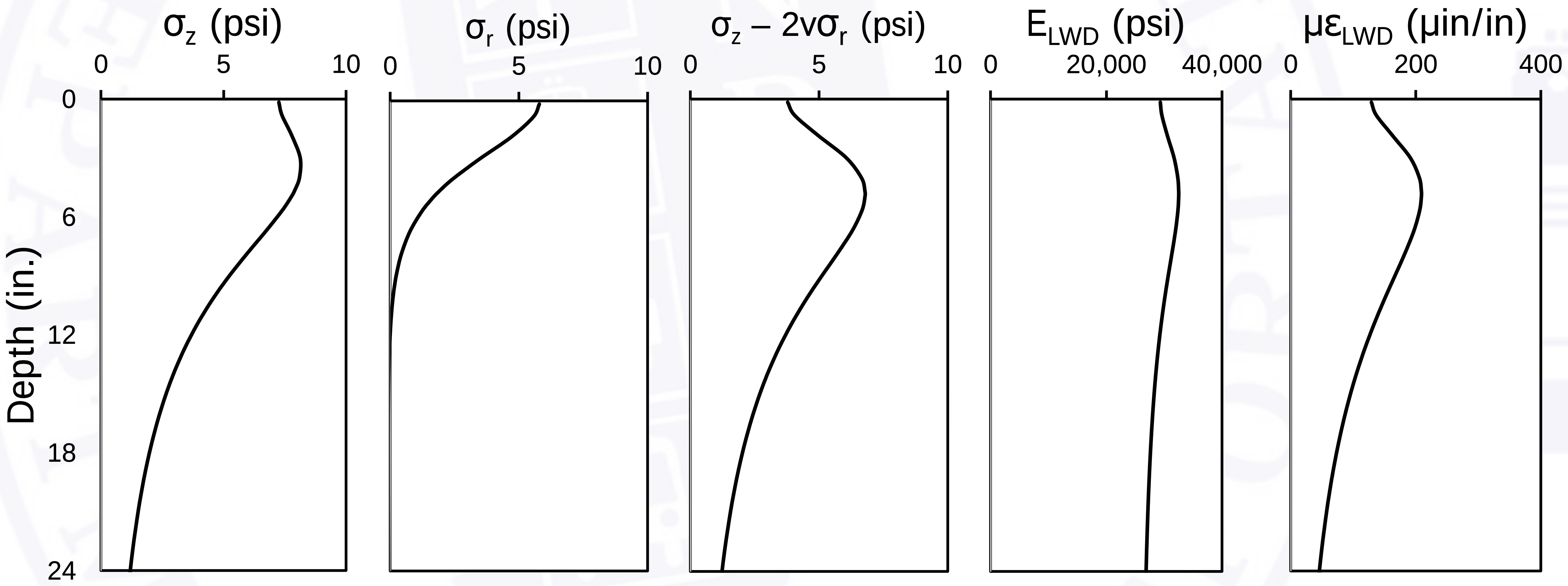
$$E_{LWD} = ae^{b(\sigma_z - 2\nu\sigma_r)}$$

Predicting In Situ E_{LWD}

Example: 4% cement; optimum moisture content; 95% relative compaction; v = 0.3 (assumed)

F_o = 1,589 lb; r_o = 5.91 in.

$$E_{LWD} = 25800e^{0.034(\sigma_z - 2\nu\sigma_r)}$$



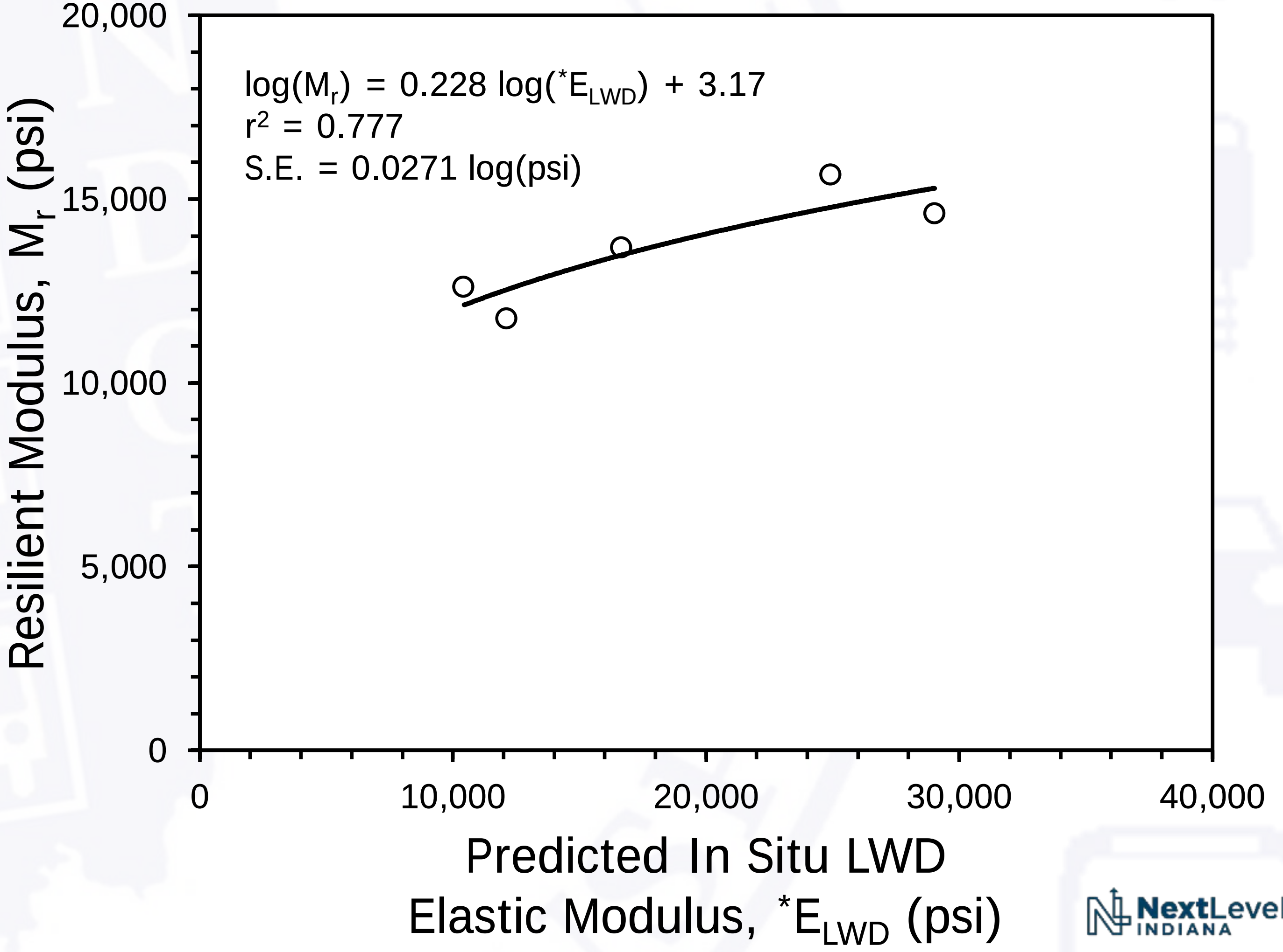
$$\delta_{LWD} = \int_0^{\infty} \varepsilon_{LWD}\, dz = 0.107 \text{ mm}$$

$$^{*}E_{LWD} = \frac{F_o(1-\nu^2)}{2r_o\delta_z} = 29{,}033 \text{ psi}$$

Correlating Predicted In Situ E_{LWD} with M_r

Resilient Modulus per AASHTO T 307

σ_3 = 2 psi, σ_d = 6 psi



Field Testing (2018 construction season)

I-65 near Frankfort (Crawfordsville District)

- Target 4% cement
- A-4 and A-2-4 subgrades
- 4 test sections

I-469 near Fort Wayne (Fort Wayne District)

- Target 5% cement
- A-6 subgrade
- 2 test sections

US-6 near Brimfield (Fort Wayne District)

- Target 4% cement
- A-1-b and A-4 subgrade
- 1 test section

Cleveland Road in South Bend (La Porte District)

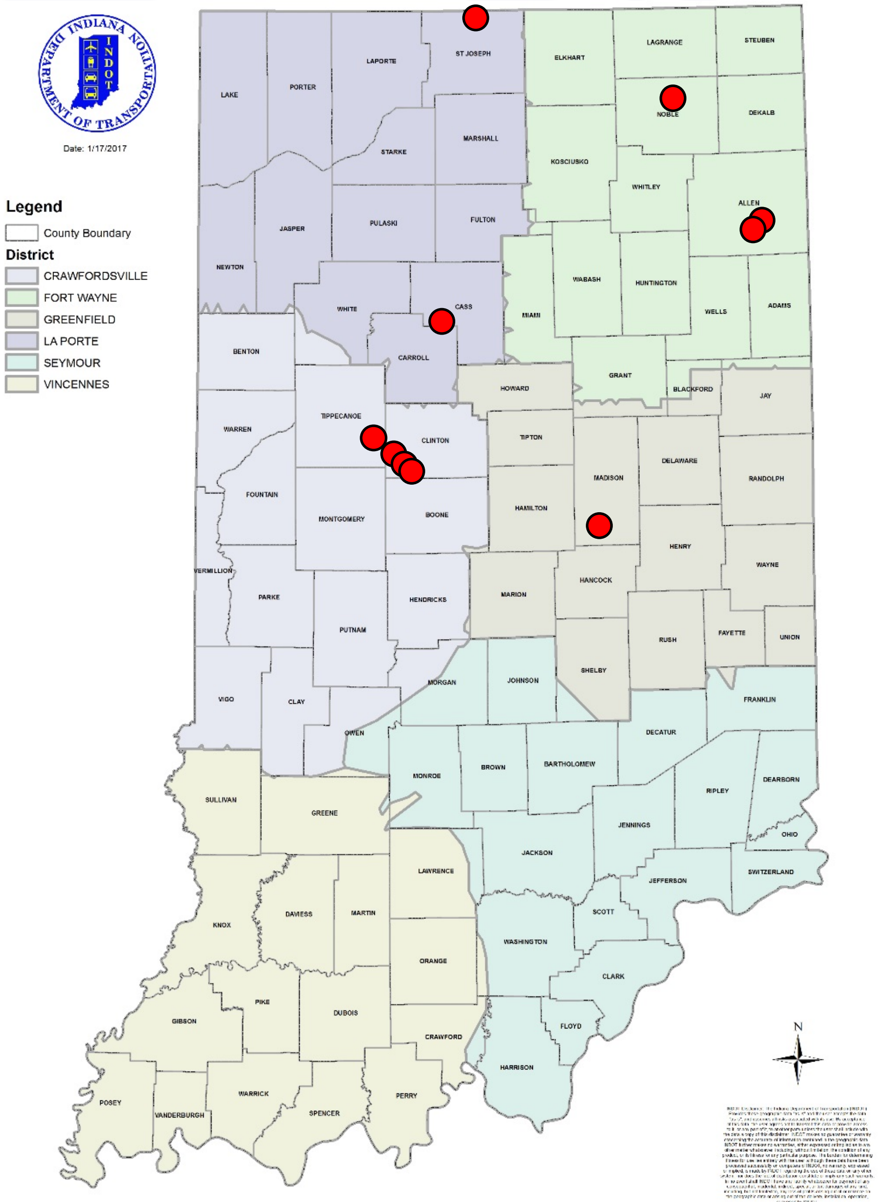
- Target 4% cement
- A-1-b
- 1 test section

CR 400 S near Clymers (La Porte District)

- Target 4% cement
- A-4
- 1 test section

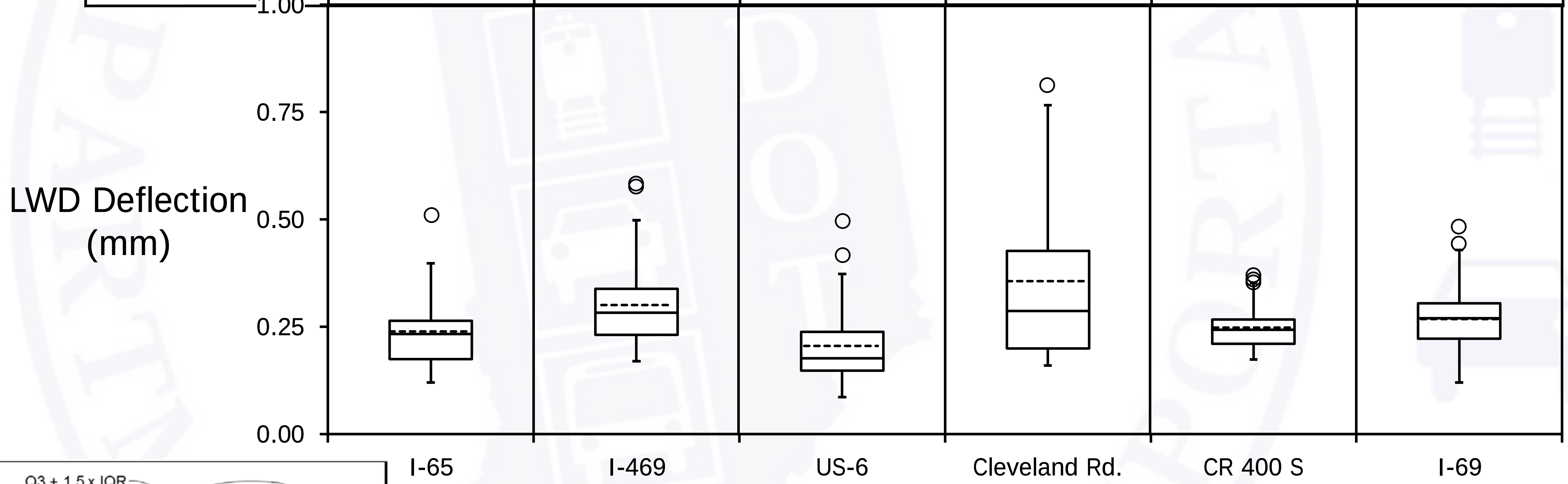
I-69 near Anderson (Greenfield District)

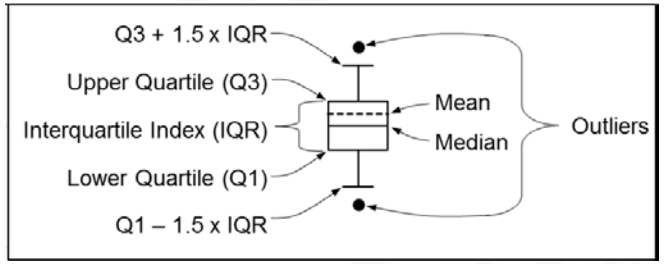
- Target 4% cement
- A-6
- 1 test section



Results of LWD Field Testing (LWD Deflection)

Average	0.239 mm	0.301 mm	0.206 mm	0.356 mm	0.249 mm	0.268 mm
Standard Deviation	0.076 mm	0.098 mm	0.102 mm	0.184 mm	0.059 mm	0.082 mm
Count	40	39	20	17	25	34

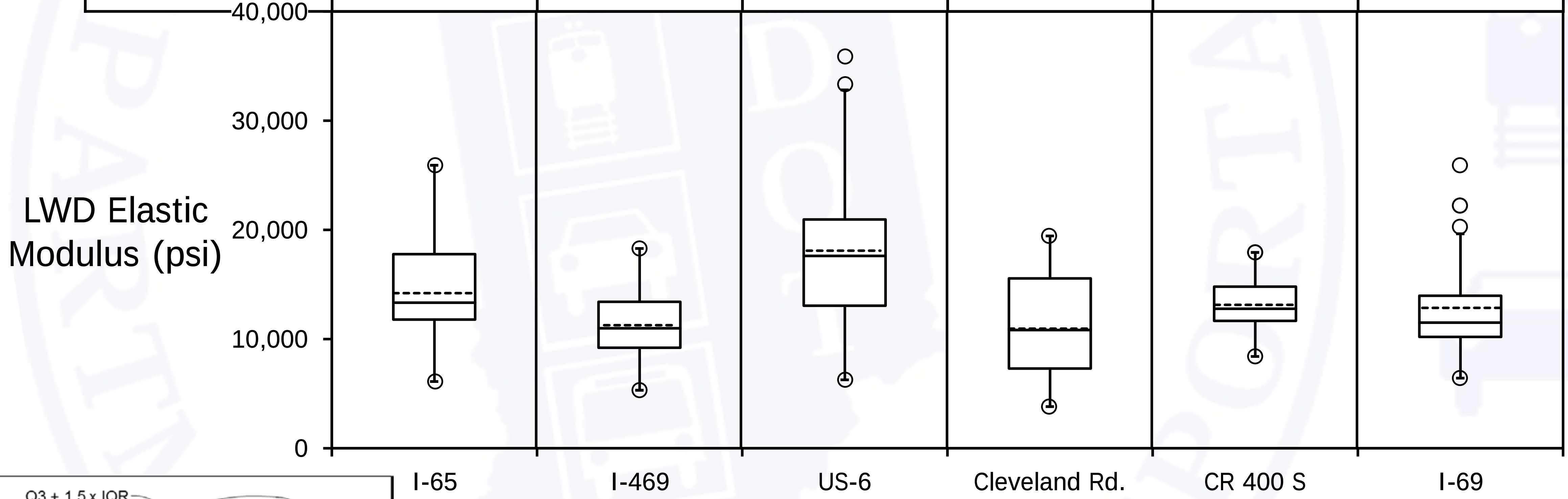


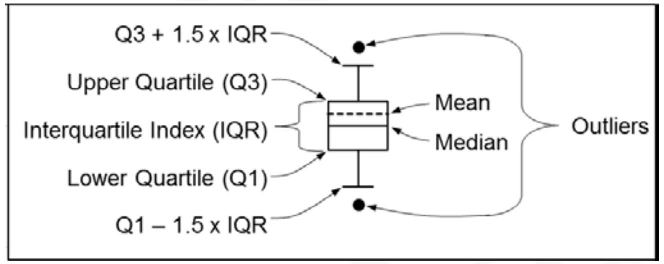


Average of all sections: 0.267 mm
Standard Deviation of all sections: 0.105 mm

Results of LWD Field Testing(LWD Elastic Modulus)

Average	14,213 psi	11,266 psi	18,081 psi	10,967 psi	13,150 psi	12,857 psi
Standard Deviation	4,147 psi	3,147 psi	7,396 psi	5,066 psi	2,894 psi	4,514
Count	40	39	20	17	25	34





$$E_{LWD} = \frac{F_o(1-\nu^2)}{2r_o\delta_z}$$

Average of all sections: 13,268 psi
Standard Deviation of all sections: 4,867 psi

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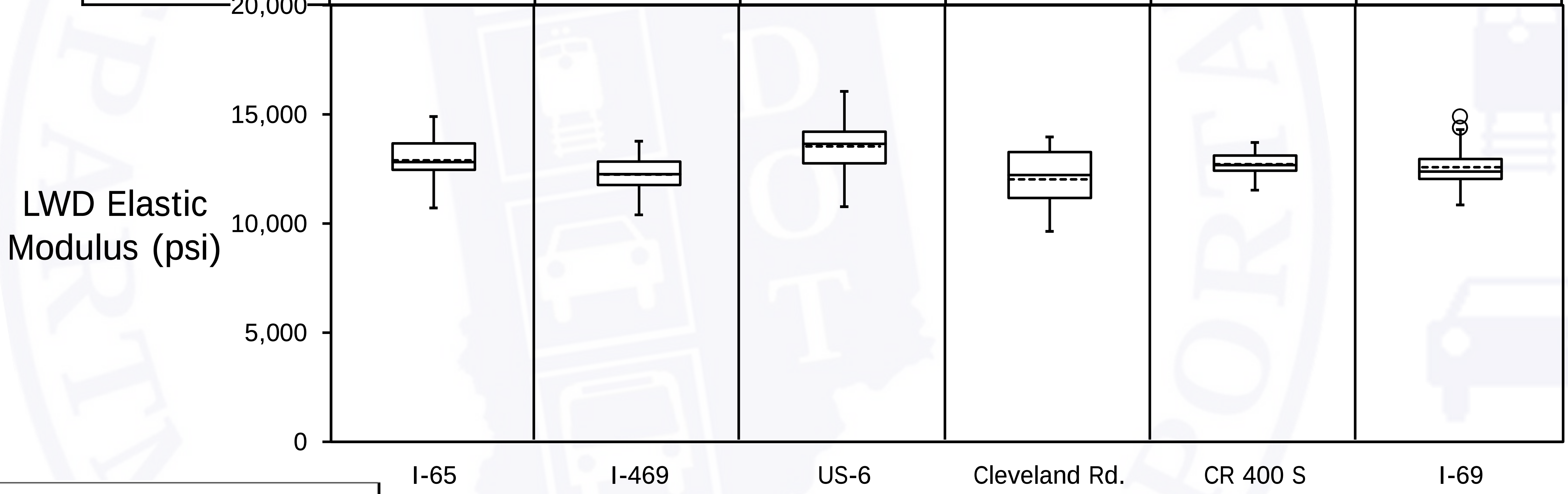
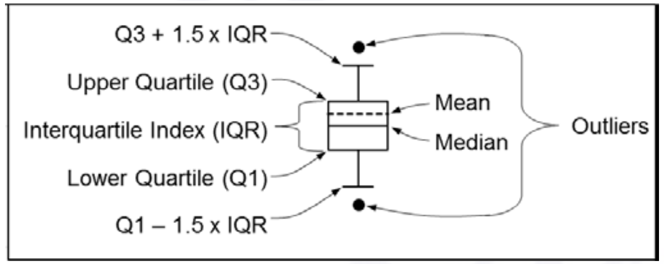
Results of LWD Field Testing (LWD correlated resilient modulus)

Average	12,903 psi	12,241 psi	13,535 psi	12,020 psi	12,716 psi	12,586 psi
Standard Deviation	873 psi	813 psi	1,309 psi	1,347 psi	657 psi	940 psi
Count	40	39	20	17	25	34





$$M_r = 1480 ^* E_{LWD}^{0.228}$$

Average of all sections: 12,654 psi
Standard Deviation of all sections: 1,039 psi

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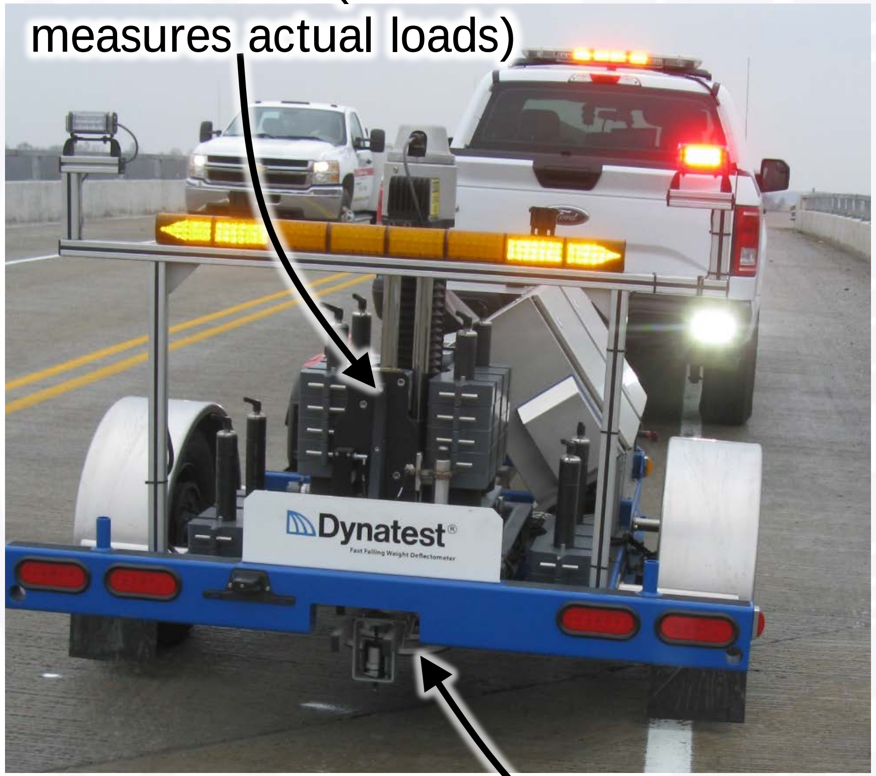
Falling Weight Deflectometer (FWD)

Applies 7 kip, 9 kip, & 11 kip nominal loads (load cell measures actual loads)



11.81 in. diameter loading plate

Geophones measuring surface deflection basin to nearest 0.01 mil

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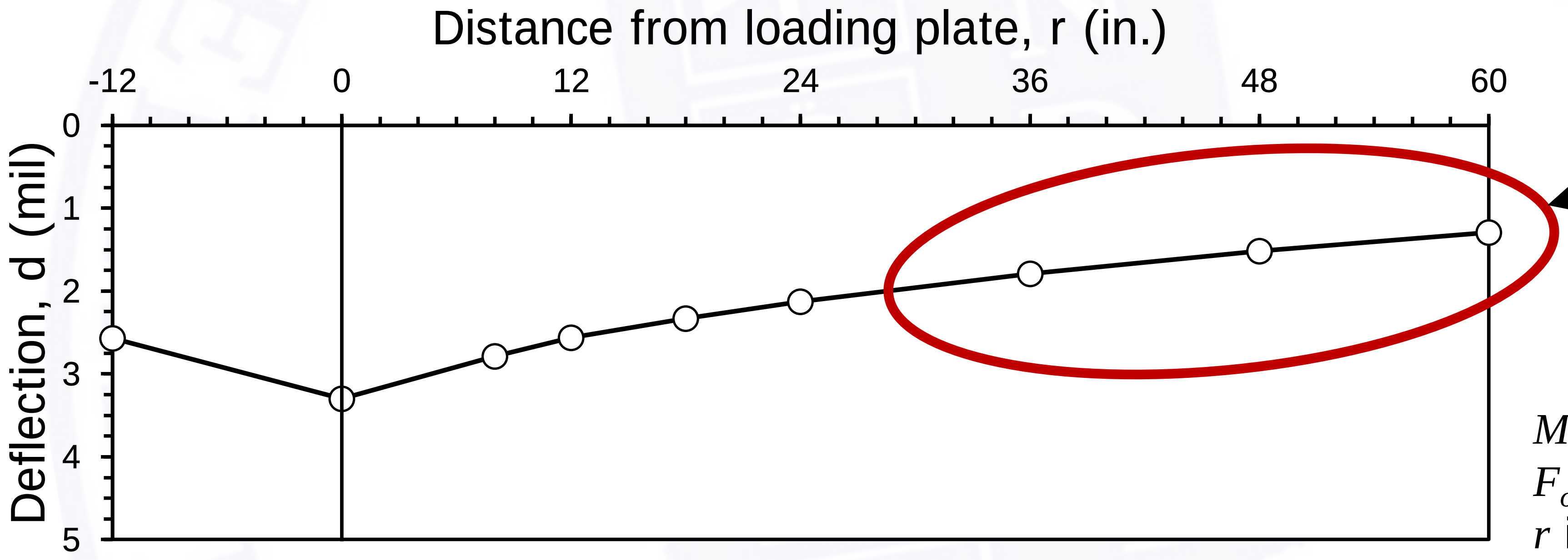
Backcalculation of Subgrade Resilient Modulus from FWD

Example: I-469 NB STA 707+00



Subgrade is primary source of deflection far away from the loading plate (≳ 36 in.)

$$M_r = C\frac{0.24F_o}{d\,r}$$

AASHTO (1993)

M_r is resilient Modulus
F_o is applied force
r is distance from loading plate
d is surface deflection
C is a correction factor (equals 0.33)

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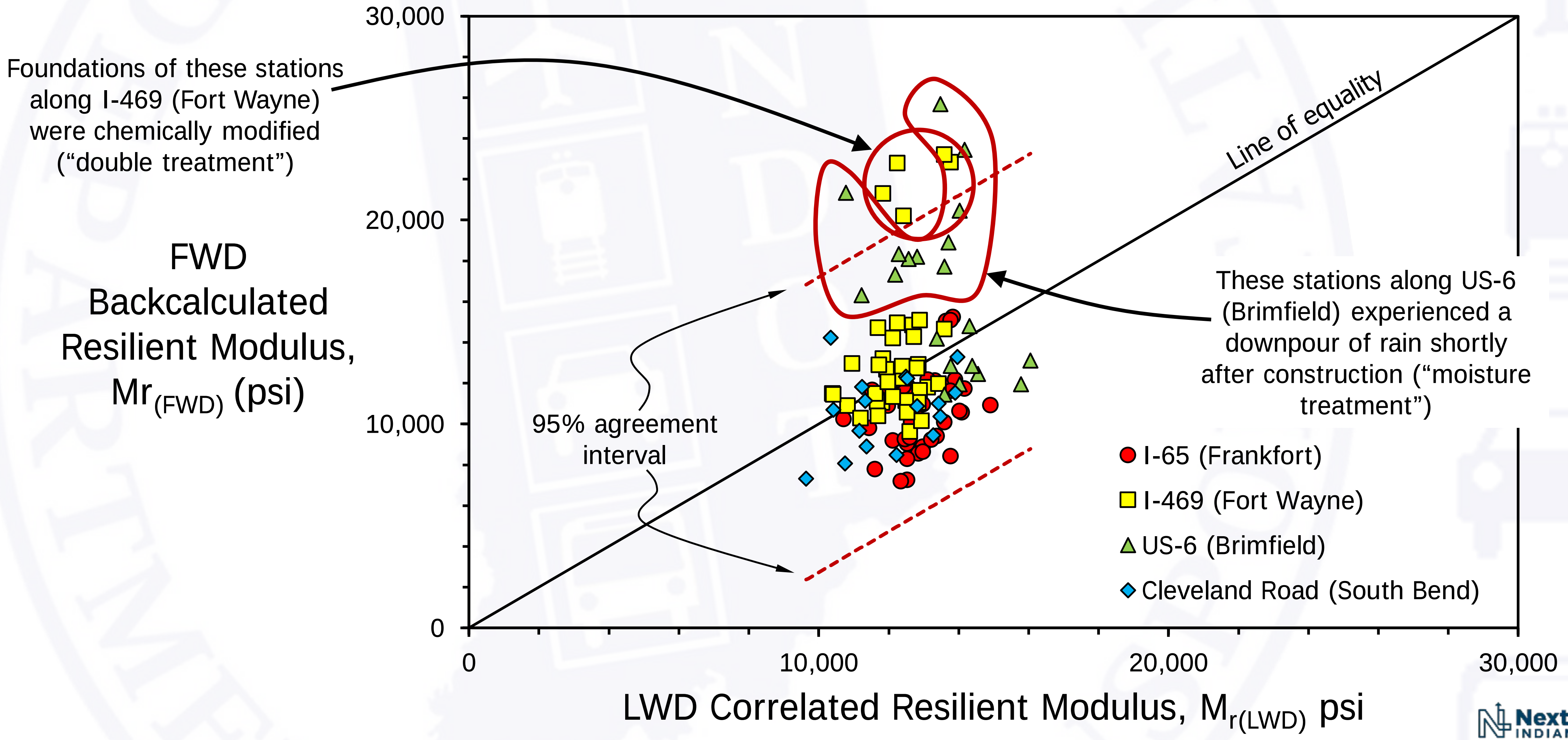
LWD and FWD Resilient Modulus Agreement



Key Findings

- The LWD measures in situ soil stiffness (LWD elastic modulus) that relate to pavement subgrade performance
- Although LWD elastic modulus and resilient modulus are not one and the same, they do correlate well with one another
- Field LWD tests provide validation of proposed LWD elastic modulus and resilient modulus correlation
- Resilient moduli correlated from LWD testing are in agreement with resilient moduli backcalculated from FWD testing

Future Work

- Improve correlation between predicted LWD deflection and resilient modulus (more samples from more soil types)
- LWD and FWD measurements from INDOT contracts during the 2019 construction season
  - Use better model for backcalculating resilient modulus from FWD
- Provide recommendations for subgrade construction acceptance
  - Maximum LWD deflection
  - Testing frequency
  - Effect of curing time
- Publish findings in JTRP technical report

Acknowledgements

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Thank you for your attention

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