Performance-Based Design of Deep Foundations within the LRFD Framework

Lance A. Roberts, Ph.D., P.E.

Assistant Professor

South Dakota School of Mines and Technology

Rapid City, South Dakota

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Deep Foundation Design

Current Design Approach

- Numerous methods exist to compute the ultimate axial capacity for static capacity techniques or from load test data. Which capacity is correct?

- The ultimate axial capacity of a deep foundation is often achieved at a deformation that is greater than the deformation that a structure can tolerate.

Performance-Based Design Approach

- A performance-based design approach for axial design of deep foundations utilizes criteria based on tolerable deformations as opposed to traditional force-based requirements.

- A design approach that is deformation based must utilize a model that can predict the load-deformation behavior of a deep foundation while ensuring strain compatibility between the various resisting components (i.e. side and tip resistance).

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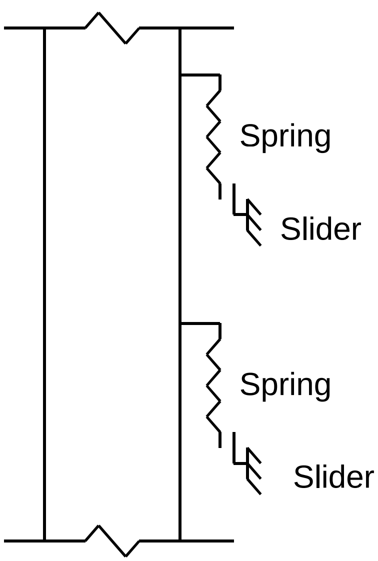
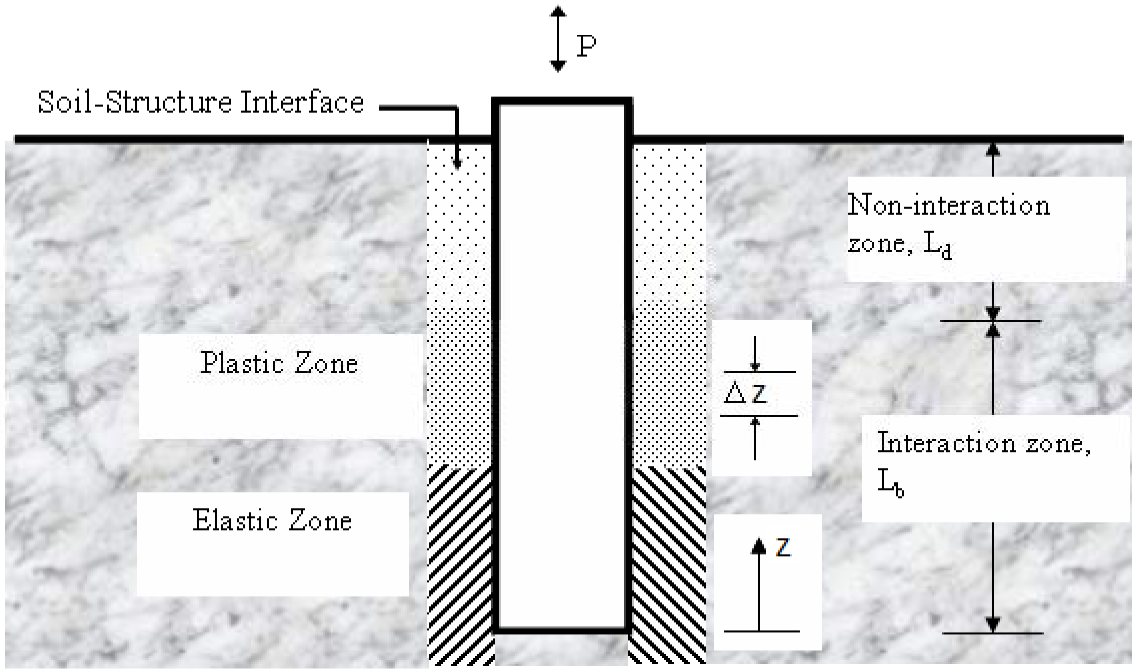
The "t-z" Model Method

- Load transfer along the soil-structure interface and tip is represented by a spring-slider system.
- This is the so-called "t-z" method of load-displacement analysis.





The "t-z" Model Method

For the soil-structure interface, the following parameters are used:

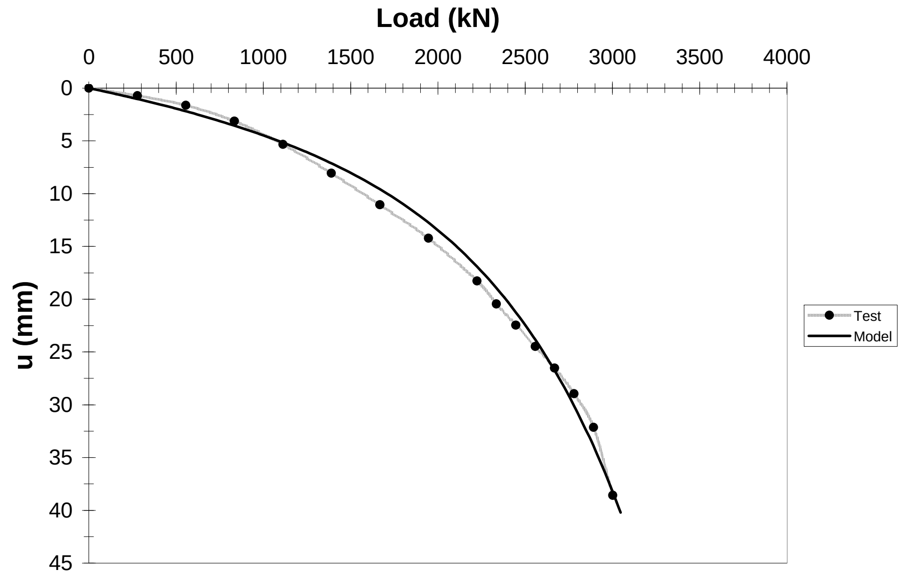
K = Shear modulus of sub-grade reaction (stiffness parameter)
τ_u = Ultimate shear strength (strength parameter)

For the tip soil, the following parameters are used:

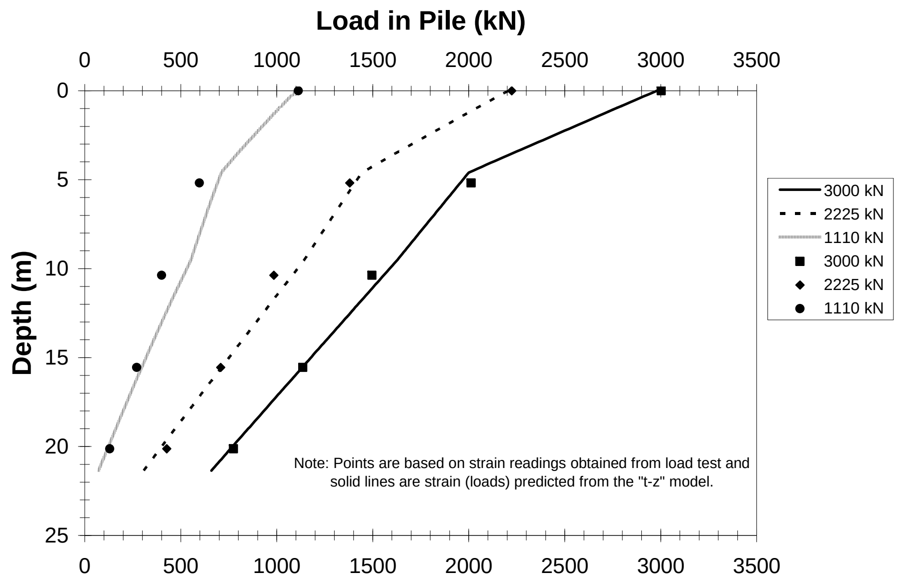
K_t = Sub-grade reaction (stiffness parameter)
q_t = Tip point bearing capacity (strength parameter)

<u>Model Parameter Determination</u>

- Subsurface exploration and laboratory test data
- Back-calculations from field load test data

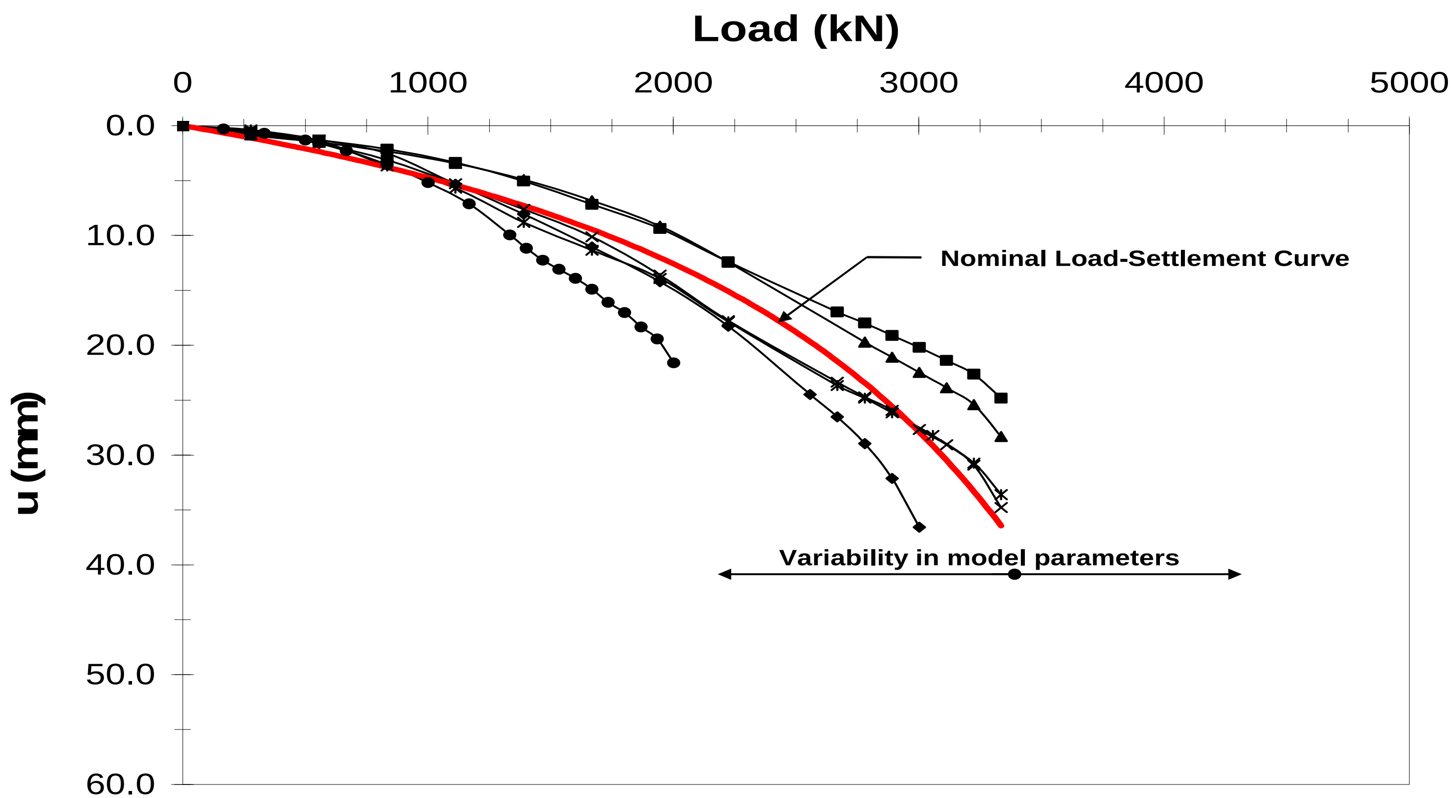


Head-settlement data



Strain gauge data

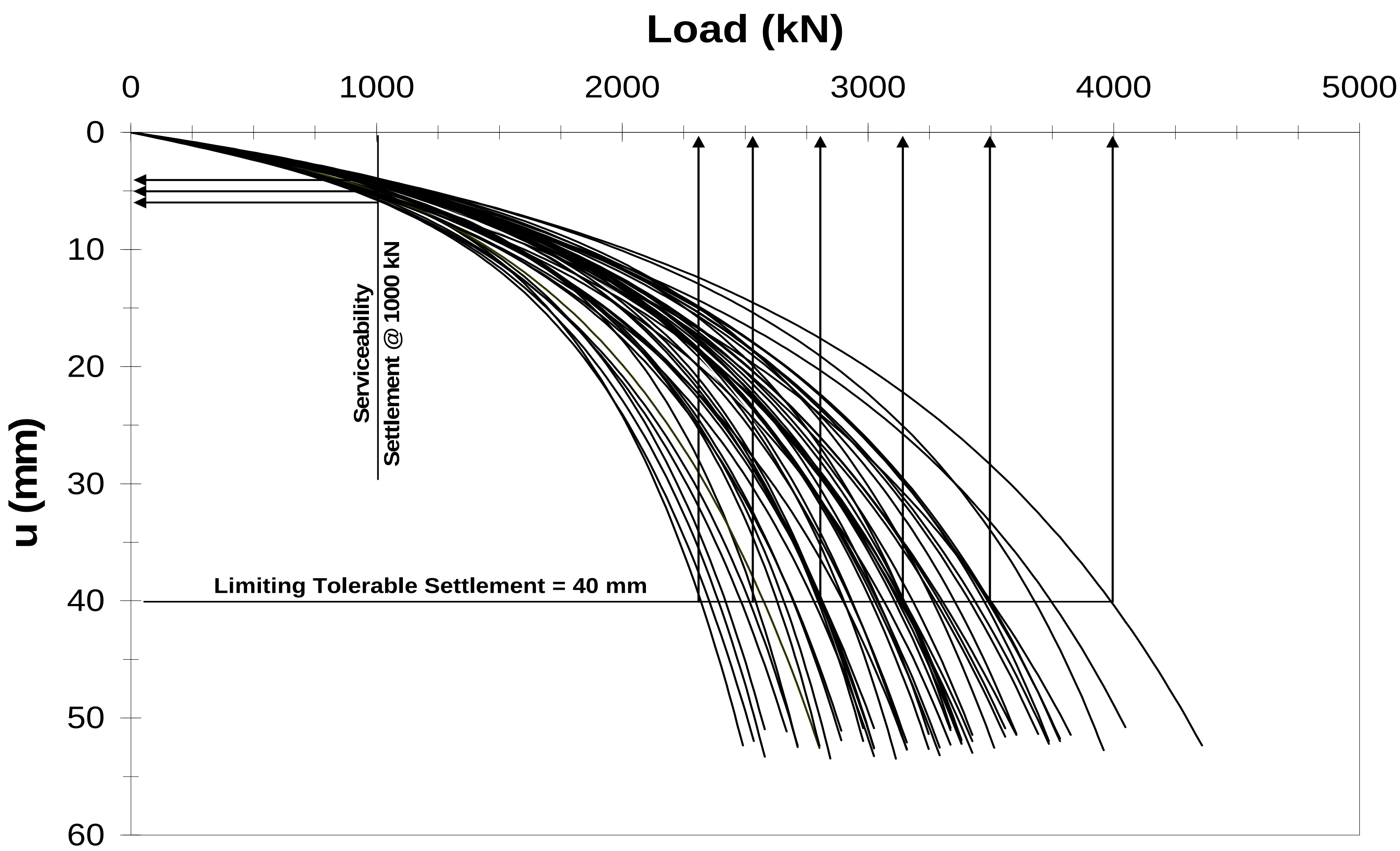
Back-analysis of ACIP pile load test using "t-z" model approach.



- The strength and stiffness of the side and tip springs are assumed to be random variables, defined by a mean and standard deviation, and are assumed to follow a probability distribution function.

- A Latin Hypercube approach is used to randomly select values for the strength and stiffness of the springs. These values are substituted into the "t-z" model.

Performance-Based Design



Analyze the randomly generated load-settlement curves at a limiting tolerable settlement and a serviceability settlement.

Performance-Based Design Criteria

Limiting Tolerable Settlement

- Corresponds to the limiting permissible settlement for the foundation element under the **factored load**.
- Settlement where the stresses within a structure become greater than allowable or where the settlement causes the structure to become inoperable.
- This defines the **Strength Limit State** design requirements.

Serviceability Settlement

- Corresponds to the desirable settlement for the foundation element under the **working load**.
- Settlement where serviceability issues may become an aesthetic problem.
- This defines the **Service Limit State** design requirements.

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Load and Resistance Factor Design

Based on the First Order, Second Moment (FOSM) method, the resistance factor, ϕ_R, can be calculated by the following (Baecher and Christian 2003):

$$\phi_R = \frac{\lambda_R \left(\frac{\gamma_D E(D)}{E(L)} + \gamma_L \right) \sqrt{\frac{1+\Omega_D^2+\Omega_L^2}{1+\Omega_R^2}}}{\left(\frac{\lambda_D E(D)}{E(L)} + \lambda_L \right) \exp\left\{ \beta_T \sqrt{\ln\left[(1+\Omega_R^2)(1+\Omega_D^2+\Omega_L^2) \right]} \right\}}$$

where: λ = Bias of the resistance, dead load and live load

Ω = COV of the resistance, dead load and live load

γ = Dead and live load factor

$E()$ = Expected value of dead and live load

β_T = Target reliability index

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Load and Resistance Factor Design

The target reliability index, β_T, is related to the probability of failure, p_f:

Typical range (2.0 – 3.5)

β_T	p_f	Expected Performance
0	0.500	-
0.5	0.309	-
1.0	0.159	Hazardous
1.5	0.067	Unsatisfactory
2.0	0.023	Poor
2.5	0.006	Below average
3.0	0.001	Above average
3.5	0.0002	-
4.0	0.00003	Good
4.5	0.000003	-
5.0	0.0000003	High

Adapted from U.S. Army Corps of Engineers (1997), Table B-1

Load and Resistance Factor Design

Bias

$\lambda_R = ?$

$\lambda_{QD} = 1.05^*$

$\lambda_{QL} = 1.15^*$

COV

$\Omega_R = ?$

$\Omega_{QD} = 0.10^*$

$\Omega_{QL} = 0.20^*$

Load Factors (AASHTO 2007)

$\gamma_D = 1.25$ (Strength Limit State) 1.0 (Service Limit State)

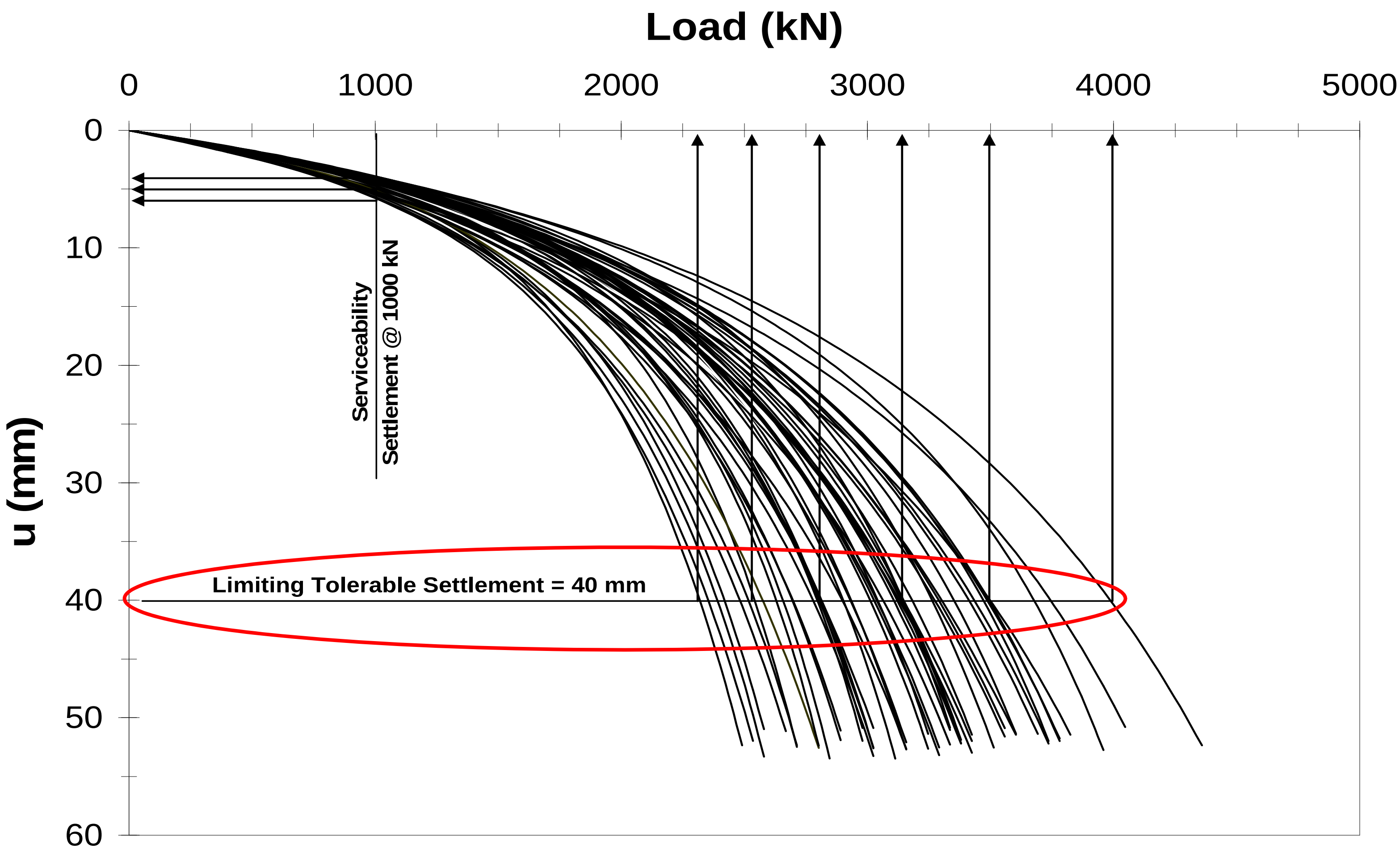
$\gamma_L = 1.75$ (Strength Limit State) 1.0 (Service Limit State)

Expected Values

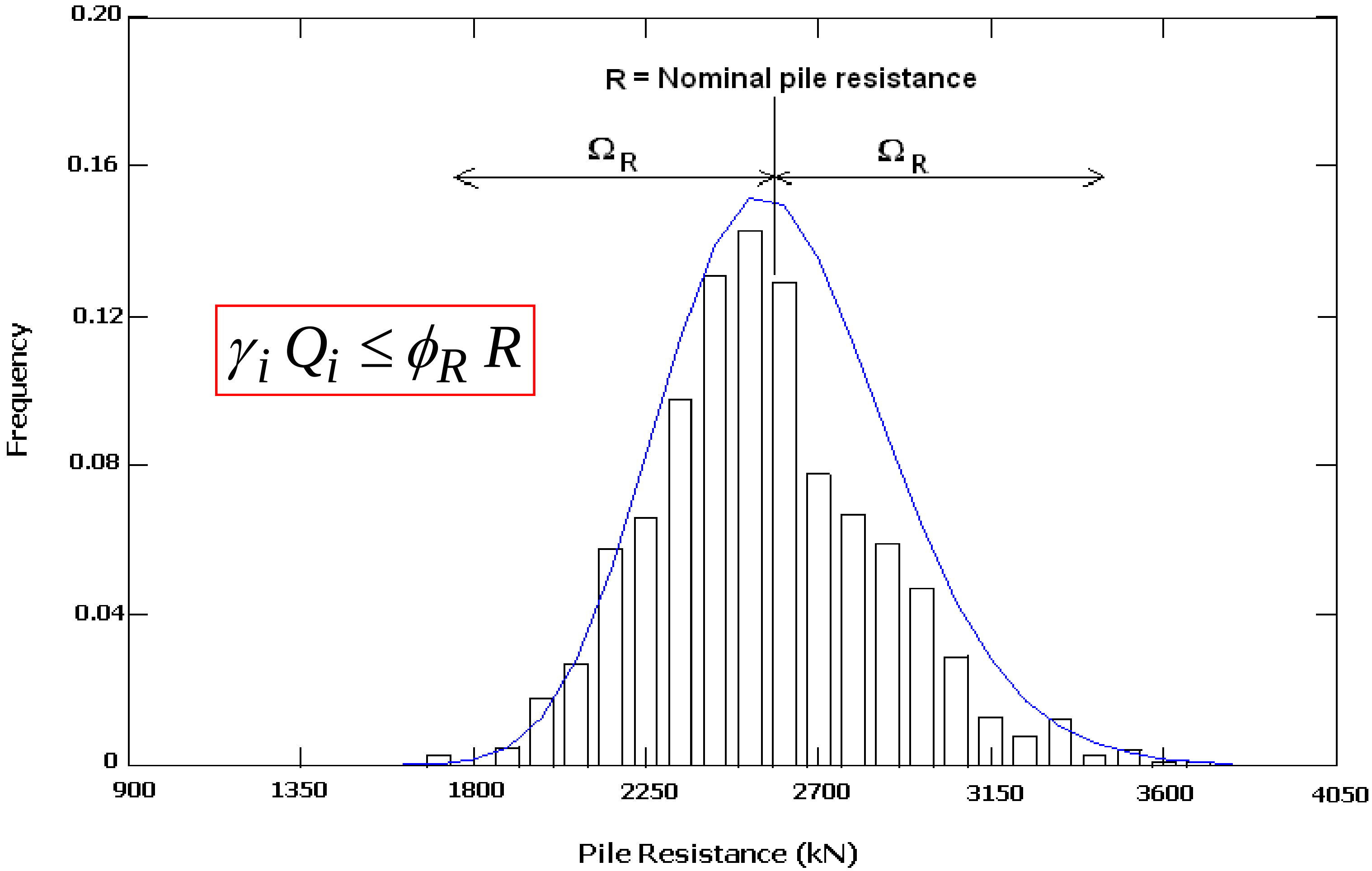
$E(Q_D) / E(Q_L) = 2.0^*$

*Based on factors used in the calibration of resistance factors reported in AASHTO (2007).

Performance-Based Design



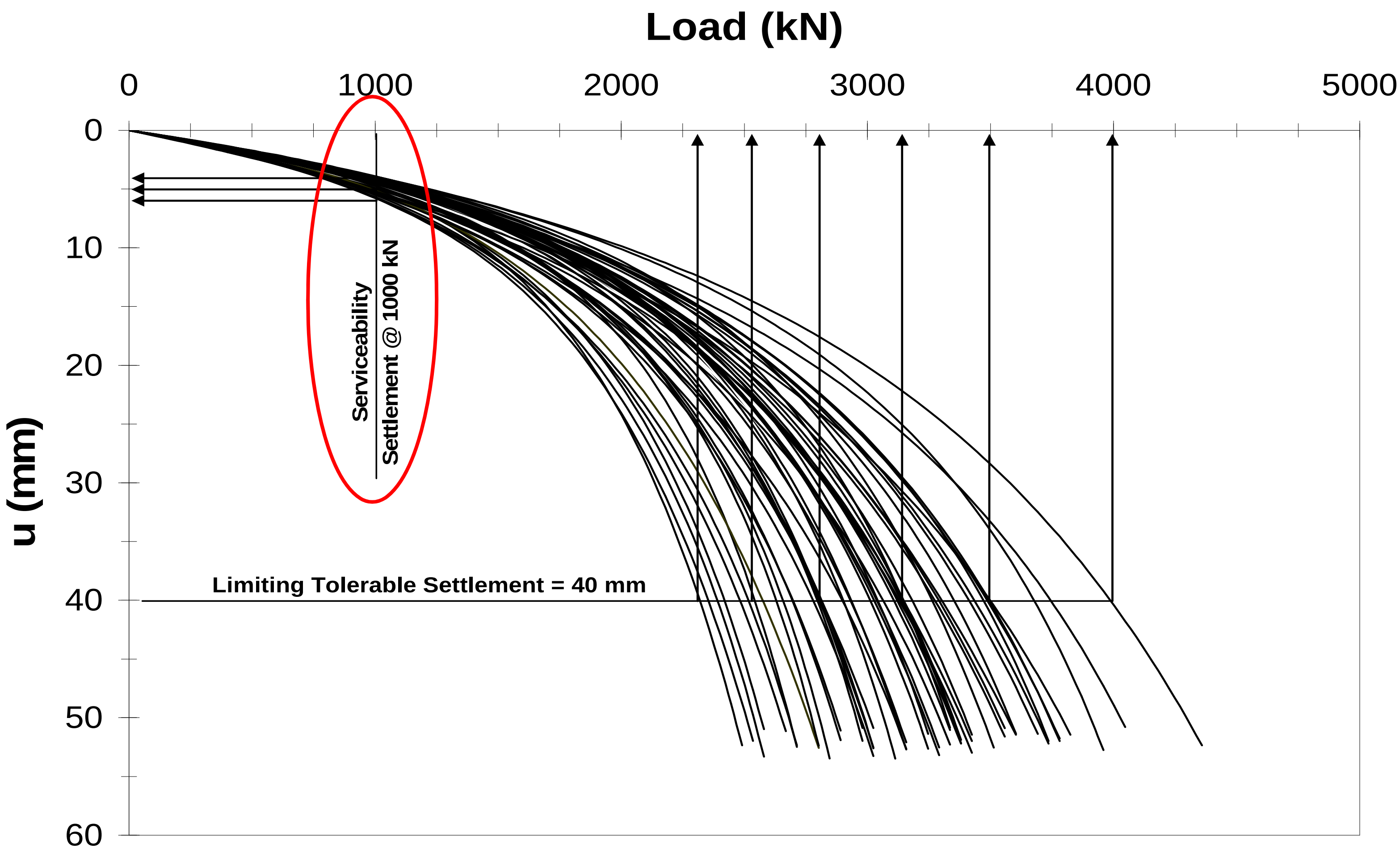
Strength Limit State Design



λ_R = 1.0 (“t-z” fit)
Ω_R = COV of PDF

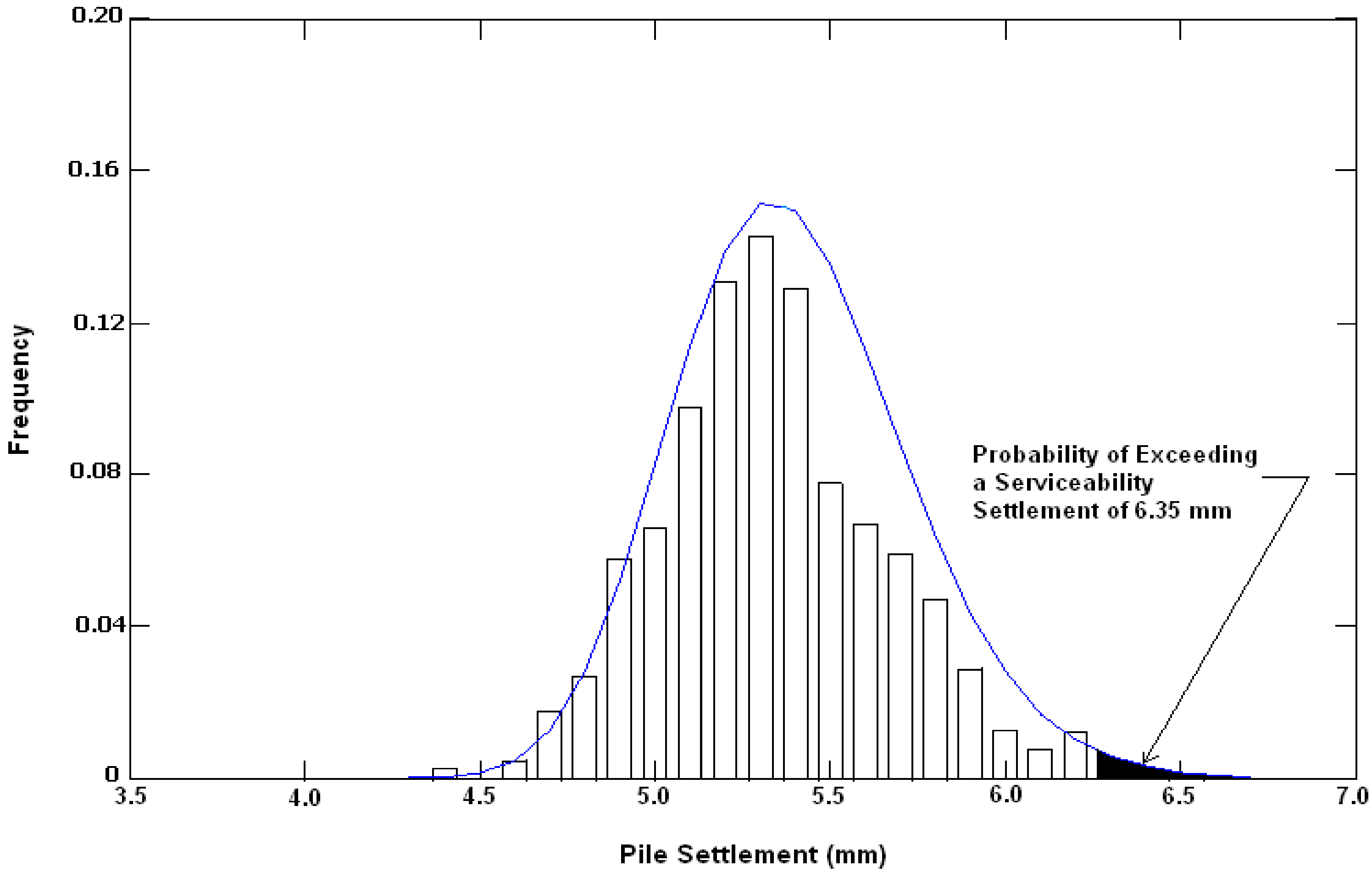
→ Substitute into resistance factor equation to obtain ϕ_R.

Performance-Based Design



Service Limit State

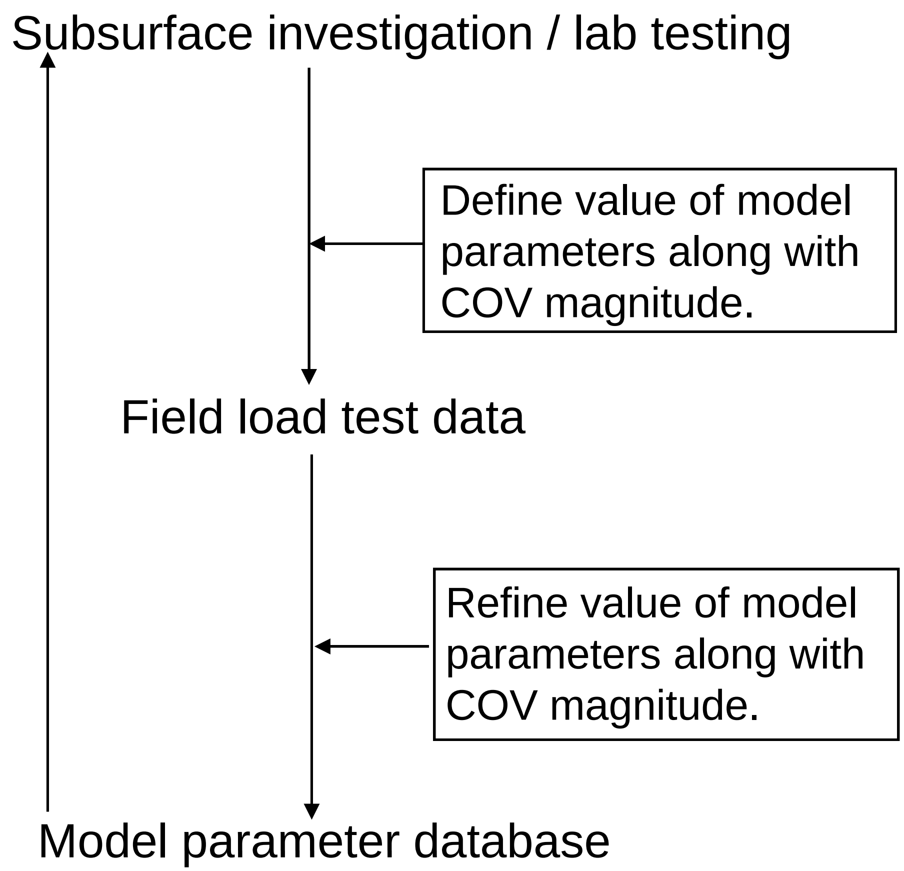
Ensure the probability of exceeding the serviceability settlement is less than a desired magnitude (≈0.5%)



Performance-Based Design

Design Methodology

- Nominal values of the “t-z” model parameters can be defined using a parameter database and site specific load test data.
- Uncertainty within the “t-z” model parameters can be defined using subsurface investigation, in-situ testing, laboratory test data, and site specific load test data.
- Further development of a model parameter database for specific types of deep foundation systems can assist in future design and resistance factor calibrations.



Performance-Based Design Example

- A site required numerous drilled displacement (DD) piles to support several new building structures.

- Service load per pile is 200 kips.
- Factored load per pile is 350 kips.

- Limiting tolerable settlement is specified as 1-inch.
- Serviceability settlement is specified as 0.25-inch.

- A series of fully-instrumented compression field load tests were conducted on piles installed to various design lengths (42' to 58') and diameters (14" and 16").

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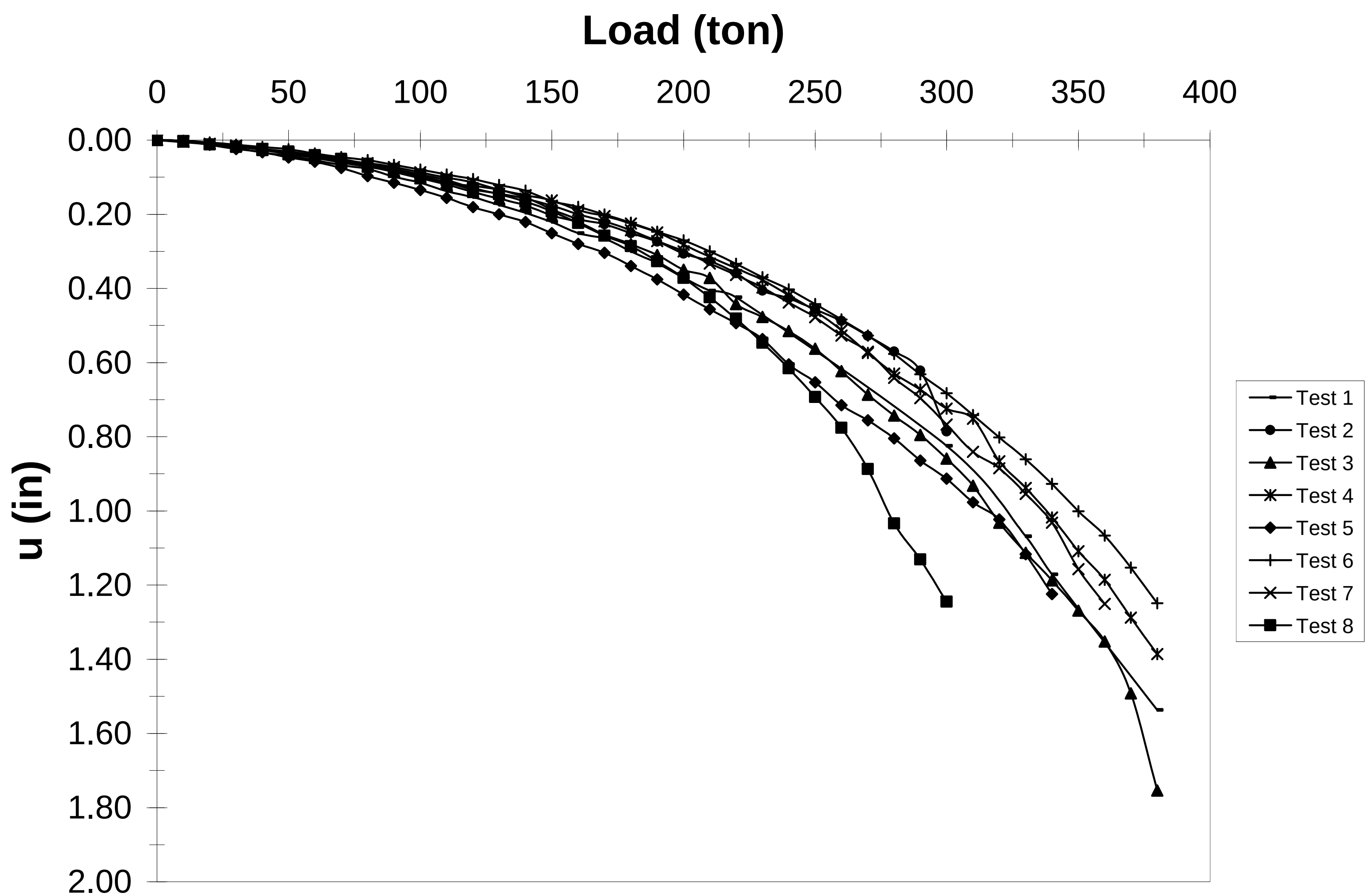
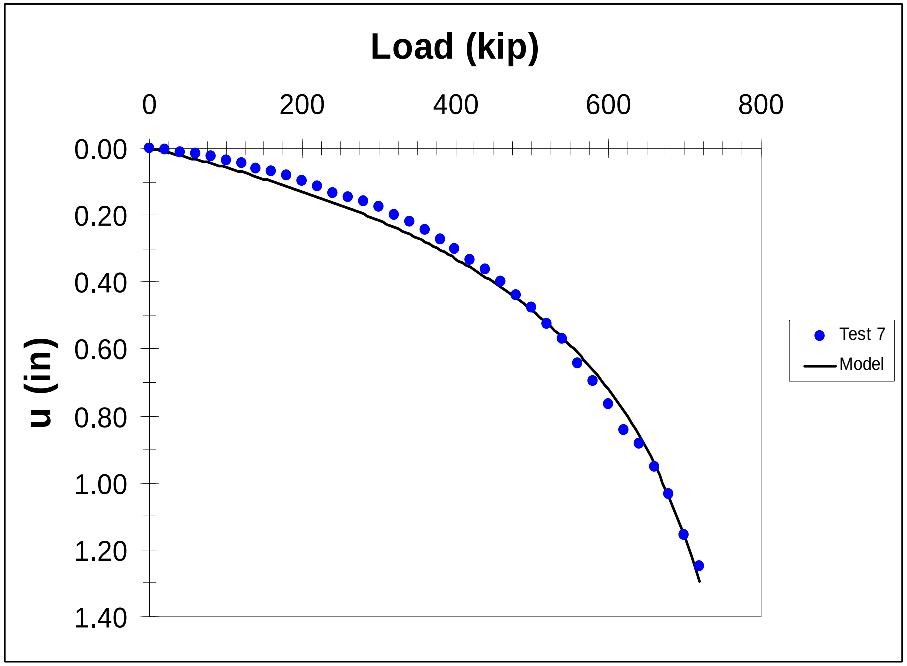
Performance-Based Design Example



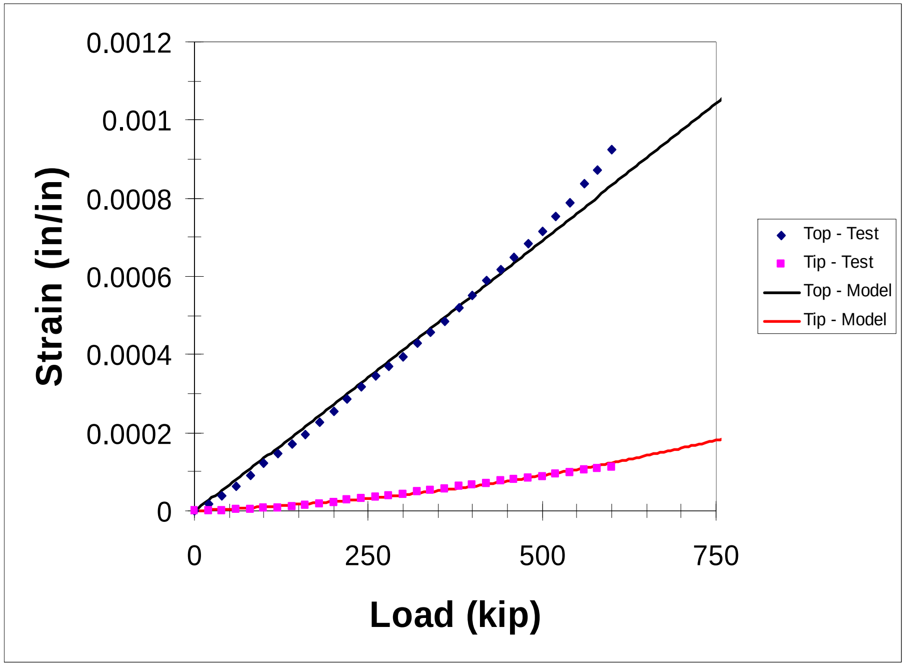
Load-settlement data for DD piles.

Performance-Based Design Example

The load-settlement curves and strain gauge data were analyzed to back-compute the “t-z” model parameters for each load test.



Load-settlement curve fitting



Strain gauge data fitting

DD pile with L=50′ and D=14″

Performance-Based Design Example

The statistics of the model parameters were computed based on the back-analysis. Since the statistics may not be considered "robust", the Three-Sigma Rule is used (Allen et al. 2005):

$$\sigma = \frac{HCV - LCV}{6}$$

where: HCV = Highest observed (or conceivable) value

LCV = Lowest observed (or conceivable) value

Model Parameter	Nominal	COV
τ_u	26 psi	7%
K	5 ksi	17%
E_s	3300 ksf	23%
q_t	150 ksf	29%

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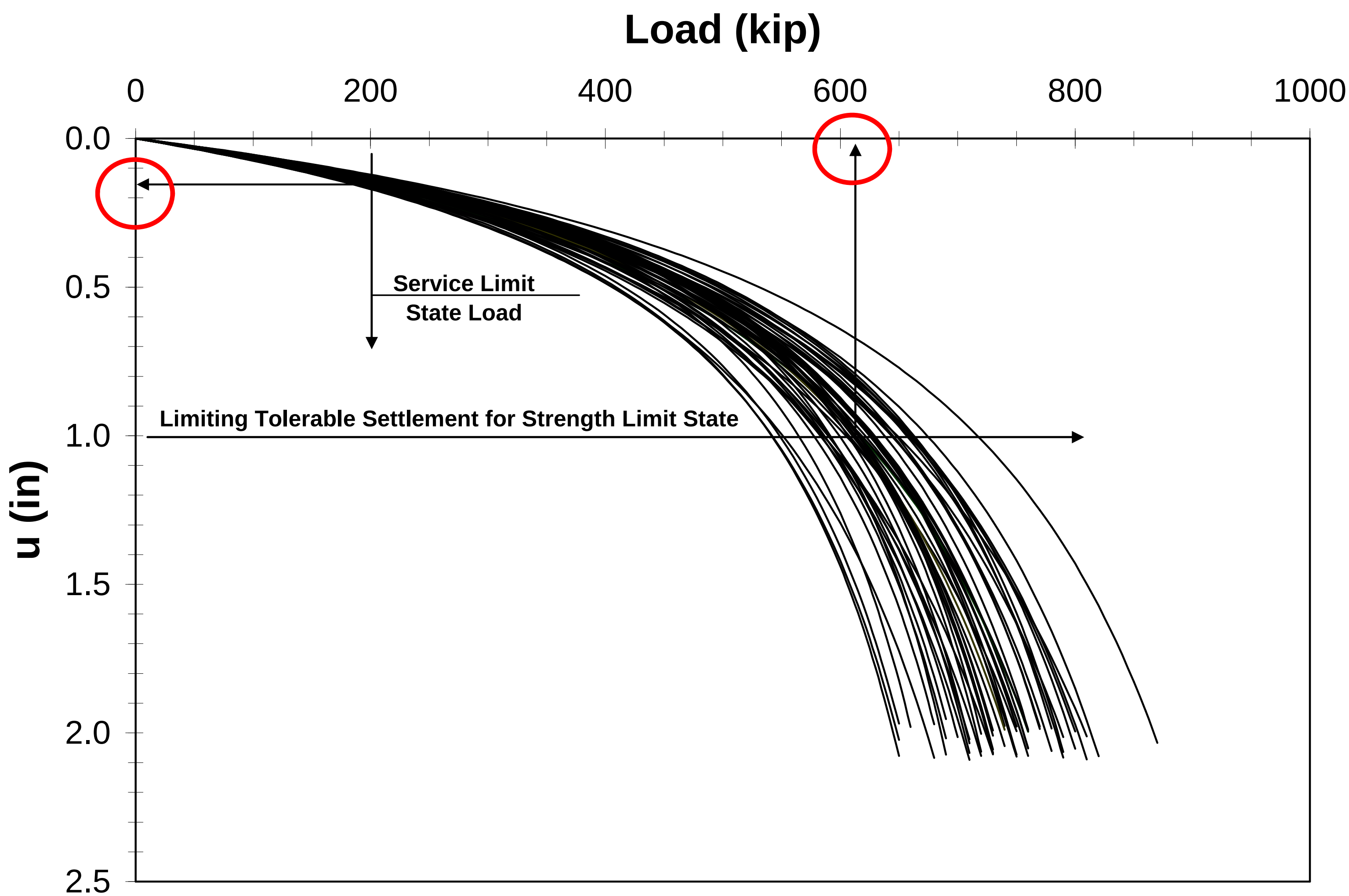
Performance-Based Design Example

- A Latin Hypercube simulation was conducted using the nominal values and COV magnitudes of each model parameter.

- Several different pile lengths and pile diameters were assumed in the simulations:
  - L = 40’ with D = 14”
  - L = 40’ with D = 16”
  - L = 60’ with D = 14”
  - L = 60’ with D = 16”

- All randomly generated load-settlement curves were analyzed at the limiting tolerable settlement for the Strength Limit State. The serviceability settlement was analyzed at the Service Limit State.

Performance-Based Design Example



Latin Hypercube Simulation with L=40′ and D=16″

Performance-Based Design Example

The resistance factors for the Strength Limit State and the settlement statistics for the Service Limit State can be computed from each set of randomly generated load-settlement curves:

		Strength Limit State Resistance			**Pile Head Settlement @ Service Load**		
Pile Diameter (in)	Pile Length (ft)	Nominal Resistance (kip)	ϕ	Factored Resistance (kip)	Nominal Settlement (in)	COV of Pile Head Settlement	Probability of Exceedance (0.25 inch)
14	40	530	0.63	330	0.16	0.10	$7e^{-4}\%$
	60	710	0.63	445	0.14	0.09	$8e^{-11}\%$
16	40	605	0.63	380	0.14	0.11	$2e^{-6}\%$
	60	805	0.64	515	0.12	0.09	$1e^{-14}\%$

Design criteria

Factored Load = 350 kips (Strength Limit State)
Service Load = 200 kips (Service Limit State)
Settlement @ Service Load = 0.25”

Summary and Conclusions

- The advantages of a performance-based design approach within the LRFD framework are numerous:

  1. The approach ensures that the performance of a structure at both the Strength and Service Limit States will be tolerable throughout the design life of the structure.

  2. The approach can rationally incorporate the numerous design and construction uncertainties known to exist in deep foundation engineering (i.e. inherent variability, measurement errors, model uncertainty, construction processes).

  3. The approach allows for the development of a site specific resistance factor that incorporates these sources of uncertainty and permits the inclusion of engineering judgment.

  4. The approach can be easily accomplished through the utilization of a reliability-based design software package recently developed at SDSM&T.

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RE-BA DEEP 1.0

Reliability-Based Deep Foundation Design

Department of Civil and Environmental Engineering
Department of Mathematics and Computer Science
501 E. Saint Joseph Street
Rapid City, South Dakota 57701

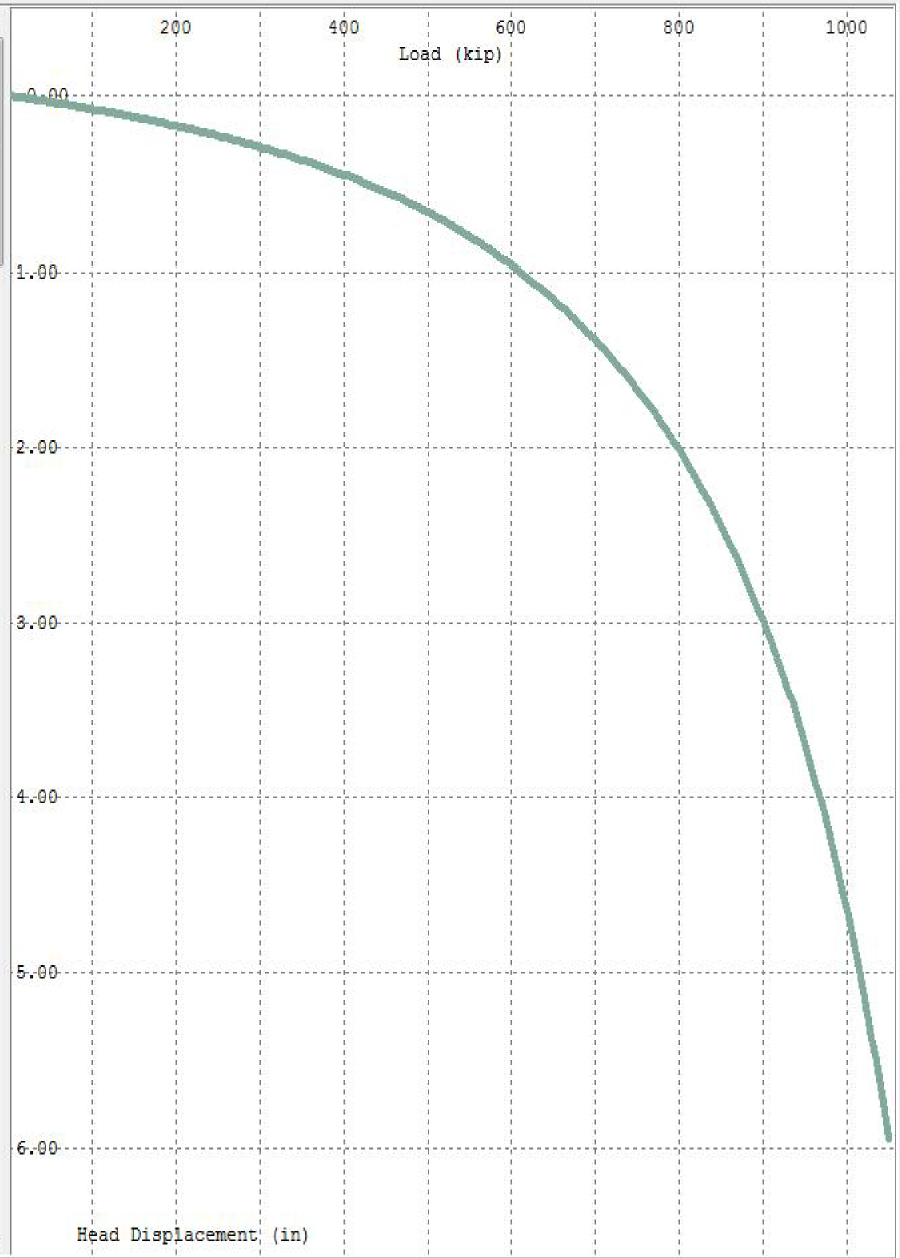
Civil, Environmental and Architectural Engineering Department
Learned Hall
1530 W. 15th Street
Lawrence, Kansas 66045

Deep Structure Design - test.dsd

File Simulation

Results

Load (kip)	Displacement at Head (in)	Displacement at Tip (in)	Load at Tip (kip)	Load along Interface (kip)
5	0.00	0.00	0.33	4.67
10	0.01	0.00	0.67	9.33
15	0.01	0.00	1.01	13.99
20	0.01	0.01	1.35	18.65
25	0.02	0.01	1.71	23.29
30	0.02	0.01	2.06	27.94
35	0.03	0.01	2.42	32.58
40	0.03	0.01	2.79	37.21
45	0.03	0.01	3.17	41.83
50	0.04	0.02	3.55	46.45
55	0.04	0.02	3.93	51.07
60	0.04	0.02	4.32	55.68
65	0.05	0.02	4.72	60.28
70	0.05	0.02	5.12	64.88
75	0.06	0.03	5.53	69.47
80	0.06	0.03	5.95	74.05
85	0.06	0.03	6.37	78.63
90	0.07	0.03	6.80	83.20
95	0.07	0.03	7.23	87.77
100	0.08	0.04	7.67	92.33
105	0.08	0.04	8.12	96.88
110	0.09	0.04	8.58	101.42
115	0.09	0.04	9.04	105.96
120	0.09	0.05	9.51	110.49
125	0.10	0.05	9.99	115.01
130	0.10	0.05	10.47	119.53
135	0.11	0.05	10.96	124.04
140	0.11	0.05	11.46	128.54
145	0.12	0.06	11.97	133.03
150	0.12	0.06	12.49	137.51
155	0.13	0.06	13.01	141.99
160	0.13	0.07	13.54	146.46
165	0.14	0.07	14.08	150.92
170	0.14	0.07	14.63	155.37
175	0.15	0.07	15.18	159.82
180	0.15	0.08	15.75	164.25
185	0.16	0.08	16.32	168.68
190	0.16	0.08	16.91	173.09
195	0.17	0.08	17.50	177.50
200	0.17	0.09	18.10	181.90
205	0.18	0.09	18.71	186.29
210	0.18	0.09	19.33	190.67



Pile Geometry Constants

Edit

Diameter (in): 16.00
Length (ft): 1.00
Foundation Stiffness (kip): 904777.92

Layers Settings

Edit

Analysis Type: Nominal Capacity Analysis (Curve Fitting)
Number of Layers: 3

Soil Data Constants

Edit

Layer 1

Layer 2

Layer 3

Nominal Tip

Load Test Data

Edit

References from Presentation

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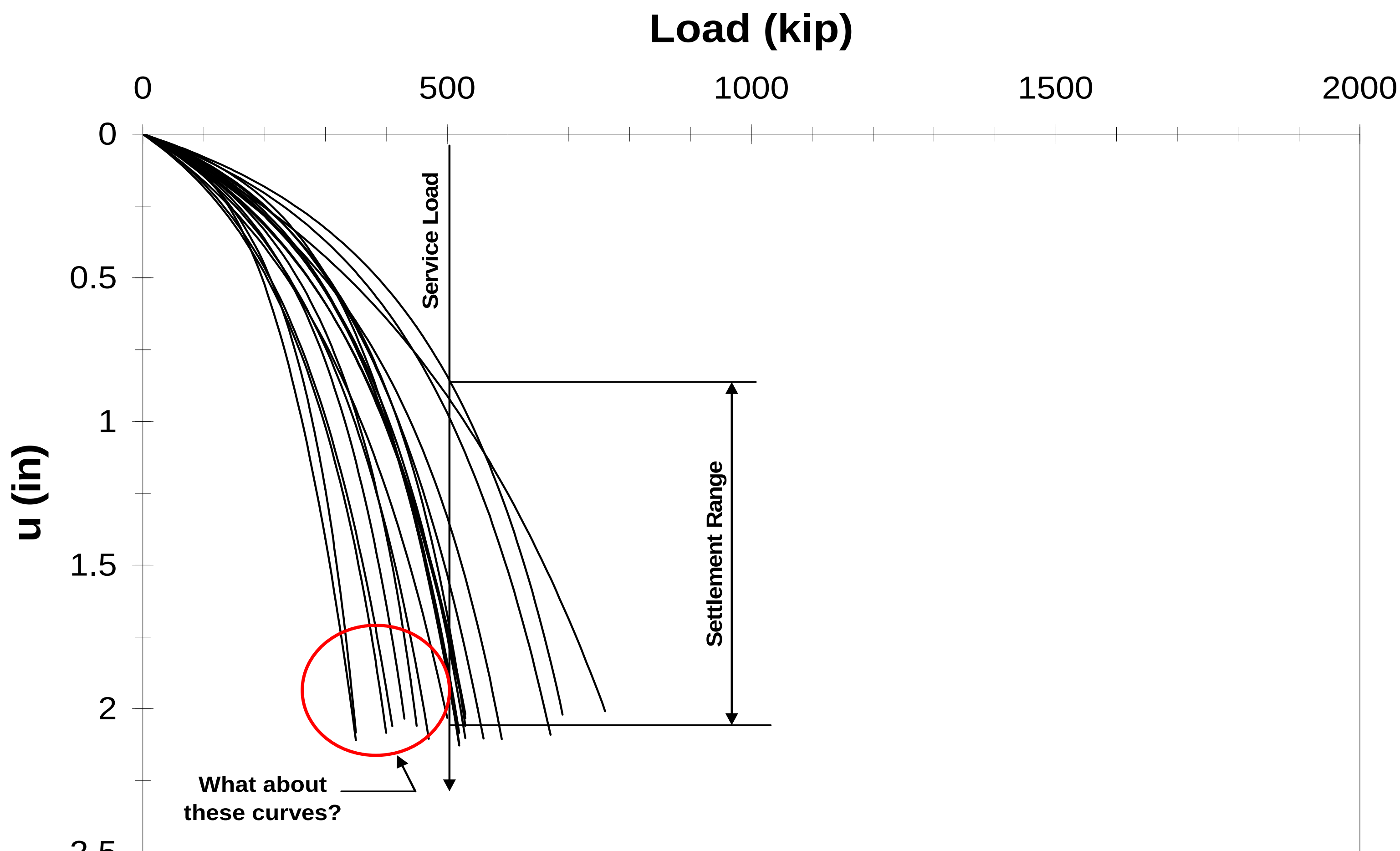
THANK YOU.

QUESTIONS?

Serviceability Settlement



Load-displacement behavior of APG pile assuming COV of "t-z" model parameters = 0.30 and length of pile = 20 ft.