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Advancing the Practice of Cyclic Softening Assessments of Silts and Clays

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19 September 2022

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Study Objectives

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- Leverage an ongoing, long-range study of the cyclic behavior of silt soils in the PacNW and beyond
- Provide an avenue for estimating cyclic strength in the absence of site-specific cyclic laboratory testing
  - Assess the risk of cyclic softening within the Simplified Method
  - Plan laboratory testing programs
  - Calibrate advanced constitutive models for numerical dynamic analyses
- Provide shear strain-dependent estimates of cyclic resistance
- Improve our understanding of the loading that can be anticipated from the CSZ (*MSF*, N_{eq})

Simplified Method for Cyclic Softening
Boulanger & Idriss (2007)

- Typical underpinning of the Simplified Method:

$$FS = \frac{CRR}{CSR}$$

- Linked to the cyclic failure criterion of γ = 3% shear strain
- Seismic loading may be estimated using:

$$CSR = 0.65\frac{\tau_{peak}}{\sigma'_{vc}} = 0.65\frac{\sigma_{vc}}{\sigma'_{vc}}\frac{a_{max}}{g}r_d$$

r_d = shear stress reduction factor

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[Study Sites & Database]

Study Sites

Largely Focused on Silts (~2016)

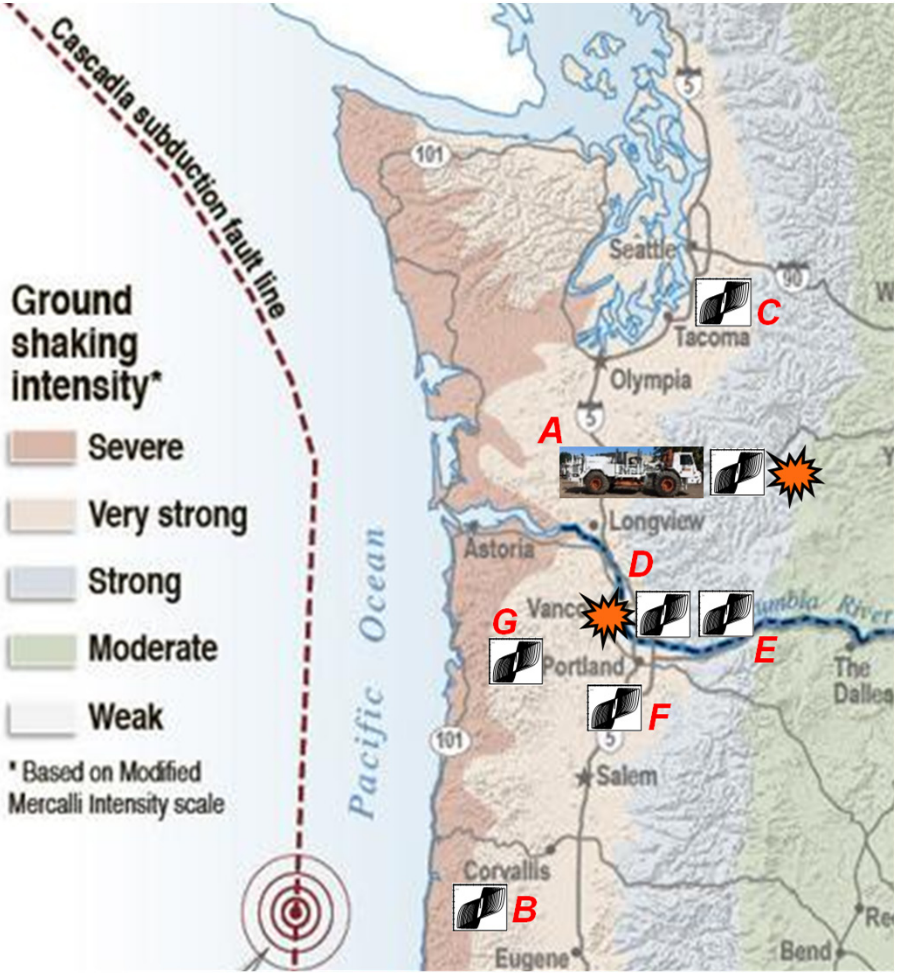
Research Approach:

- Cyclic Direct Simple Shear Tests
- Controlled Blasting
- Vibroseis Truck, T-Rex 

Each site includes: Sampling + testing, CPT, V_s

Test Sites:

- Site A: Barlow Point, Longview, WA 
- Site B: Van Buren Bridge, Corvallis, OR
- Site C: Tacoma, WA
- Site D: Port of Portland, PDX, Portland, OR
- Site E: Port of Portland, PDX-TS4, Portland, OR
- Site F: Boone Bridge, Wilsonville, OR
- Site G: Portland, OR



Database* (*by the numbers*)

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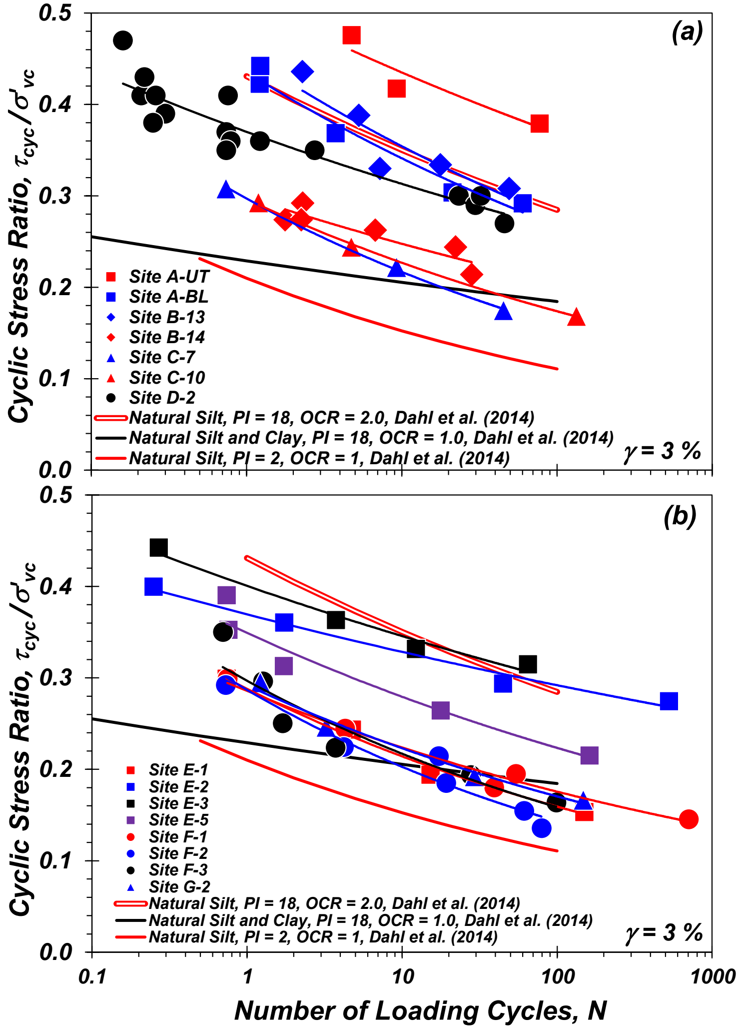
Contributed by consultants (Sites H, I, J)

Site	A	B	C	D	E	F	G	H	I	J
Location	Columbia River, Longview, WA	Willamette River, Corvallis, OR	Tacoma, WA	Columbia River, Portland, OR	Columbia River, Portland, OR	Willamette River, Wilsonville, OR	Willamette River, Portland, OR	Anchorage, AK	Newport, OR	Victoria, BC
Number of Stress-Controlled Cyclic Tests	8	11	6	16	27	17	4	3	3	4
Range in Sample Depth (m)	2.4 - 3.2	2.4 - 9.3	5.3 - 9.1	9.1 - 11.2	7.3 - 12.0	6.2 - 10.1	14.6 - 15.2	3.5 - 7.9	3 - 9.6	4.7 - 6.8
Natural Water Content, w_n (%)	44 - 59	38 - 62	40 - 44	75	39 - 92	28 - 43	44	23 - 31	37 - 62	14 - 24
Liquid Limit, *LL* (%)	39 - 51	39 - 48	35 - 40	70	38 - 81	28 - 50	35 - 40	32	76	NA
Plasticity Index, *PI* (%)	10. - 19	11. - 16	9	14 - 39	10. - 28	0 - 20	10	0 - 12	0 - 29	1. - 23
Vertical Effective Consolidation Stress, σ'_{vc} (kPa)	32 - 36	50 - 160	80 - 100	98 - 112	95 - 215	150 - 160	160	60 - 105	78 - 411	82 - 105
Overconsolidation Ratio, *OCR*	3.0 - 4.2	1.4 - 2.0	1.5 - 1.6	1.6 - 2.2	1.0 - 2.2	1.0 - 2.7	1.2	1.9 - 2.6	1 - 1.6	4

Natural, intact specimens at σ'_{v0} + limited artificially-NC, only

Synthesis(?) of Cyclic Resistance

- Novel data in the silt database shown here (w/ some previously-reported data)
- On the surface, cyclic resistance appears to vary significantly for the study sites
- Trends in *CRR* need to be extracted and synthesized
- Statistical regression analysis provides the means to tease out predictor variables



[Regression Analysis: Models for Cyclic Resistance]

Regression Models Developed

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Model	Discussed Today?
Exponent ***b*** in ***CRR = aN***$^{-b}$	**Yes**
Strain-dependent model for cyclic resistance ratio, ***CRR***	
- with PI-agnostic exponent (γ = 0.5 to 10%)	**Yes**
- with PI-dependent exponent (γ = 0.5 to 10%)	*No*
Strain-dependent model for cyclic strength ratio, τ_{cyc}/s_u	*No*
Magnitude scaling factors and N_{eq} for subduction zone earthquakes (M_w: 6 to ~9.2)	~ *Yes*

Staged Regression Analysis

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Stage 1: Explore trends and basic functional forms for various models

- Consider only those specimens sheared under *in-situ* stress conditions, and in some cases elevates stresses to identify *NC* behavior
- Divide high-quality dataset into two groups:
  - Training dataset: 50 to 90 (depends on strain magnitude)
  - Testing dataset: 15 to 30
- Evaluate trends and confirm suitability of proposed statistical models

Stage 2: Develop final statistical models using full dataset

Statistical Model for Exponent b

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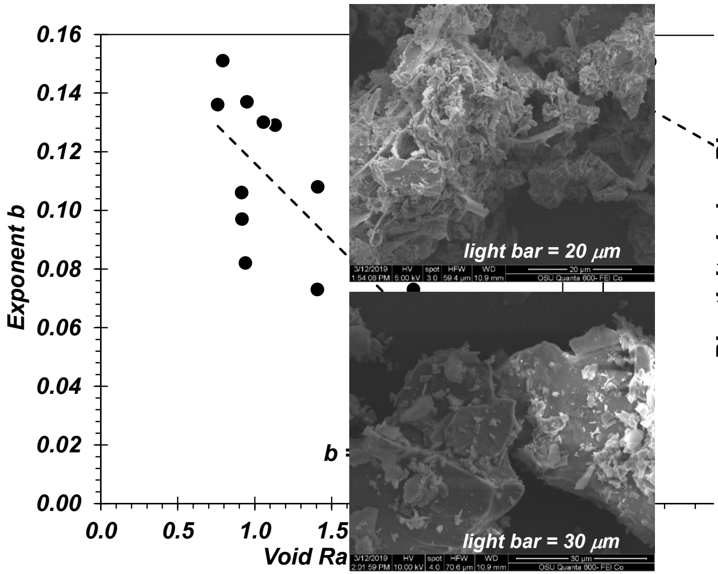
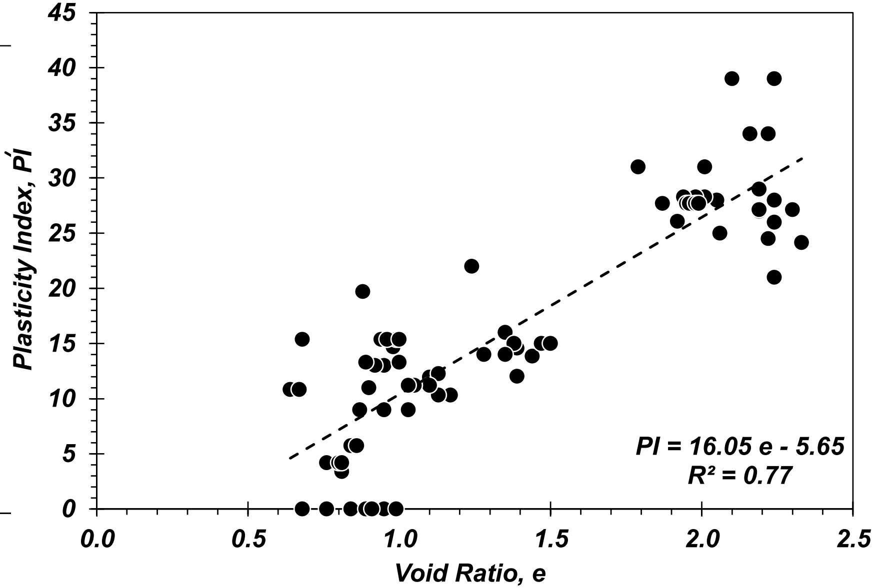
- First check: which independent variables suitably predict the exponent *b* in $CRR = a\,N^{-b}$
- Void ratio, *e*: strong correlation to *b* ($R^2 = 0.65$), *p*-value < $1E^{-3}$
- Plasticity index, *PI*: strong correlation to *b* ($R^2 = 0.66$), *p*-value < $1E^{-3}$
- *OCR*: no correlation, disregarded
- ISSUE: *e* and *PI* **strongly correla**





Statistical Model for Exponent *b*

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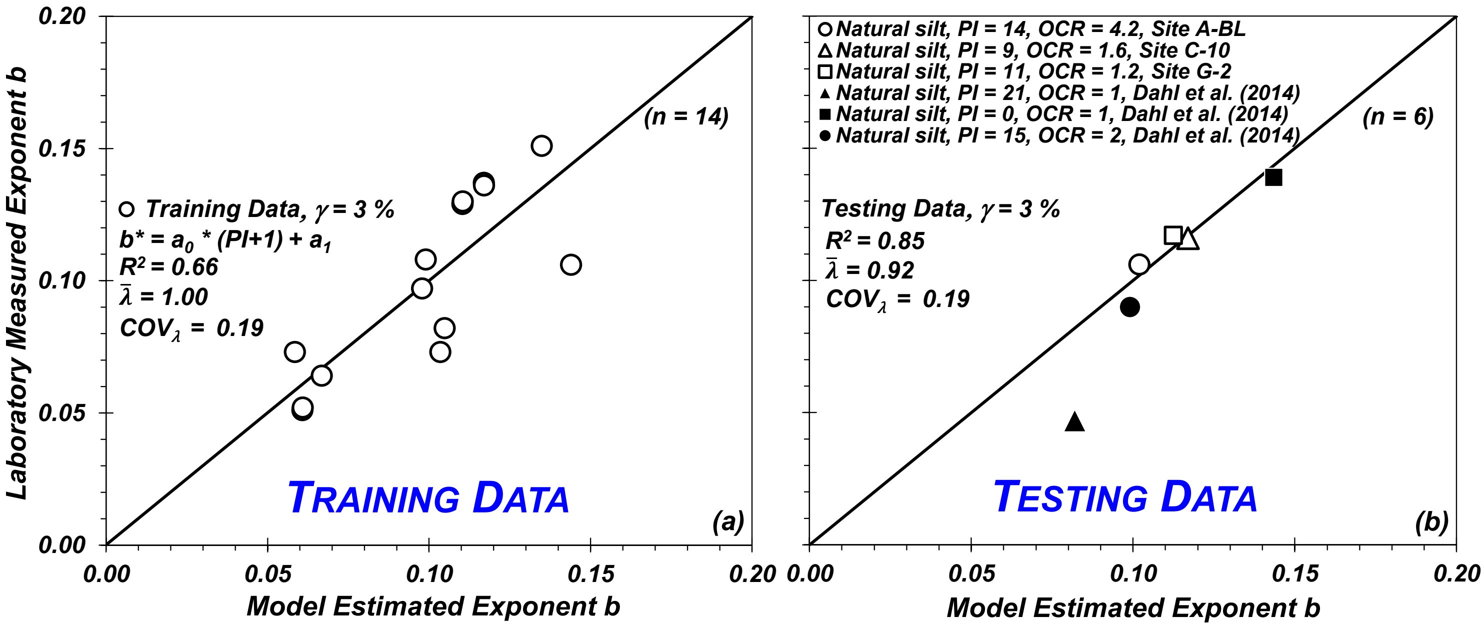
- Proposed exponent *b* model: $b = a_0*(PI+1) + a_1$
- Goodness of fit evaluation with point bias, λ:

$$\lambda = \frac{b_{measured}}{b_{estimated}}$$

and:

$$COV_\lambda = \frac{\sigma_\lambda}{\bar{\lambda}}$$



Statistical Model for Exponent *b*

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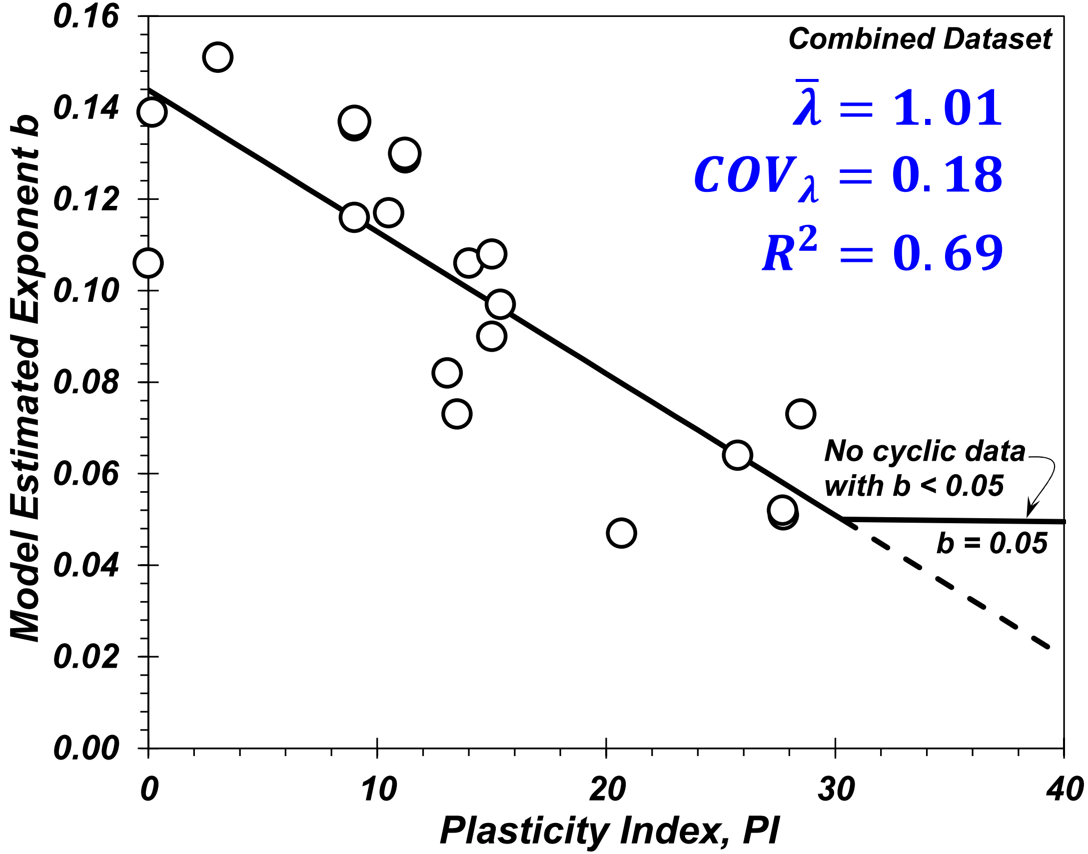
- **FINAL MODEL (combined dataset):**
  - $b = a_0 * (PI+1) + a_1$

    $a_0 = -0.0031$; *p-value* $< 1E^{-05}$

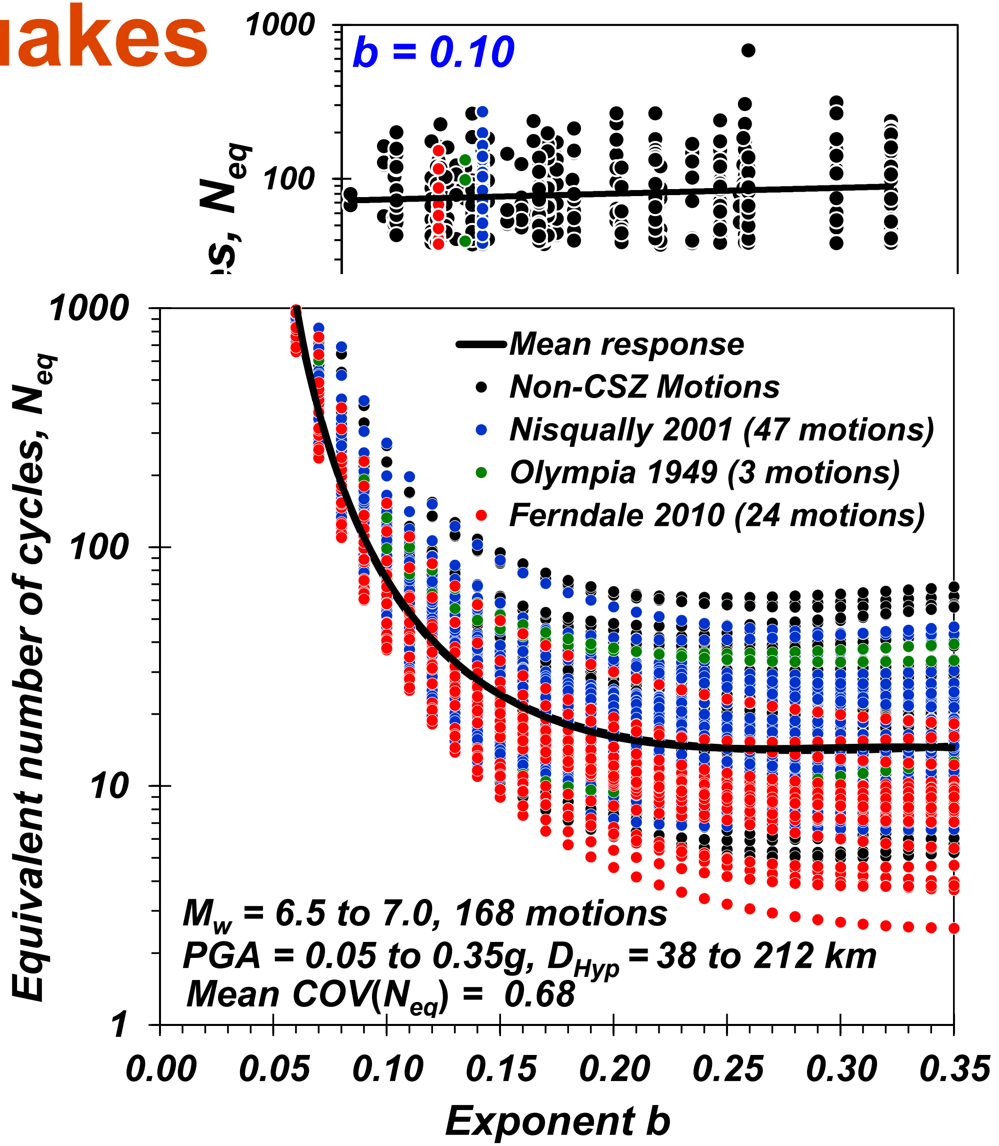
    $a_1 = 0.147$; *p-value* $< 1E^{-11}$
  - Compare to $b = 0.135$ assumed for plastic silts in original Simplified Method
  - Based at limited data available at that time

$$b = 0.147 - 0.0031\,(PI + 1)$$



Subduction Zone Earthquakes = *Large* N_{eq}

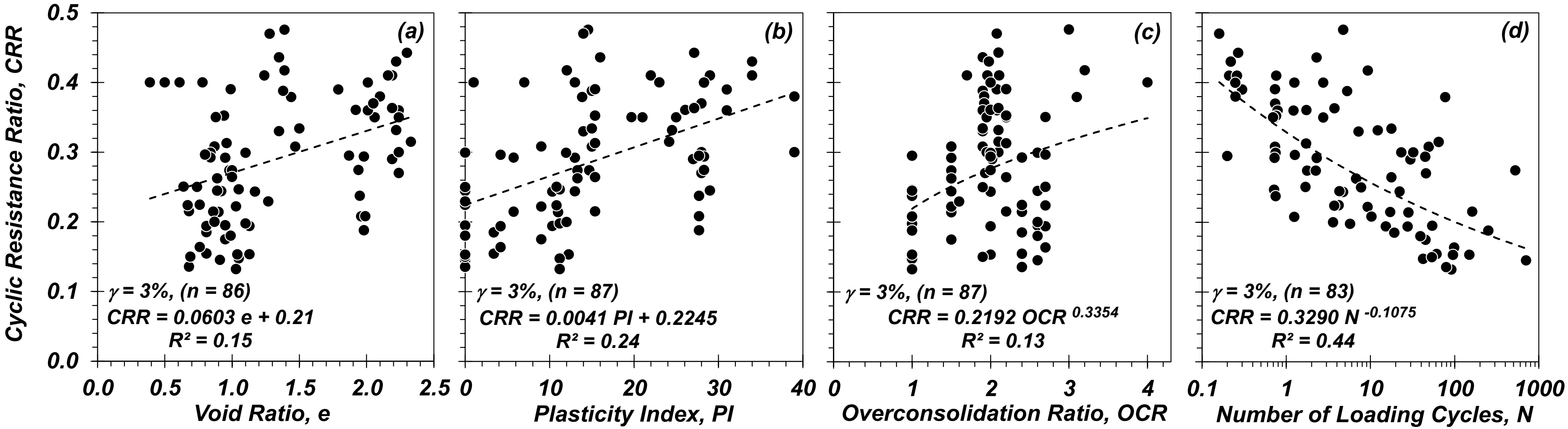
- Resistance: $CRR(N_{\gamma=3\%}) = \frac{\tau_{cyc}}{\sigma'_{v0}} = a \cdot N^{-b}$
- Curvature of the power law driven by ***PI*** → number of loading cycles driven by ***PI***
- Effect of ***b*** on N_{eq} assessed using motions screened from *NGASub* database
- For typical ***b*** = **0.1** (low *PI* silts):
  - M_w = 9.0, N_{eq} ranges from *40* to *300*, w/ mean $N_{eq} \approx 93$
  - M_w = 6.8, N_{eq} ranges from *37* to *273*, w/ mean $N_{eq} \approx 74$



Statistical Model for *CRR-N* (γ = 3%)

- First check: which independent variables suitably predict **CRR = a *N*** $^{-b}$
- Void ratio, *e*: weak, linear correlation (R^2 = 0.15)
- Plasticity index, *PI*: weak, linear correlation (R^2 = 0.24)
- *OCR*: weak, power law correlation (R^2 = 0.13)
- Number of cycles, *N*: moderate power law correlation (R^2 = 0.44)

All Statistically Significant



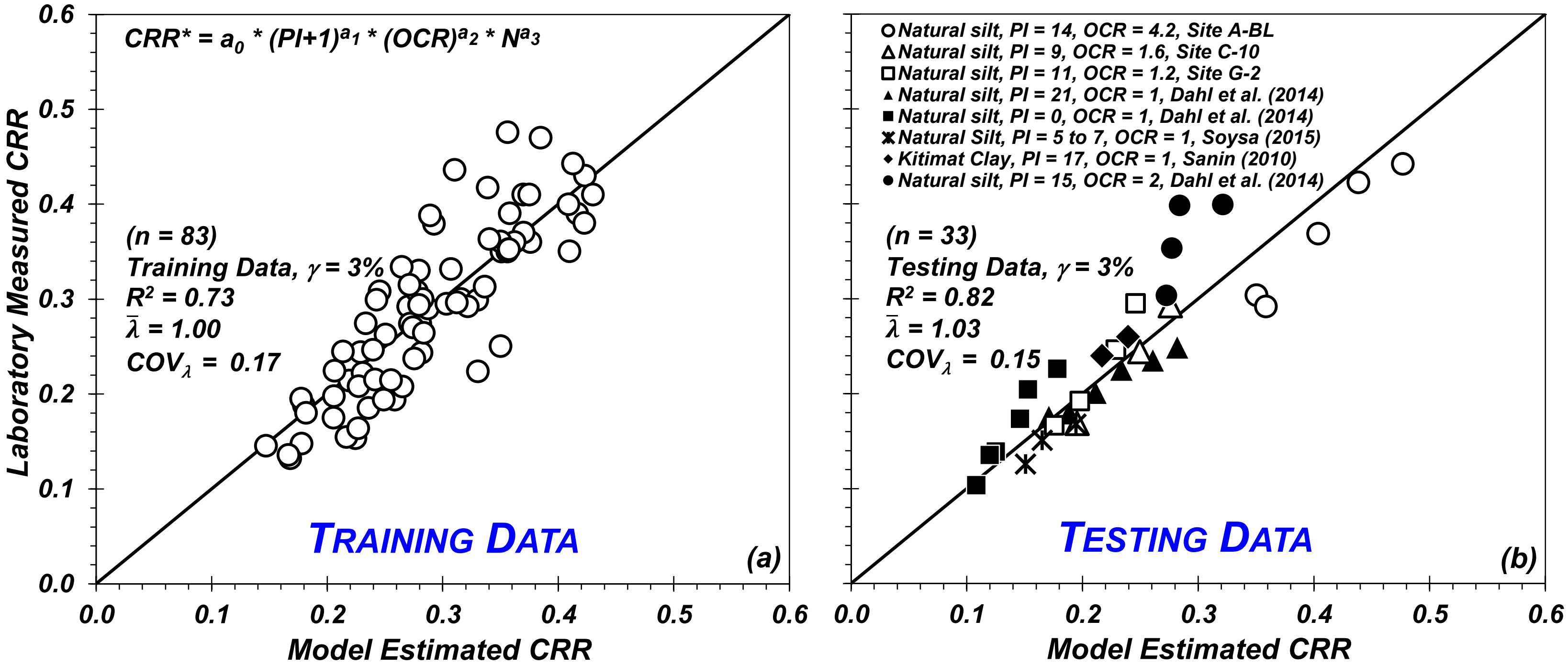
Statistical Model for *CRR-N* (γ = 3%)

- Example model fit with training dataset and evaluation using testing dataset: $CRR = a_0 (PI + 1)^{a_1} OCR^{a_2} N^{a_3}$
- *p*-value < $1E^{-10}$ all a_i
- Final model:

$\bar{\lambda} = 1.00$

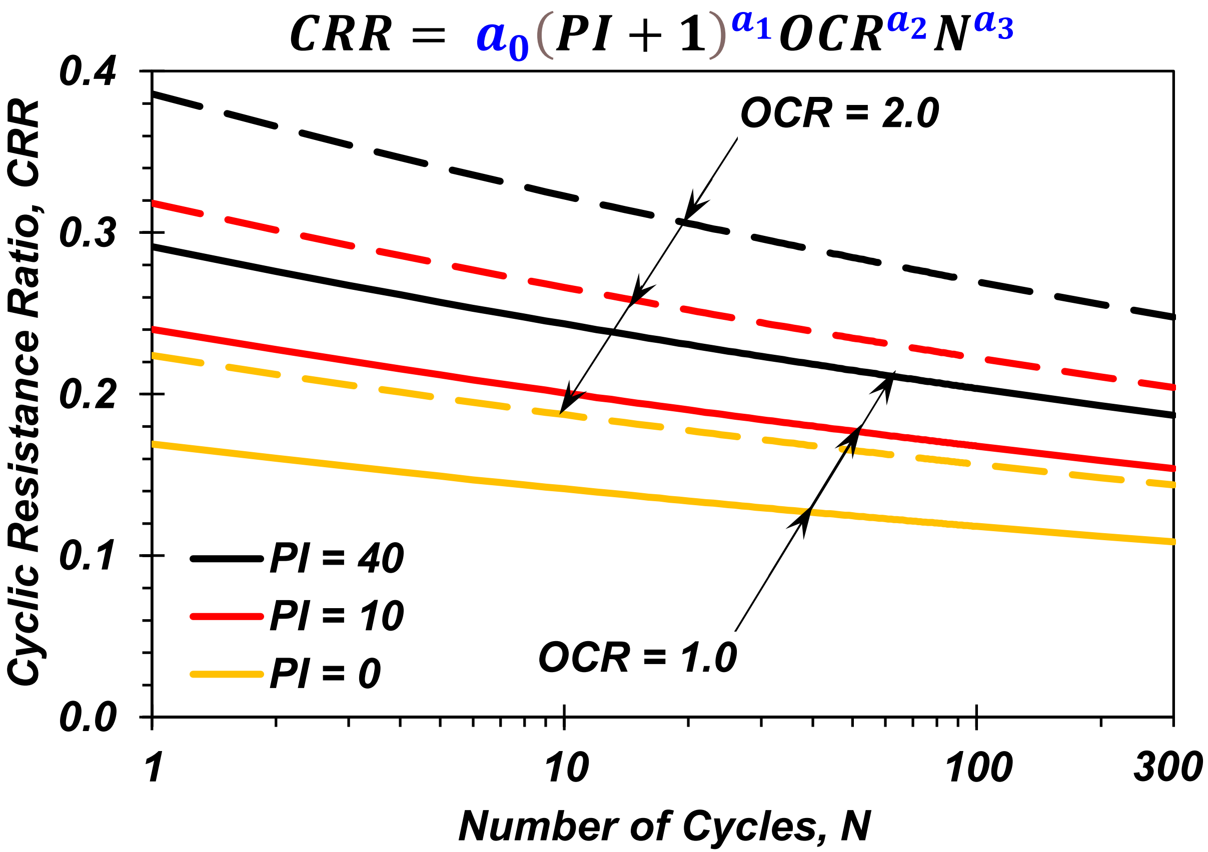
$COV_\lambda = 0.16$

$R^2 = 0.76$



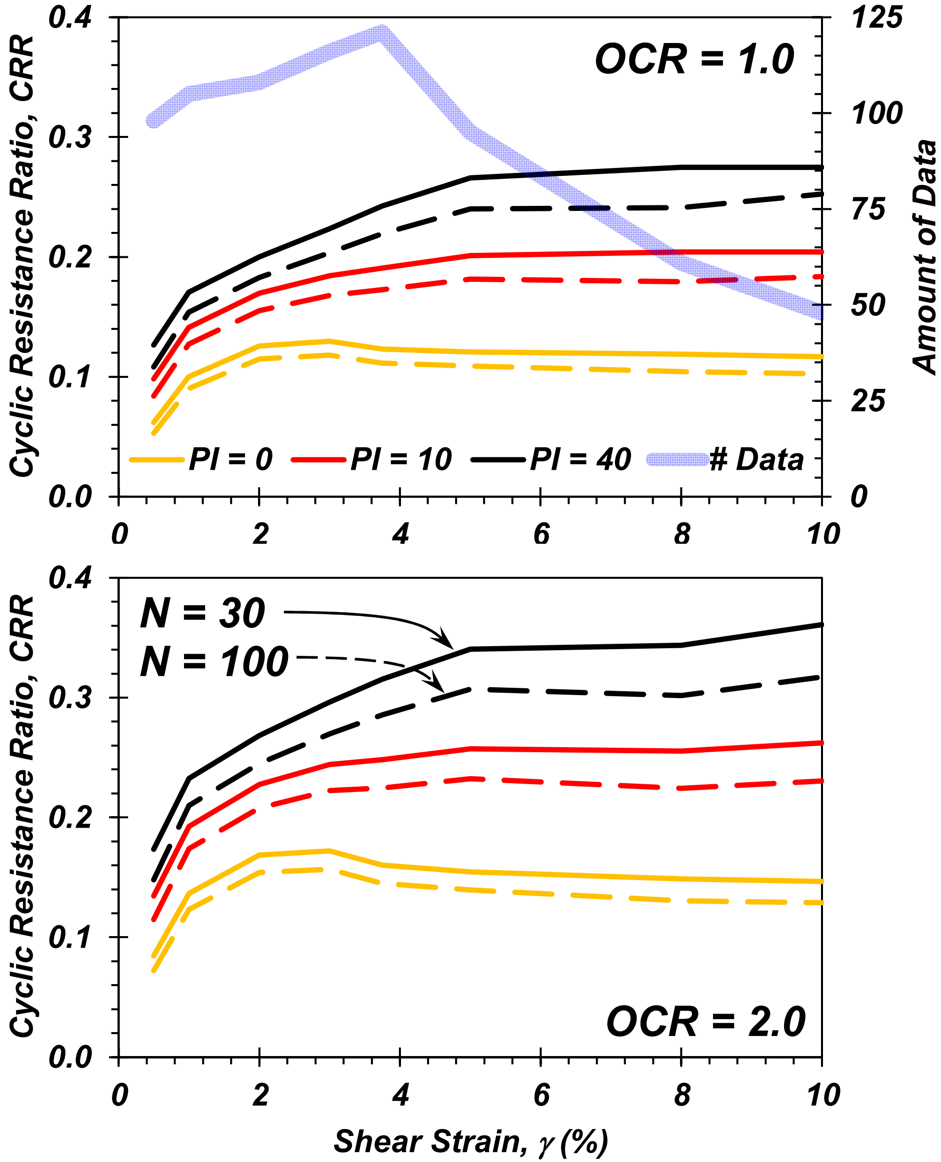
Statistical Model for *CRR-N* (γ = 3%)

- Strain-dependent formulation with constant functional form
- Each predictor variable statistically significant
- Increases in *OCR* → increases in *CRR*
- Low plasticity silts > nonplastic
- Additional increase in *PI* produces smaller increment in *CRR* gain



Strain-Dependence

- All fitted model parameters statistically significant
- 100⁺ specimens to γ = 3.75%, then a rather sharp reduction (data dominated by OSU dataset)
- "True" fitted parameters may be approached as # specimens increases (*in the future*)
- Facilitates checks on site response, constitutive model calibration
- Seamless integration with Simplified Method for Cyclic Softening



[Concluding Remarks]

Concluding Remarks

- Proposed statistical models capture cyclic resistance over a wide range of variables
- Tools developed allow:
  - Estimates of the slope of the ***CRR-N*** curve, driven by exponent ***b*** in ***CRR*** = ***a N***$^{-b}$
  - Strain-dependent estimates of ***CRR-N*** and τ_{cyc}/s_u-***N*** curves
  - Estimates of N_{eq} using analyses of the NGASub Database, aid selection of ***CRR*** for a given magnitude earthquake
  - Planning of laboratory cyclic testing programs
  - Calibration of constitutive models in the absence of available data
- Stay tuned for G/G_{max} and ***damping*** curves from $\gamma = 10^{-5}$ to 10^{1}%