Mainstreaming of Micropiles: Probabilistic Calibration of Axial Resistance for Load and Resistance Factor Design

J. Erik Loehr, Ph.D., P.E.
Glen A. Barton Professor, University of Missouri

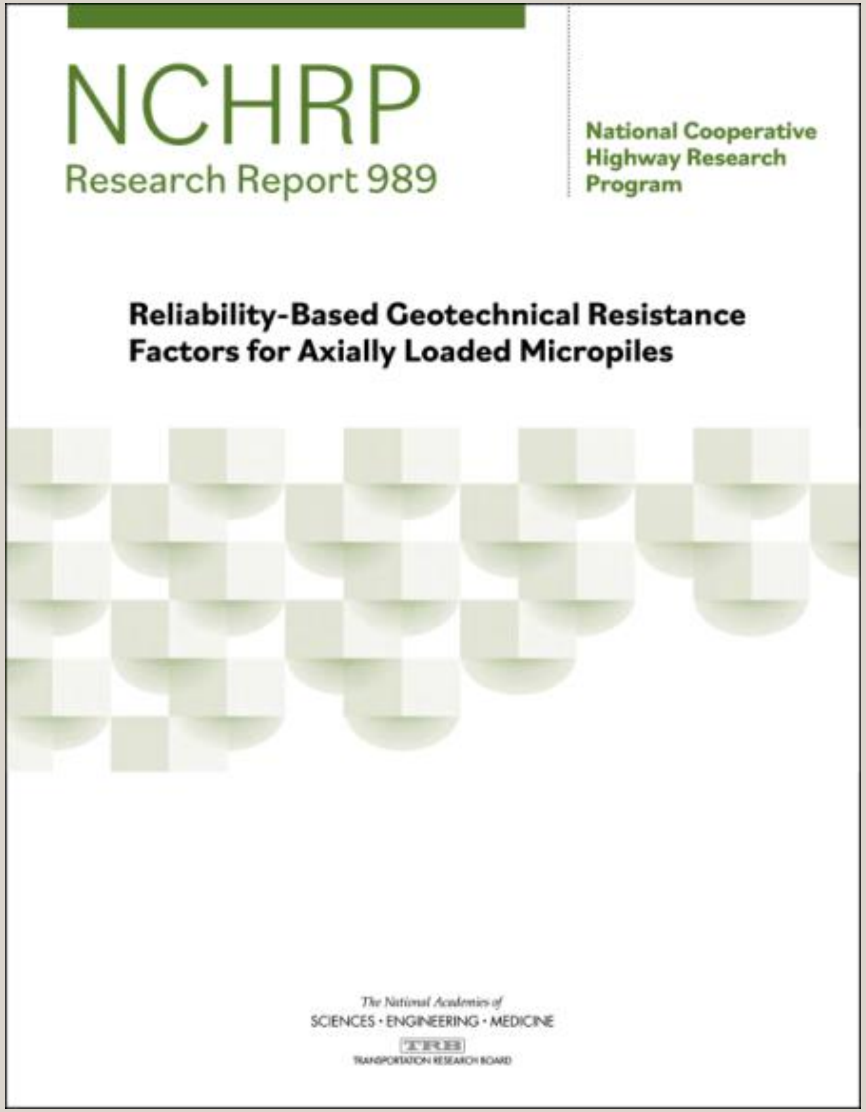
11th Lizzi Lecture, 15th International Workshop on Micropiles
Vail, Colorado
May 31, 2023

ISM INTERNATIONAL SOCIETY FOR MICROPILES

TAKING MICROPILES TO NEW HEIGHTS

15th International Workshop On Micropiles
The Sebastian | Vail, Colorado
May 31-June 2, 2023

Basis for presentation



NCHRP

Research Report 989

National Cooperative
Highway Research
Program

Reliability-Based Geotechnical Resistance Factors for Axially Loaded Micropiles

The National Academies of
SCIENCES · ENGINEERING · MEDICINE
TRB
TRANSPORTATION RESEARCH BOARD

- Conducted 2017-2019
- Key activities included:
  - Collection of load test records
  - Development and evaluation of design methods
  - Probabilistic calibration of resistance factors
  - Reporting and revisions to AASHTO LRFD Specifications
- Exclusively addresses geotechnical axial response

Current AASHTO Specifications

Limit State	ance Factor
Compression – Single MP	0.55
	0.50
	.5.2.3-1 <= 0.70
Block Failure	0.60
Uplift Resistance Single MP	0.55
	.5.2.3-1 <= 0.70
Uplift Resistance Group	0.50

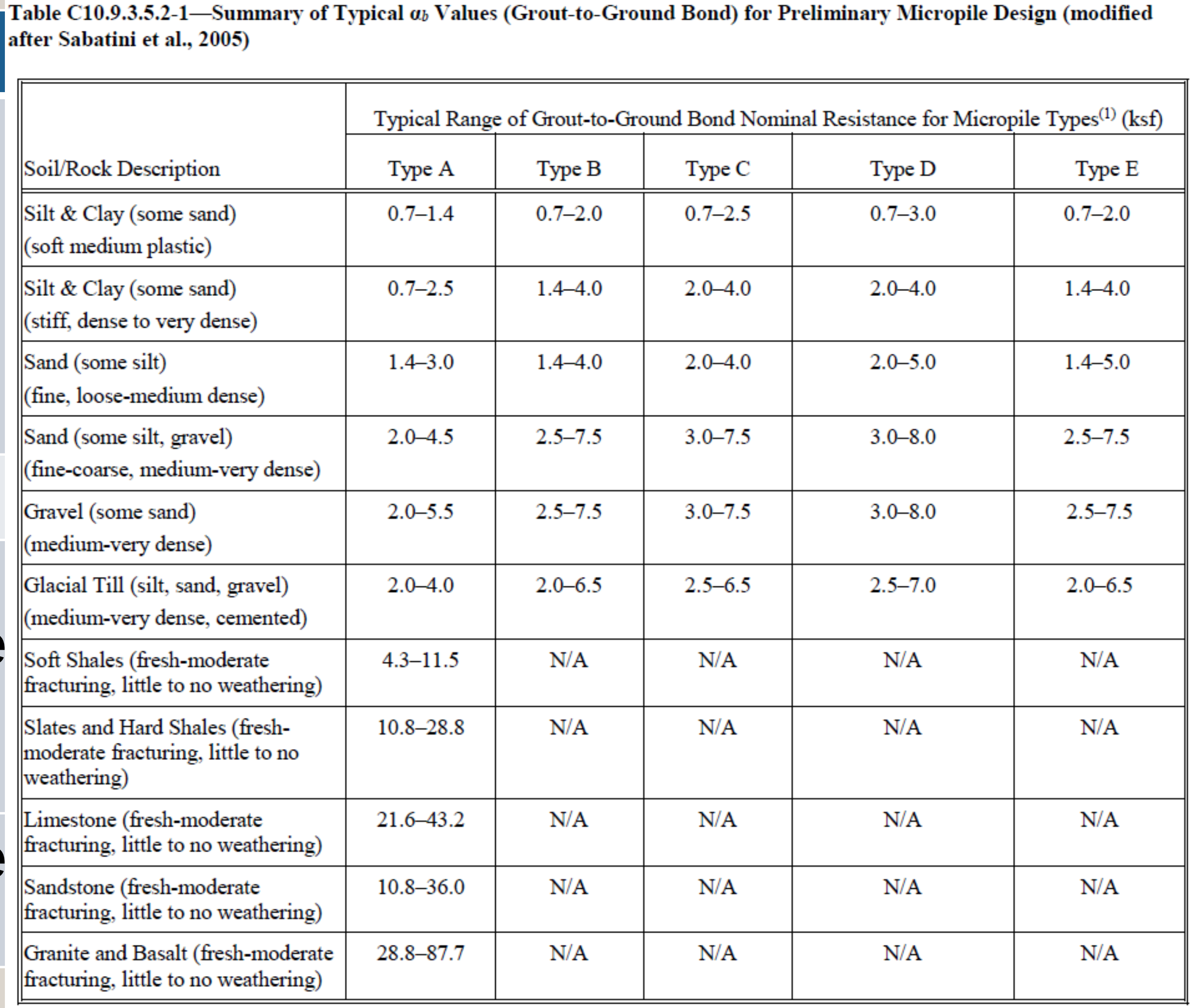
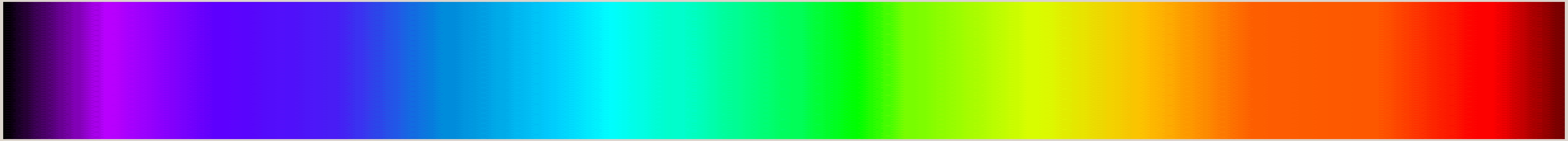


Table C10.9.3.5.2-1—Summary of Typical α_b Values (Grout-to-Ground Bond) for Preliminary Micropile Design (modified after Sabatini et al., 2005)

Soil/Rock Description	Typical Range of Grout-to-Ground Bond Nominal Resistance for Micropile Types[(1)] (ksf)				
	Type A	Type B	Type C	Type D	Type E
Silt & Clay (some sand) (soft medium plastic)	0.7–1.4	0.7–2.0	0.7–2.5	0.7–3.0	0.7–2.0
Silt & Clay (some sand) (stiff, dense to very dense)	0.7–2.5	1.4–4.0	2.0–4.0	2.0–4.0	1.4–4.0
Sand (some silt) (fine, loose-medium dense)	1.4–3.0	1.4–4.0	2.0–4.0	2.0–5.0	1.4–5.0
Sand (some silt, gravel) (fine-coarse, medium-very dense)	2.0–4.5	2.5–7.5	3.0–7.5	3.0–8.0	2.5–7.5
Gravel (some sand) (medium-very dense)	2.0–5.5	2.5–7.5	3.0–7.5	3.0–8.0	2.5–7.5
Glacial Till (silt, sand, gravel) (medium-very dense, cemented)	2.0–4.0	2.0–6.5	2.5–6.5	2.5–7.0	2.0–6.5
Soft Shales (fresh-moderate fracturing, little to no weathering)	4.3–11.5	N/A	N/A	N/A	N/A
Slates and Hard Shales (fresh-moderate fracturing, little to no weathering)	10.8–28.8	N/A	N/A	N/A	N/A
Limestone (fresh-moderate fracturing, little to no weathering)	21.6–43.2	N/A	N/A	N/A	N/A
Sandstone (fresh-moderate fracturing, little to no weathering)	10.8–36.0	N/A	N/A	N/A	N/A
Granite and Basalt (fresh-moderate fracturing, little to no weathering)	28.8–87.7	N/A	N/A	N/A	N/A

AASHTO (2020) Table 10.5.5.2.5-1

Philosophy



Kennedy, et al. (2022)

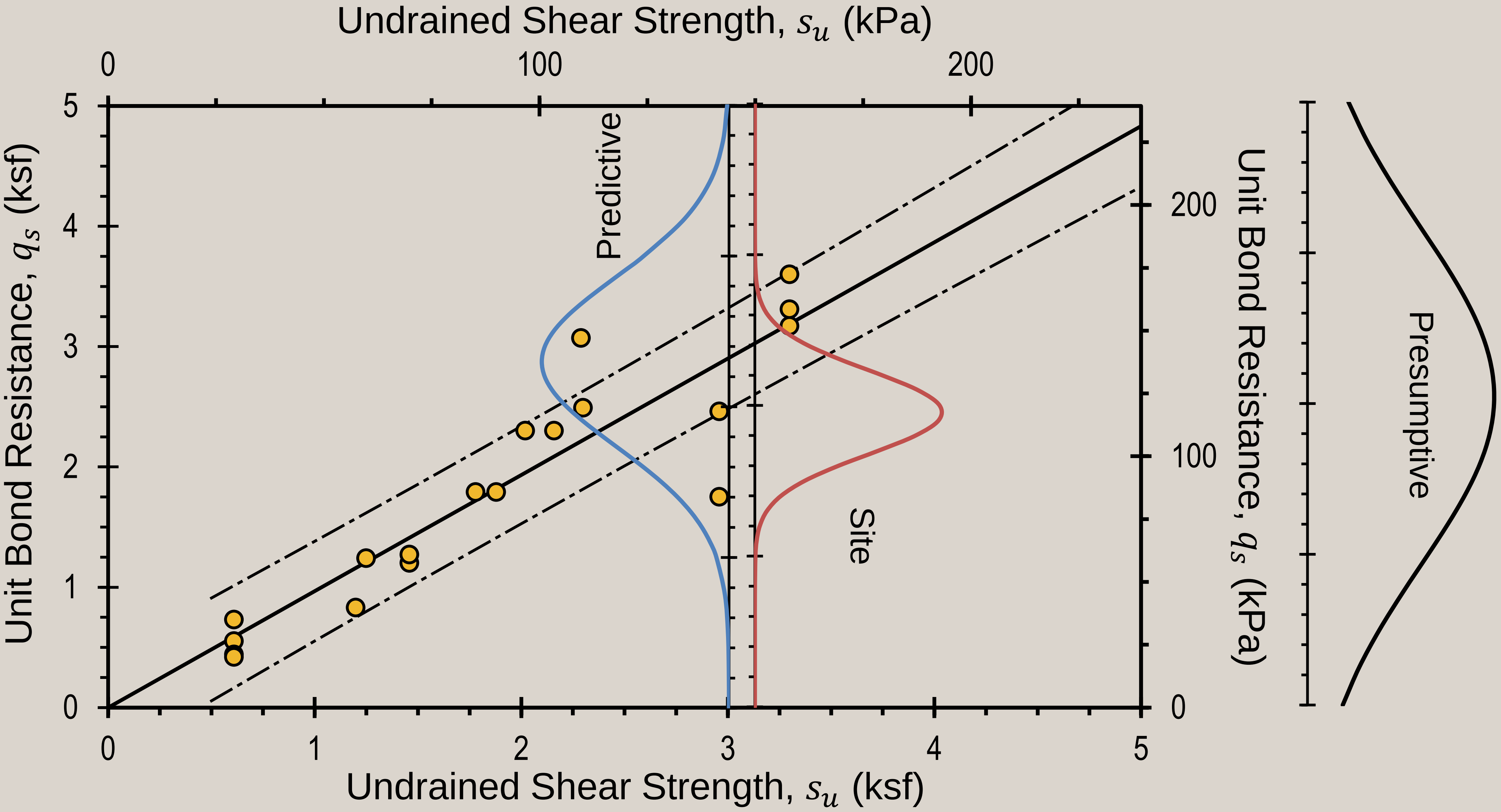
Courtesy of Tim Siegel, Dan Brown & Assoc.

Limited Information→
Conservative Design

Typical Information→
Normal Design

Extensive Information→
Efficient Design

Design approaches



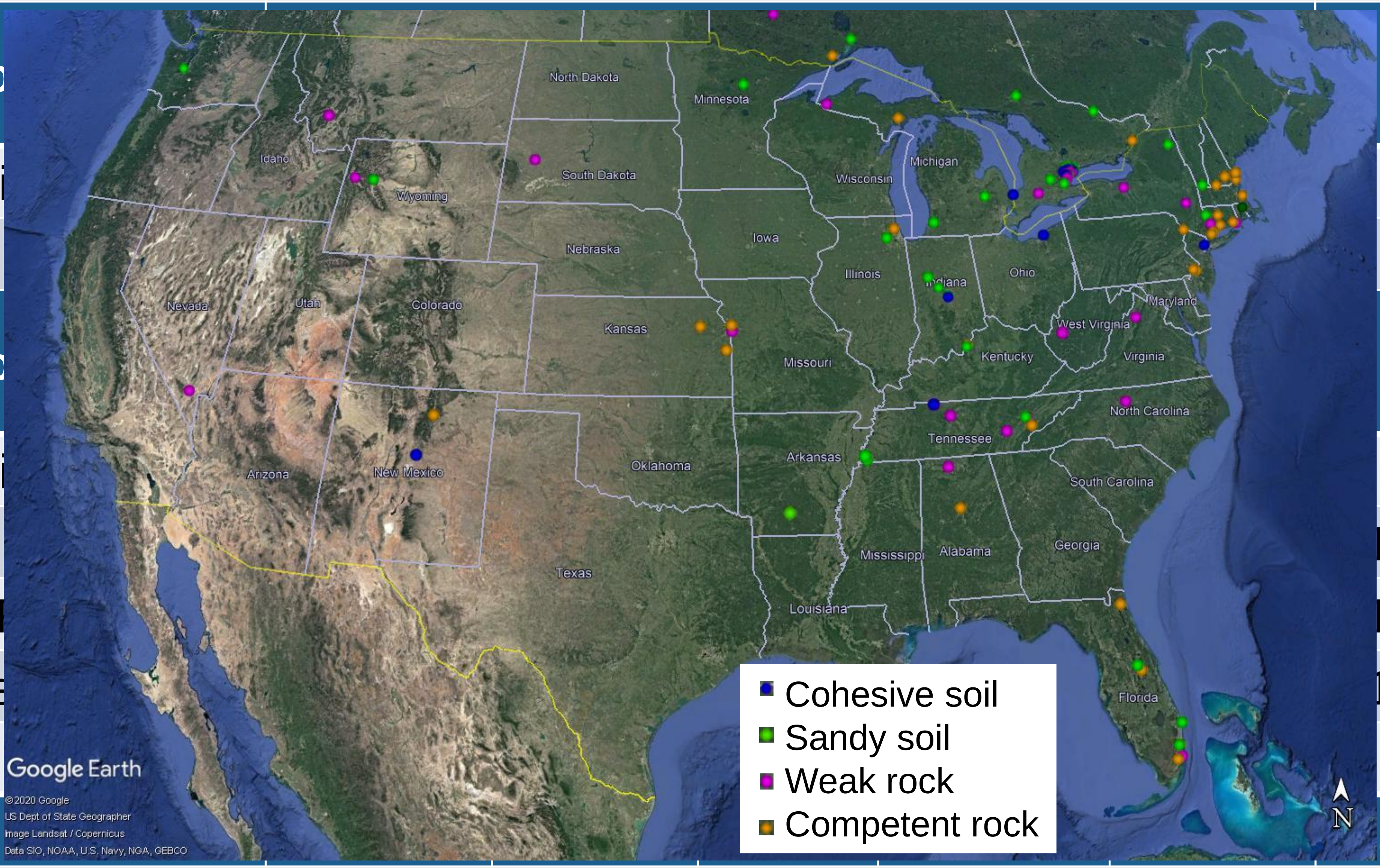
Collected load test records

Uncensored Tests

So	Total
Cohesi	12 (7)
Sandy	36 (21)

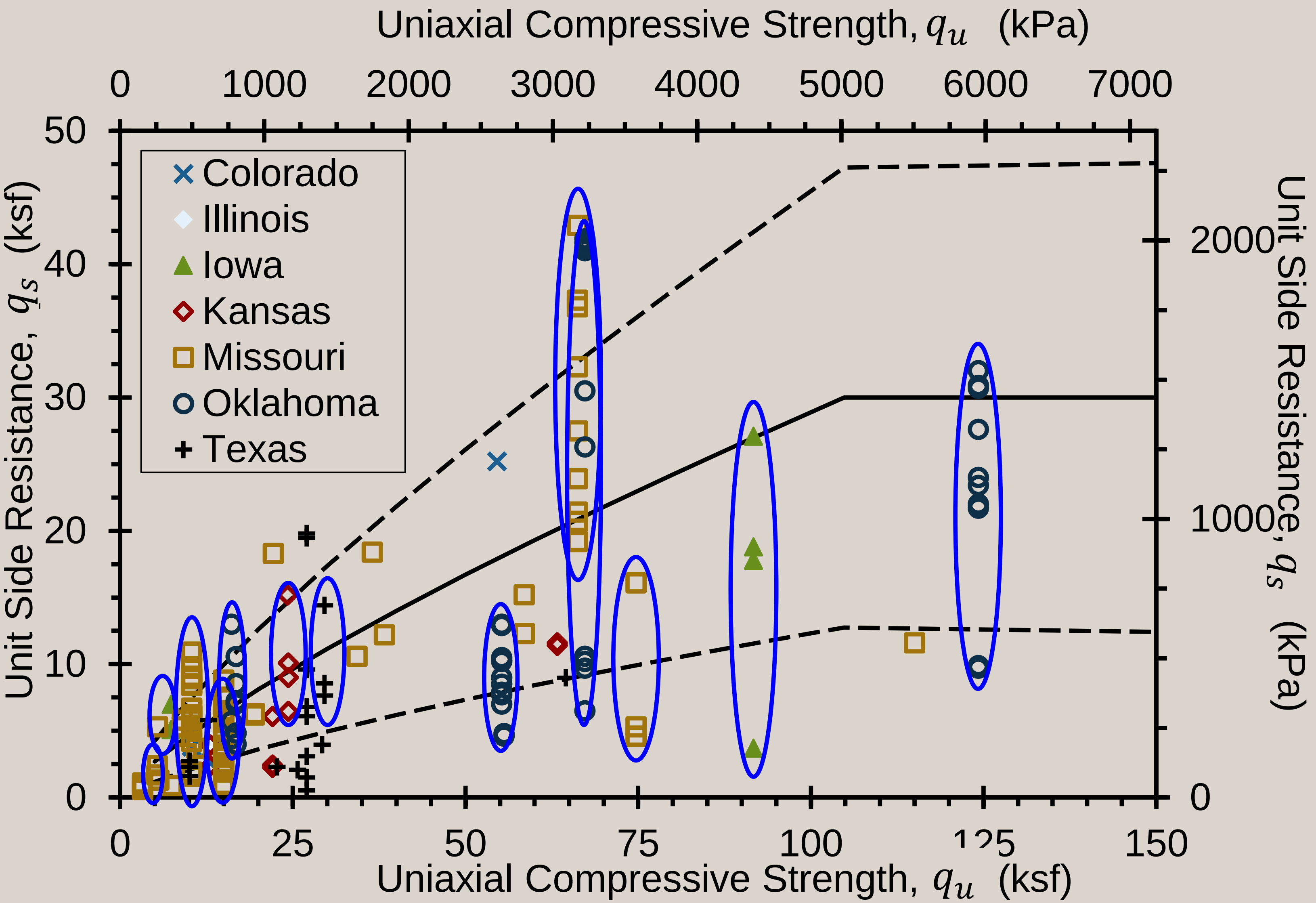
Censored Tests

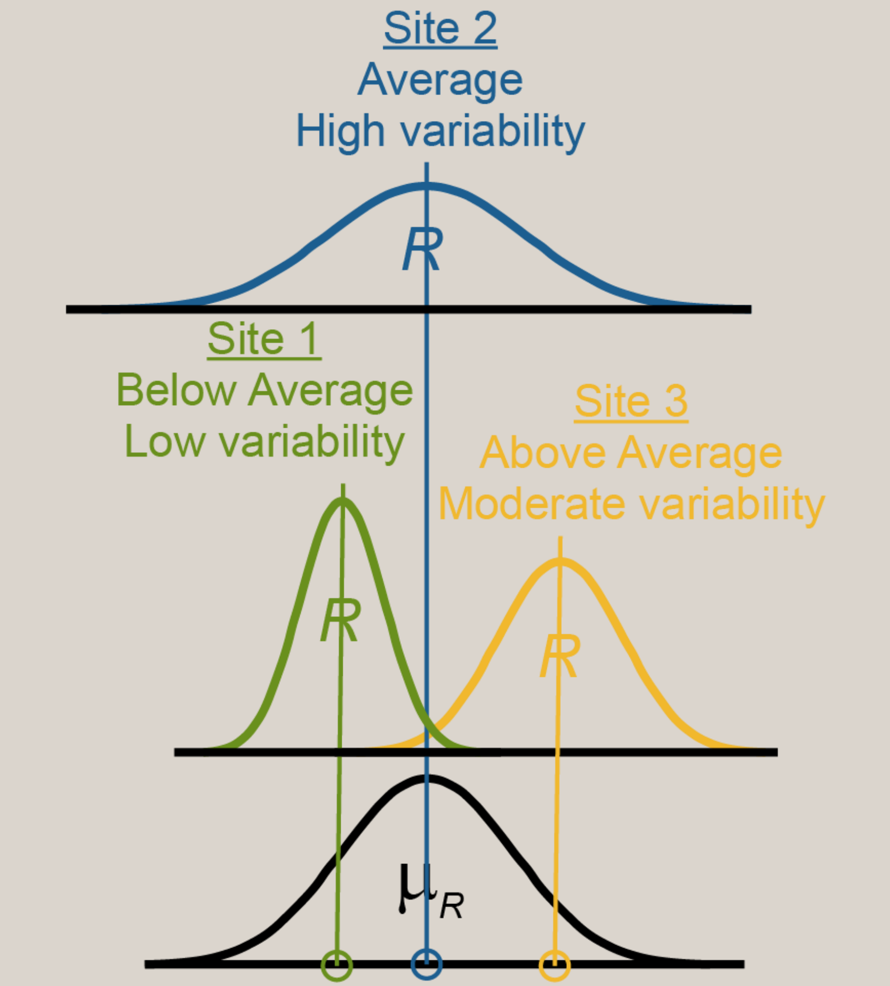
So	Total
Cohesi	38 (20)
Sandy	147 (55)
Weak	161 (42)
Compe	115 (43)
Mixed	163 (3)
	24 (163)



- Cohesive soil
- Sandy soil
- Weak rock
- Competent rock

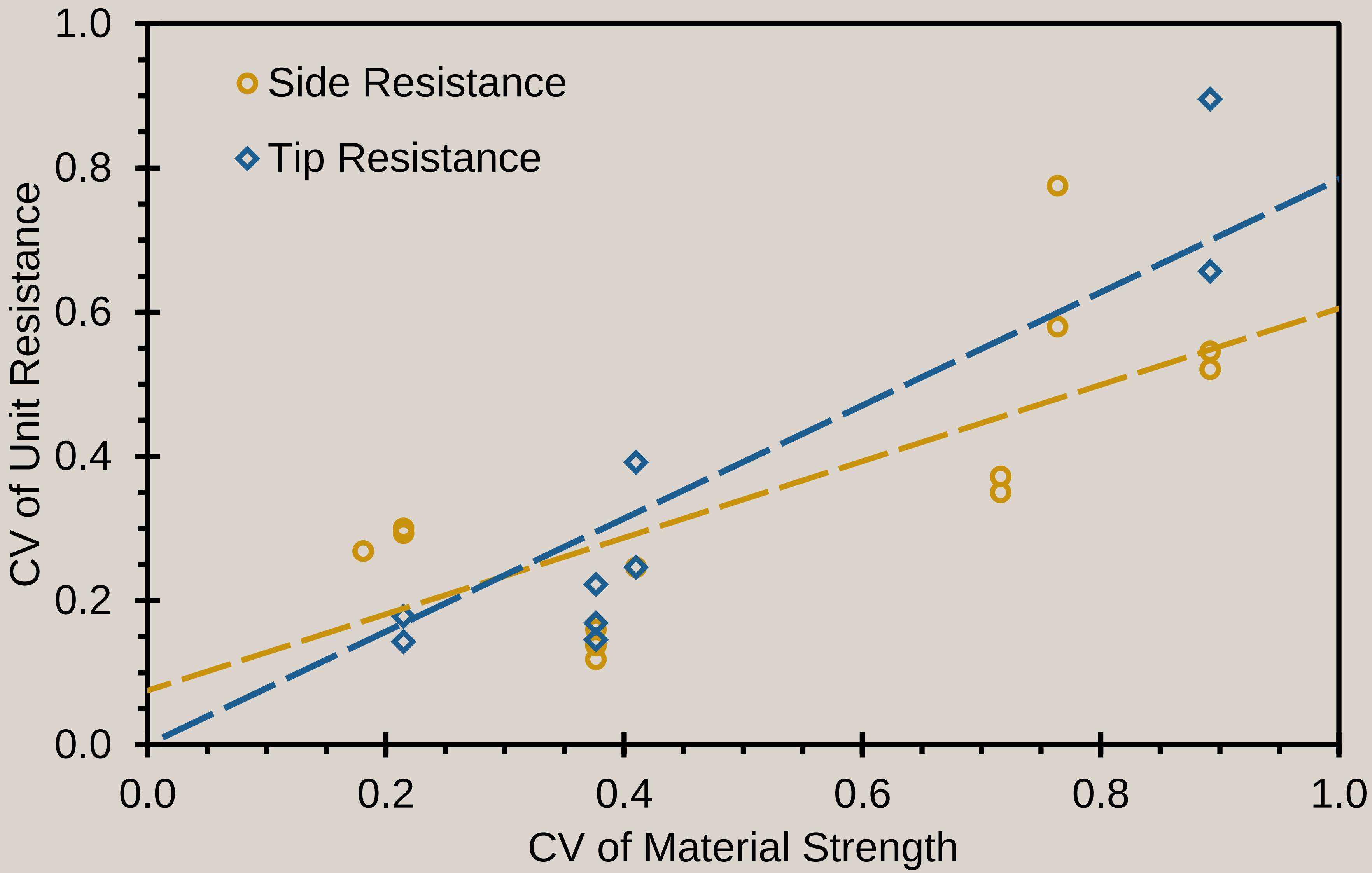
Within-site variability and Among-site variability



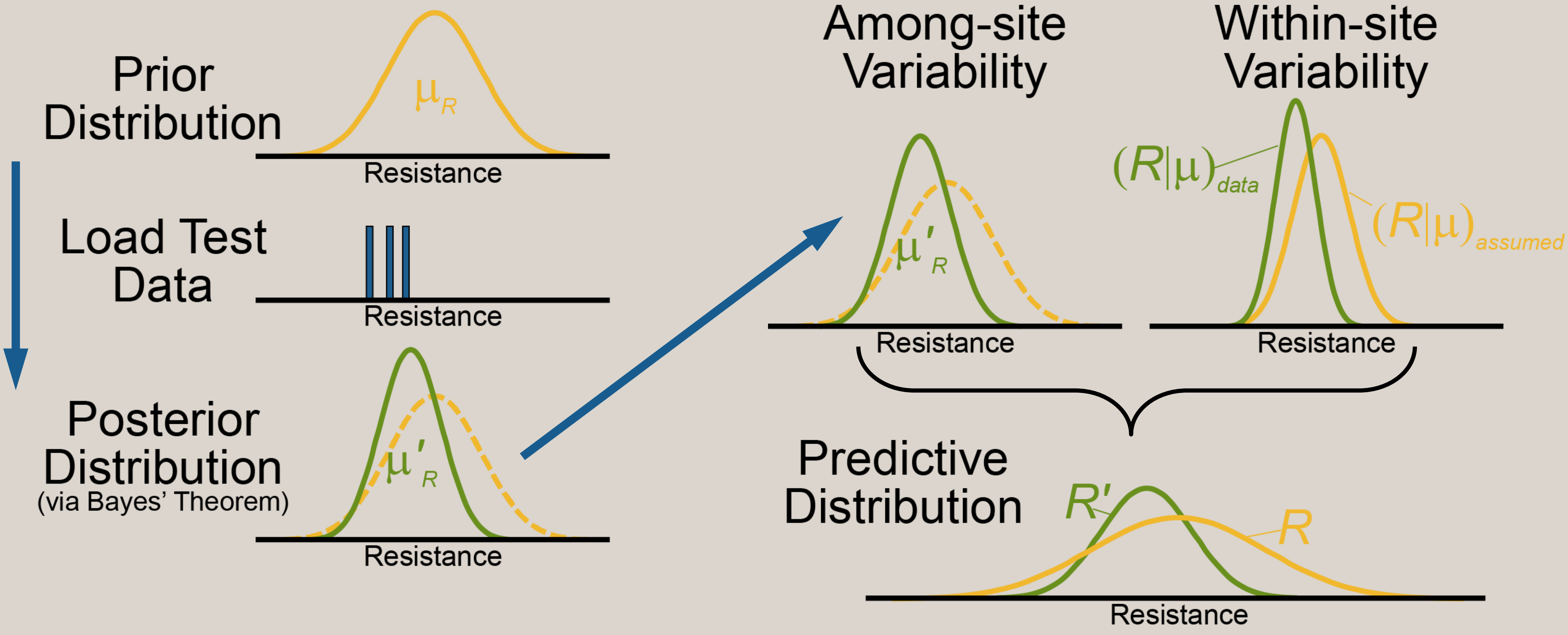


Among-site variability
(distribution of mean resistances)

Observed within-site variability for drilled shafts



Bayesian updating



Prior Distribution

Load Test Data

Posterior Distribution
(via Bayes' Theorem)

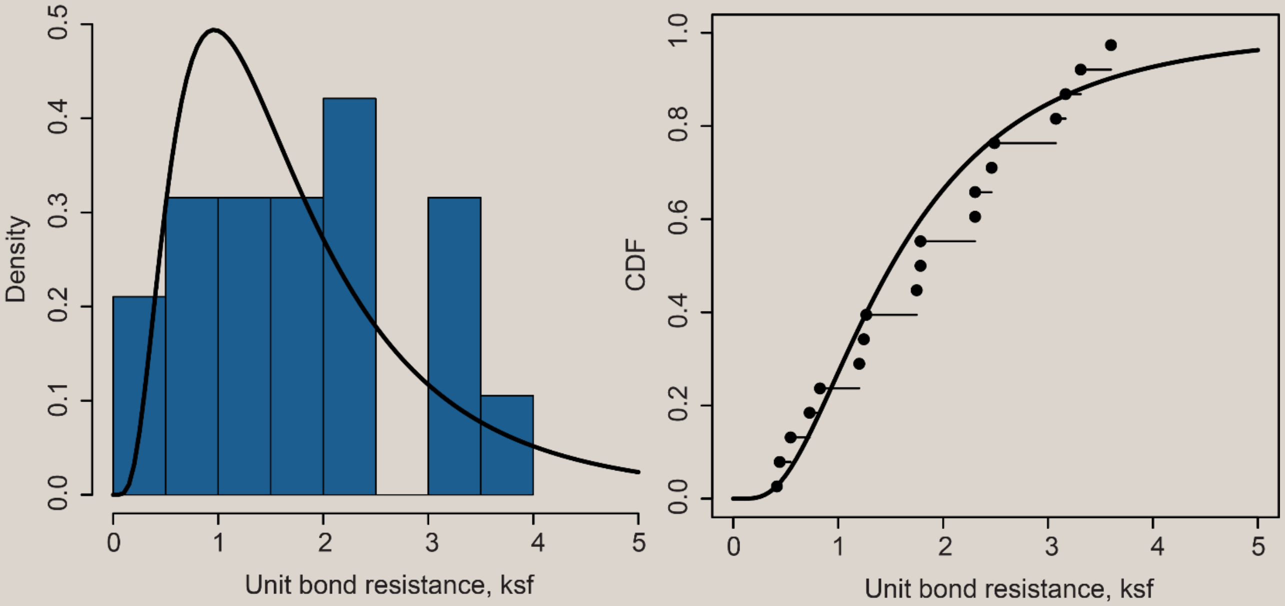
Among-site Variability

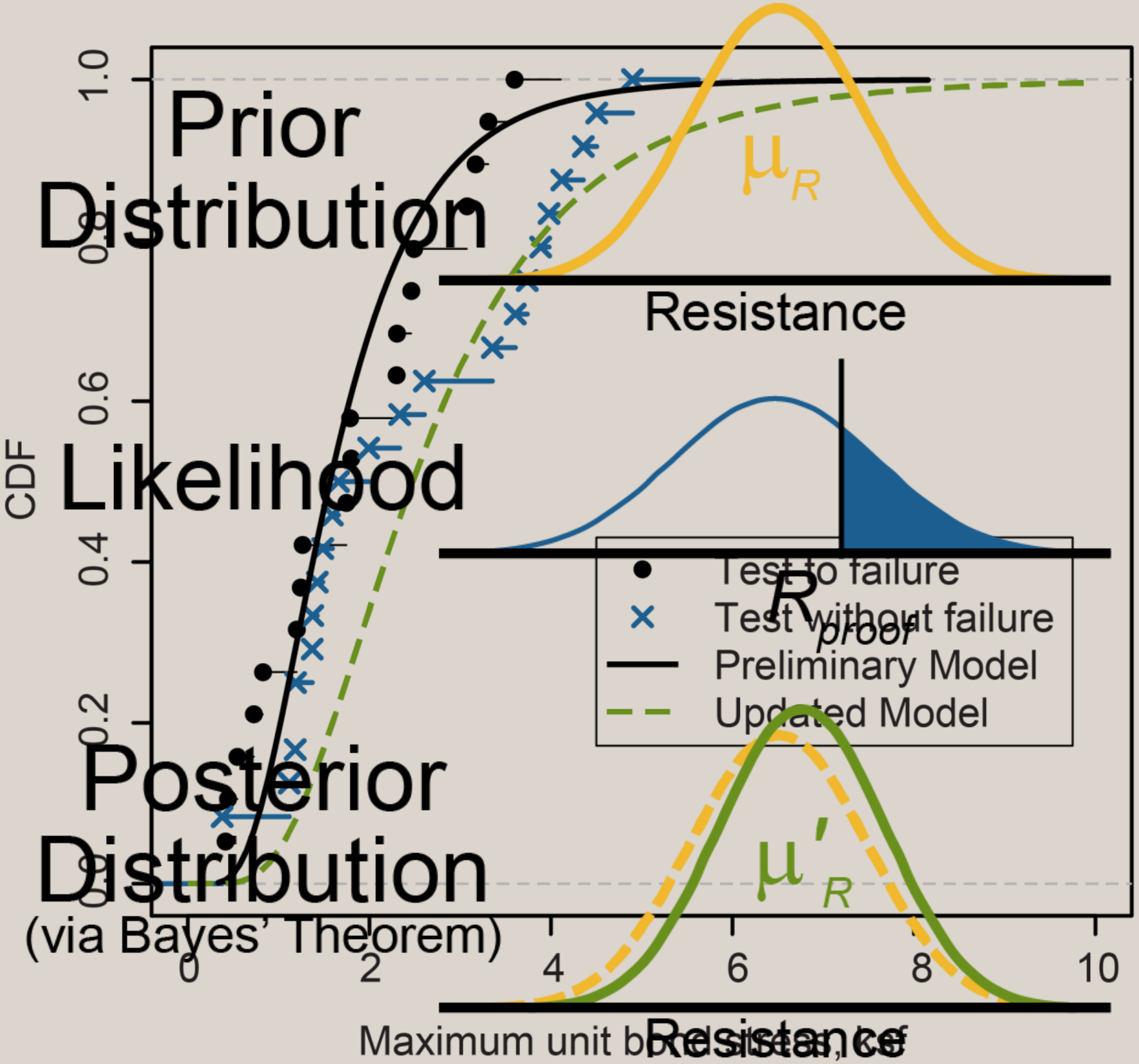
Within-site Variability

Predictive Distribution

Presumptive design methods

Micropiles in Cohesive Soil





Prior Distribution

Likelihood

Posterior Distribution

(via Bayes' Theorem)

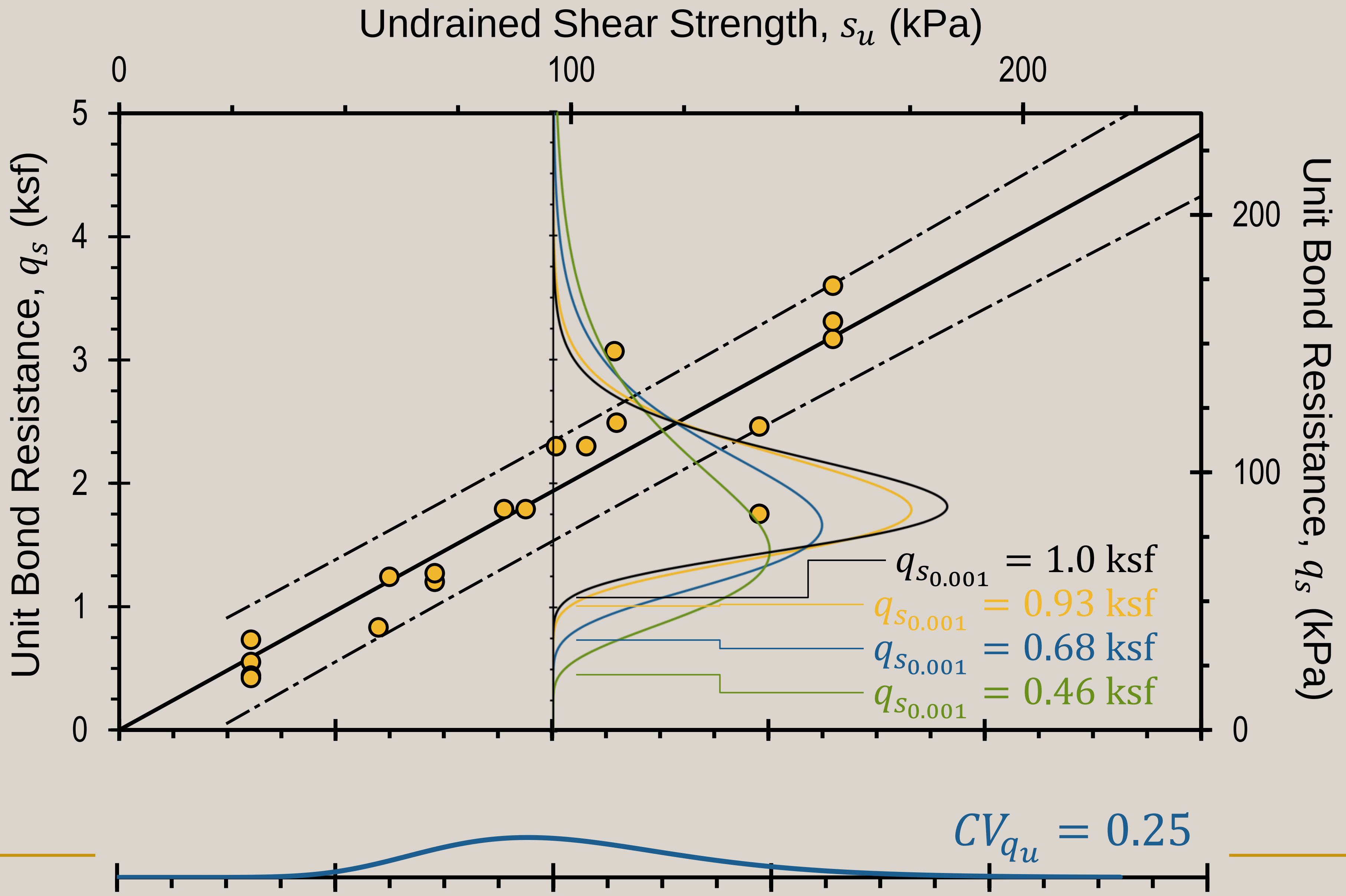
Recommended presumptive design models

Bond Material	Preliminary Models			AASHTO Range	pdated Models	
	n	μ_{q_s}(ksf)	CV_p		μ_{q_s}(ksf)	CV_{pred}
Cohesive Soil	19	1.8	0.5	0.7 – 4.0	2.9	0.55
Clean Sand	8	4.0	0.4	1.4 – 8.0	6.9	0.43
Gravelly Sand	8	4.5	0.4	2.0 – 8.0	5.8	0.46
Silty/Clayey Sand	20	4.0	0.	0.7 – 8.0	7.7	0.63
Argillaceous Rock	17	16.8	0.4	2.0 – 28.8	19.8	0.44
Limestone	7	25.9	0.	21.6 – 43.2	45.9	0.32
Karstic Limestone	6	12.2	0.		21.4	0.25
Sandstone	0	7.9	0.	10.8 – 36.0	13.3	0.48
Gneiss	0	15.1	0.		24.8	0.48
Granite & Basalt	0	7.1	0.	28.8 – 97.7	16.7	0.48

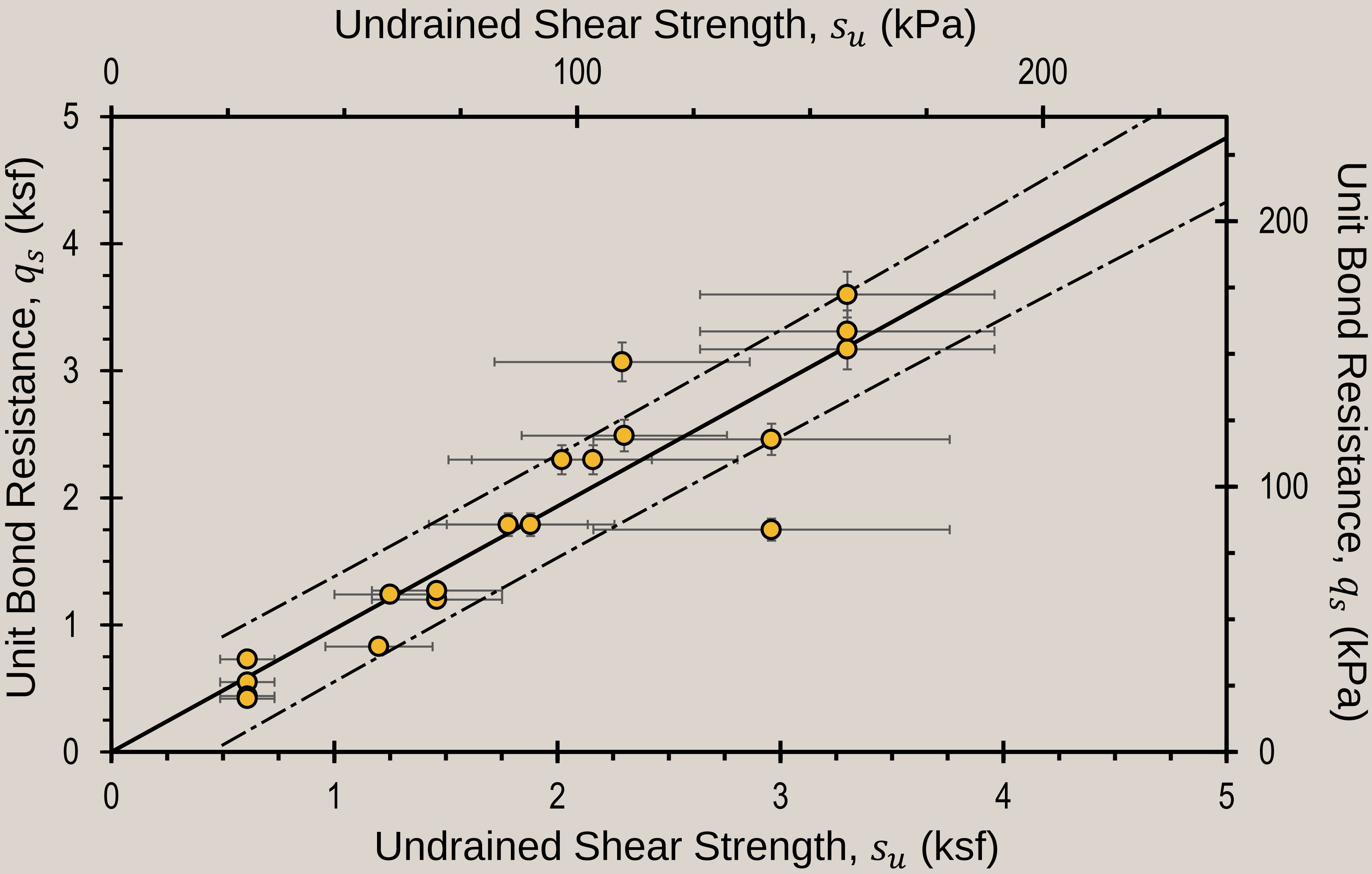
Resistance factors for presumptive design models

Bond Material	Nom. Resist., q_s (ksf)	Resistance Factor, φ_{q_s}		Fact. Resist., $\varphi_{q_s} \cdot q_s$ (ksf)
		Calibrated	Recommended	
Cohesive Soil	2.9	0.18	0.20	0.6
Clean Sand	6.9	0.26		1.4
Gravelly Sand	5.8	0.24		1.2
Silty/Clayey Sand	7.7	0.14		1.5
Argillaceous Rock	19.8	0.25		4.0
Limestone	45.9	0.37		9.2
Karstic Limestone	21.7	0.46		4.3
Sandstone	13.3	0.22		2.7
Gneiss	24.8	0.22		5.0
Granite & Basalt	16.7	0.22		3.3

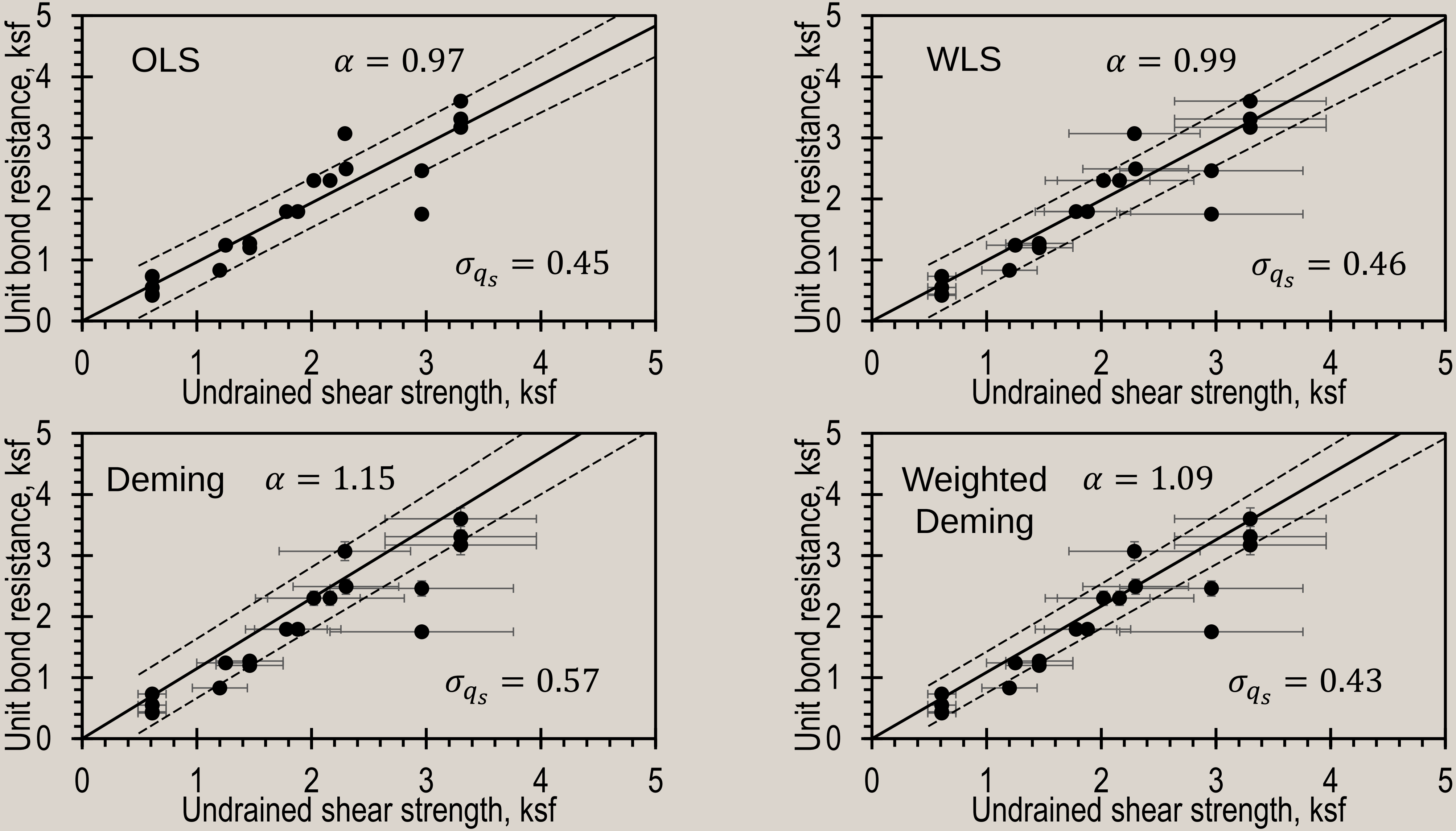
Predictive design method – cohesive soil



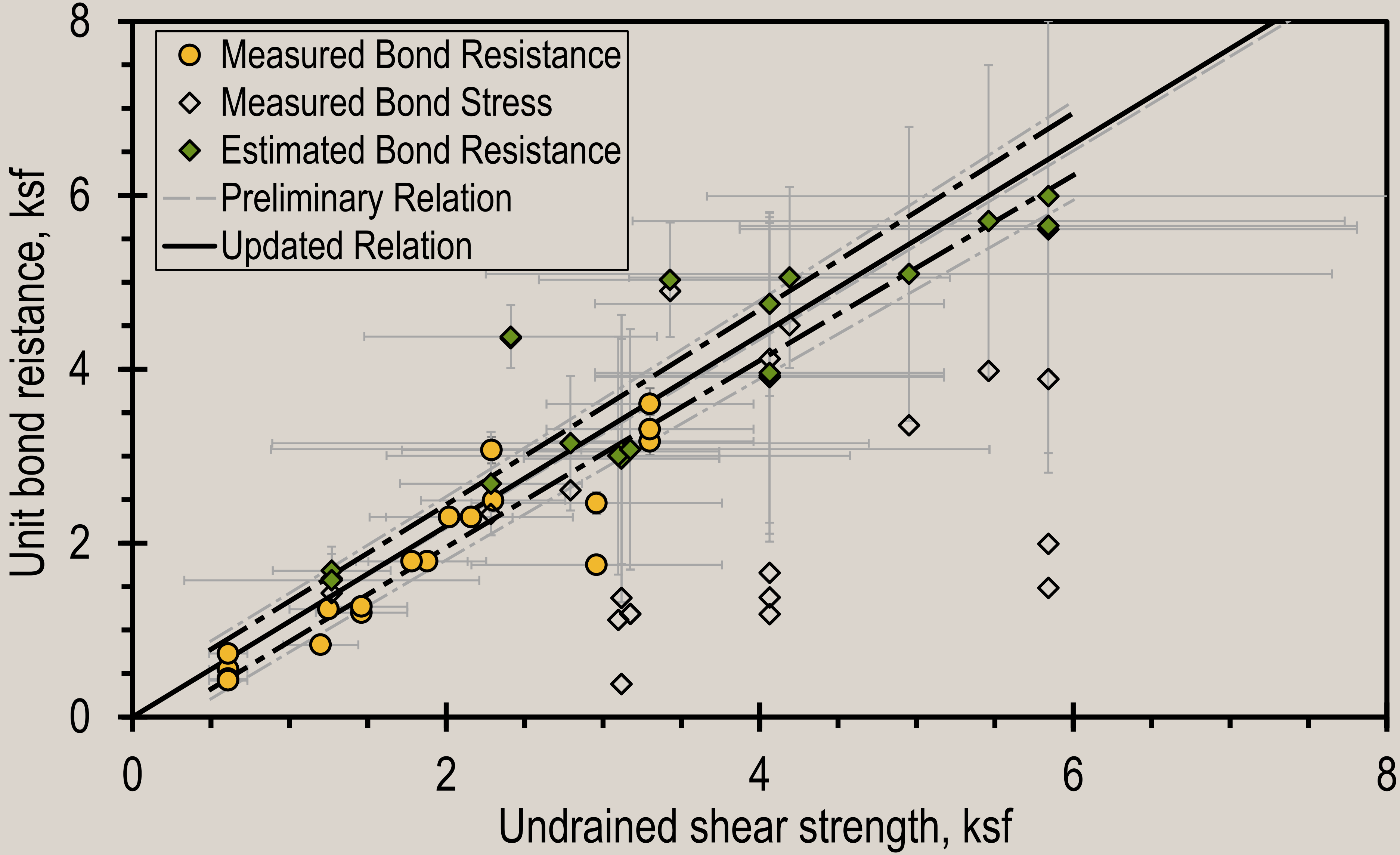
Predictive design method – cohesive soil



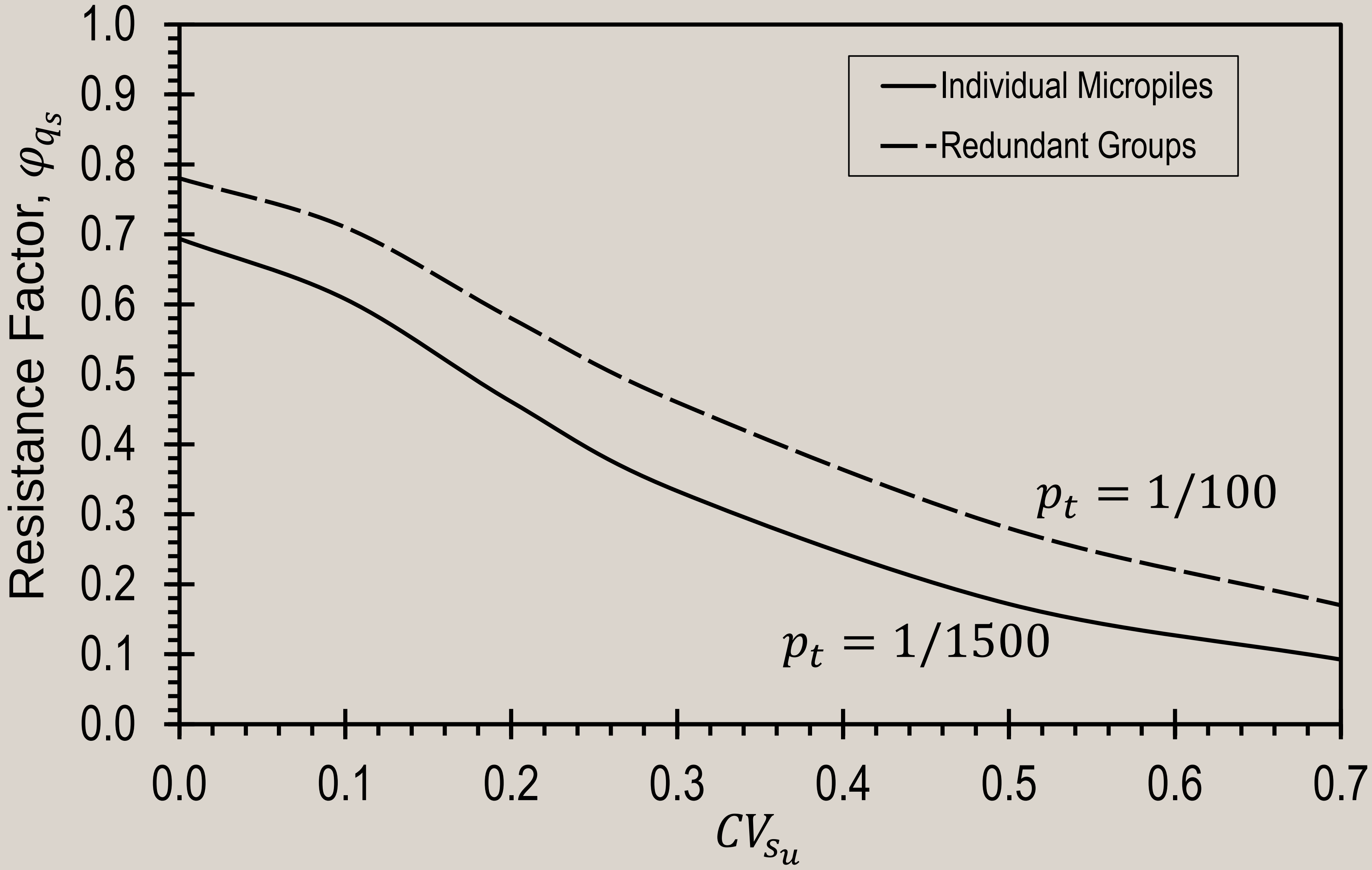
Predictive design methods – cohesive soil



Predictive design methods – cohesive soil



Resistance factors for predictive design – cohesive soil



Resistance factors for design based on load tests

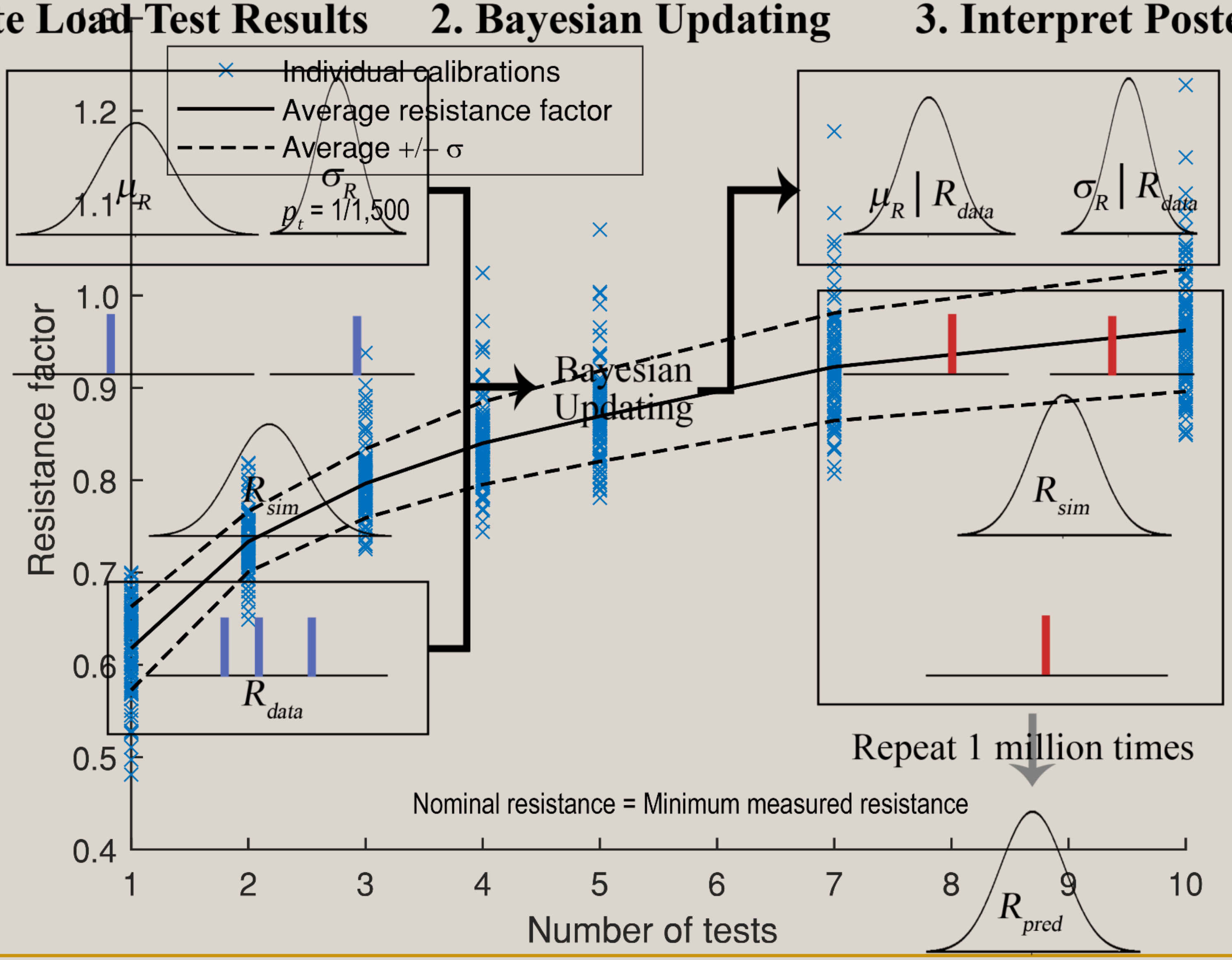
1. Simulate Load Test Results 2. Bayesian Updating 3. Interpret Posterior Distribution

Prior Distributions
of mean resistance μ and standard deviation resistance σ

Pair of μ, σ Values
from random sampling of prior distributions

Site-Specific Distribution
defined by μ, σ pair

Load Test Results
from random sampling of site-specific distribution



Posterior Distributions
of mean resistance μ and standard deviation resistance σ

Pair of μ, σ Values
from random sampling of posterior distributions

Site-Specific Distribution
defined by μ, σ pair

One Value of R
from random sampling of site-specific distribution

Design (Predictive) Distribution

Design based on site-specific load tests

Number of Tests	Resistance Factor	
	Non-redundant	Redundant
1	0.57	0.81
2	0.70	0.94
3	0.76	1.01
4	0.79	1.06
5	0.81	1.09
7	0.84	1.14
10	0.89	1.18

- Nominal resistance established as minimum measured resistance from all tests
- No distinction regarding whether failure observed
- Agnostic to method used to establish bond resistance
- Number of tests constrained to individual “construction control areas” and consistent construction procedure

Conclusions

- Recommended design provisions provide flexibility for different design situations while still achieving target reliability
  - Site-specific load tests produce most efficient design
  - Predictive design methods produce intermediate design efficiency
  - Presumptive design methods produce least efficient designs
- Resistance factors for presumptive and predictive design methods are lower than currently adopted, but without requirement for site-specific load tests
- Resistance factors for site-specific load tests are similar to or greater than currently prescribed in AASHTO Specifications

What’s next?

- Consideration by AASHTO COBS
- More research
  - Greatest knowledge gap for predictability is in rock
  - Redundancy
  - Within-site variability
  - load transfer relations

Thank you!