


SHRP2 SOLUTIONS
STRATEGIC HIGHWAY RESEARCH PROGRAM

Service Limit State Design for Bridges

Background Information on the Proposed Geotechnical Revisions to AASHTO LRFD

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U.S. Department of Transportation
Federal Highway Administration

American Association of State Highway and Transportation Officials
AASHTO

SHRP2 Implementation

- **SHRP2 Solutions** – **63 products** bundled into 40 implementation efforts
- **Solution Development** – **processes, software, testing procedures, and specifications**
- **Field Testing** – refined in the field
- **Implementation** – **350+ transportation projects**; goal to adopt as standard practice
- **SHRP2 Education Connection** – connecting next-generation professionals with next-generation innovations

51

States + DC

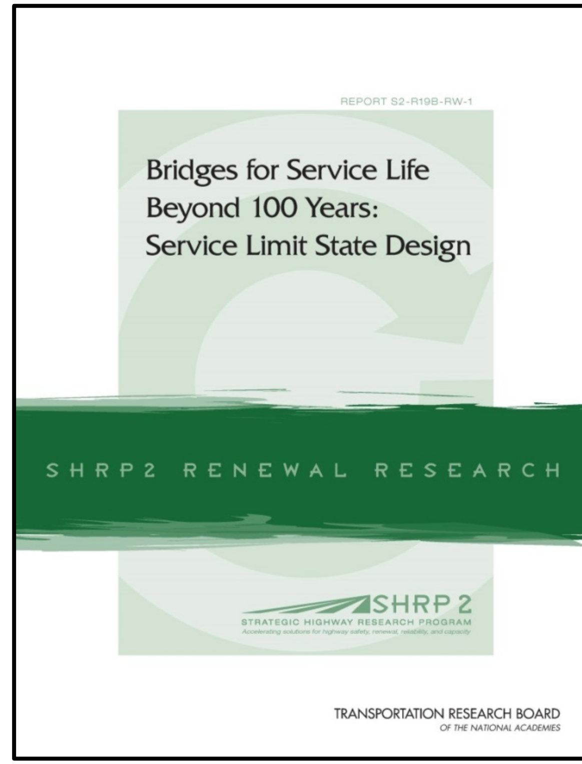
350+

projects

Initial SHRP2-TRB Research Team for R19B

- Modjeski and Masters (M&M)
  - John M. Kulicki (Principal Investigator)
  - Wagdy G. Wassef (formerly M&M)
- University of Delaware (UD)
  - Dennis R. Mertz
- University of Nebraska – Lincoln (UNL)
  - Andrzej S. Nowak (now at Auburn)
- NCS Consultants, LLC (NCS)
  - Naresh C. Samtani

Report S2-R19B-RW-1

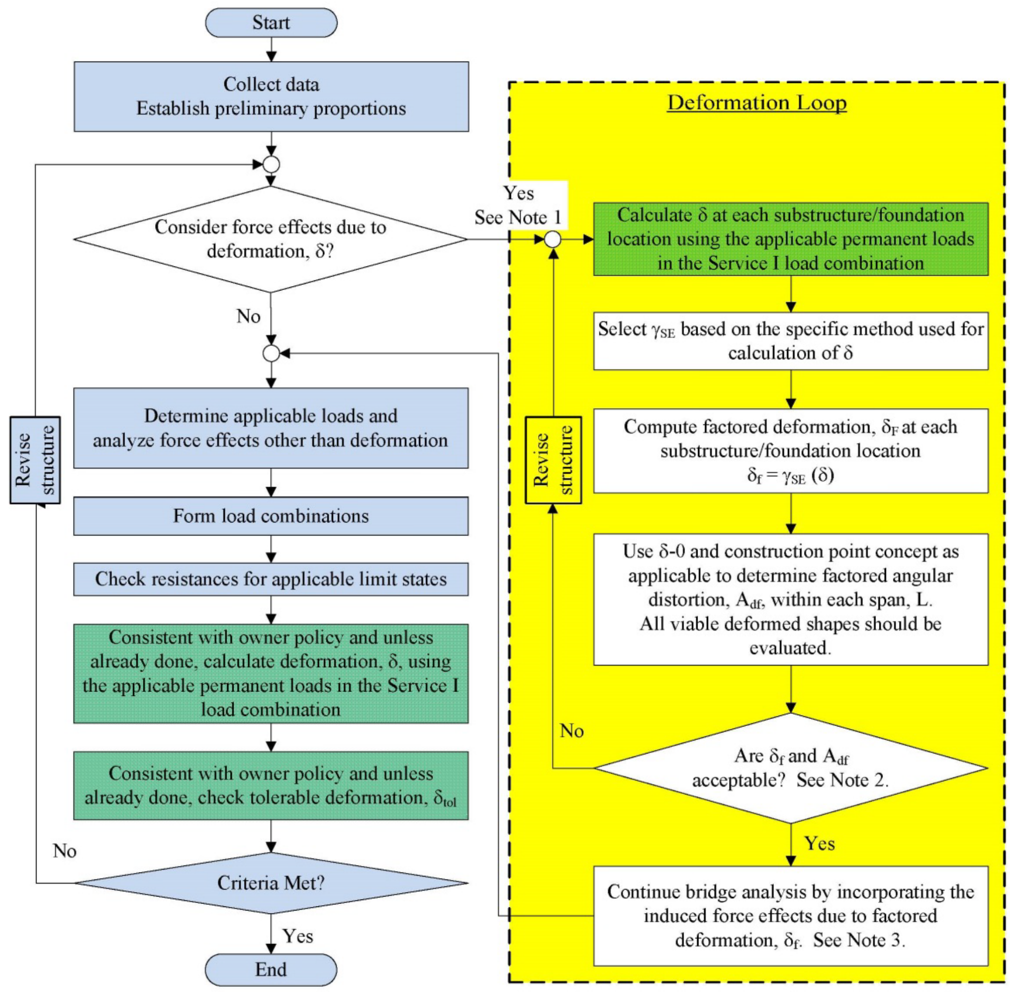


Work Under TRB-SHRP2

- General calibration process was developed for SLS and was revised to fit specific requirements for different limit states.
- The **following limit states were calibrated**:
  - o Fatigue I and Fatigue II limit states for steel components
  - o Fatigue I for compression in concrete and tension in the reinforcement
  - o Tension in prestressed concrete components
  - o Crack control in decks
  - o Service II limit state for yielding of steel and for bolt slip
  - o Foundation deformation(s)

Implementation Tools

- Several examples
- White paper
- Flow Chart
- Proposed LRFD specification revisions and commentaries
- SHRP2 Round 7 Implementation Assistance Program (IAP)

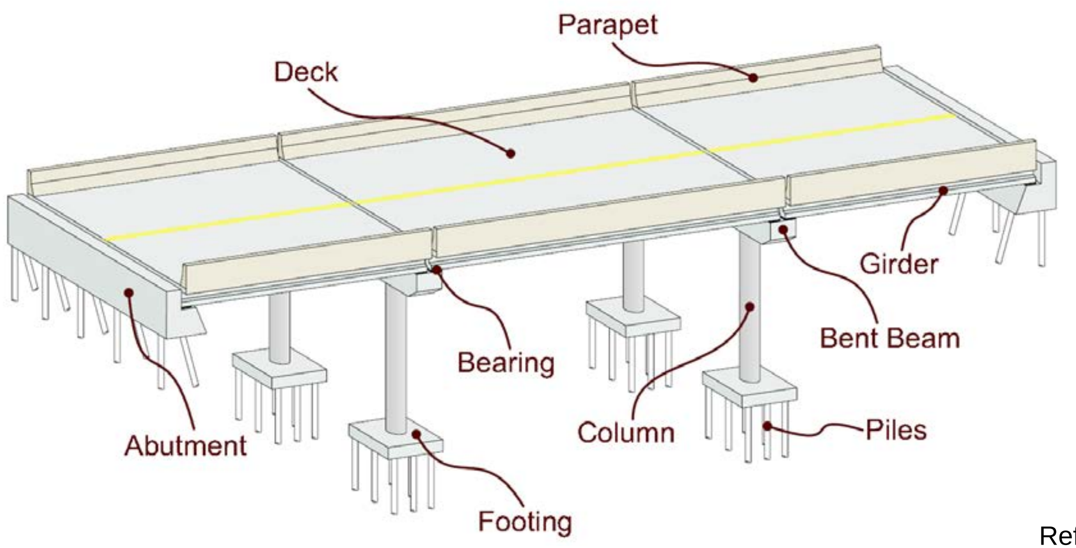


Note 1: It may be efficient to run some early design iterations without including this loop until the proportions of the bridge are well developed, and then include this loop to consider the force effects from differential deformations.

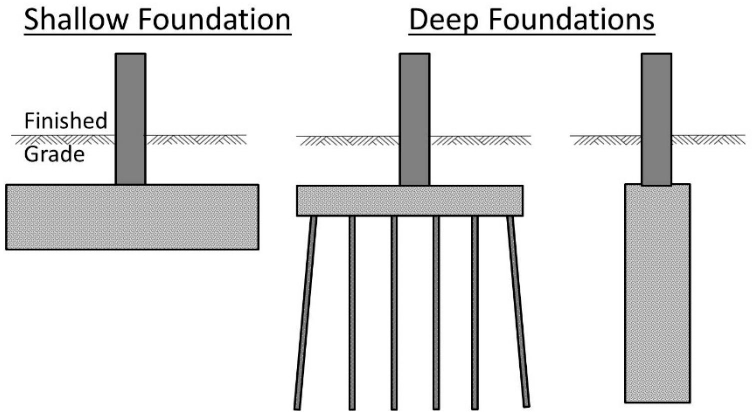
Note 2: Compare A_{df} to permissible angular distortion criteria and δ_f to permissible values at abutment interfaces and within spans in terms of vertical clearance under bridge. Guidance in Article 10.5.2 may be used to establish permissible values. Owner may establish other permissible values.

Note 3: Note that the γ_{SE} is used to factor the deformations as shown in this flow chart. γ_{SE} also appears in Table 3.4.1-1 (Load Combinations and Load Factors). This does not imply a second application of γ_{SE} in the load combinations but rather it is an acknowledgement that the deformations have already been factored. Use of the factored deformations in a structural analysis program ensures that the output is factored value.

Bridge Configuration and Foundation Types



Reference: Nielson (2005)



Foundation Deformations

- Vertical (Settlement)
- Lateral (Horizontal)
- Rotation

AASHTO Table 3.4.1-1

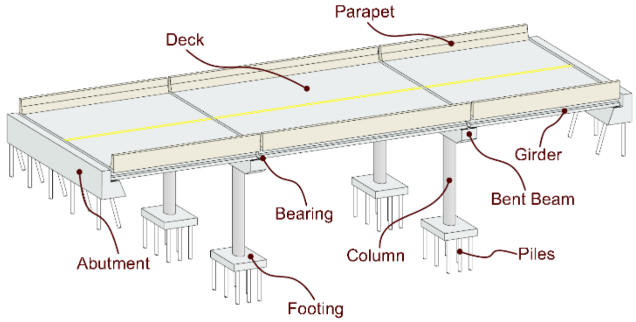
Superimposed Deformations

Load Combination Limit State		*DC DD DW EH EV ES EL PS CR SH*	*LL IM CE BR PL LS*	*WA*	*WS*	*WL*	*FR*	*TU*	*TG*	*SE*	Use One of These at a Time *EQ*	*BL*	*IC*	*CT*	*CV*
STRENGTH LIMIT	I	γ_p	1.75	1.00	—	—	1.00	0.50/1.20	γ_{TG}	γ_{SE}	—	—	—	—	—
	II	γ_p	1.35	1.00	—	—	1.00	0.50/1.20	γ_{TG}	γ_{SE}	—	—	—	—	—
	III	γ_p	—	1.00	1.40	—	1.00	0.50/1.20	γ_{TG}	γ_{SE}	—	—	—	—	—
	IV	γ_p	—	1.00	—	—	1.00	0.50/1.20	—	—	—	—	—	—	—
	V	γ_p	1.35	1.00	0.40	1.0	1.00	0.50/1.20	γ_{TG}	γ_{SE}	—	—	—	—	—
EXTREME EVENT	I	γ_p	γ_{EQ}	1.00	—	—	1.00	—	—	—	1.00	—	—	—	—
	II	γ_p	0.50	1.00	—	—	1.00	—	—	—	—	1.00	1.00	1.00	1.00
SERVICE LIMIT	I	1.00	1.00	1.00	0.30	1.0	1.00	1.00/1.20	γ_{TG}	γ_{SE}	—	—	—	—	—
	II	1.00	1.30	1.00	—	—	1.00	1.00/1.20	—	—	—	—	—	—	—
	III	1.00	0.80	1.00	—	—	1.00	1.00/1.20	γ_{TG}	γ_{SE}	—	—	—	—	—
	IV	1.00	—	1.00	0.70	—	1.00	1.00/1.20	—	1.0	—	—	—	—	—
FATIGUE - *LL, IM & CE* only	I	—	1.50	—	—	—	—	—	—	—	—	—	—	—	—
	II	—	0.75	—	—	—	—	—	—	—	—	—	—	—	—

Superimposed Deformations

Article 3.12.6 – Settlement

- "Force effects due to extreme values of differential settlement among substructures and within individual substructure units shall be considered."

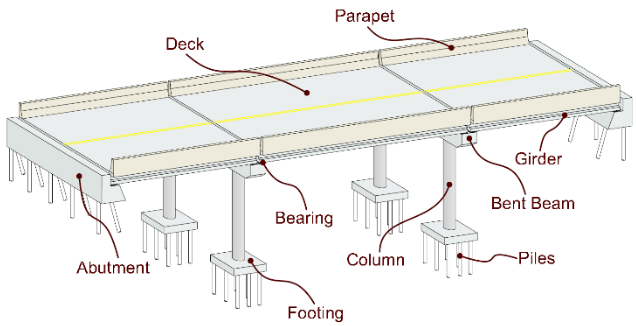


Commentary

- "Force effects due to settlement may be reduced by considering creep. Analysis for the load combinations in Tables 3.4.1-1 and 3.1.4-2 which include settlement should be repeated for settlement of each possible substructure unit settling individually, as well as combinations of substructure units settling, that could create critical force effects in the structure."

Standard Specifications – 17th Edition (2002)

- **Article 3.3 – DEAD LOAD**
  3.3.2.1 "If differential settlement is anticipated in a structure, consideration should be given to stresses resulting from this settlement."



- Since the above stipulation is under the parent article (3.3, Dead Load), it implies that settlement effects should be considered wherever dead load appears in the allowable stress design (ASD) or load factor design (LFD) load combinations.

Key Points

- Evaluation of differential deformation is mandated by AASHTO bridge design specification regardless of design platform (ASD, LFD, or LRFD).
  - It is not a new requirement.

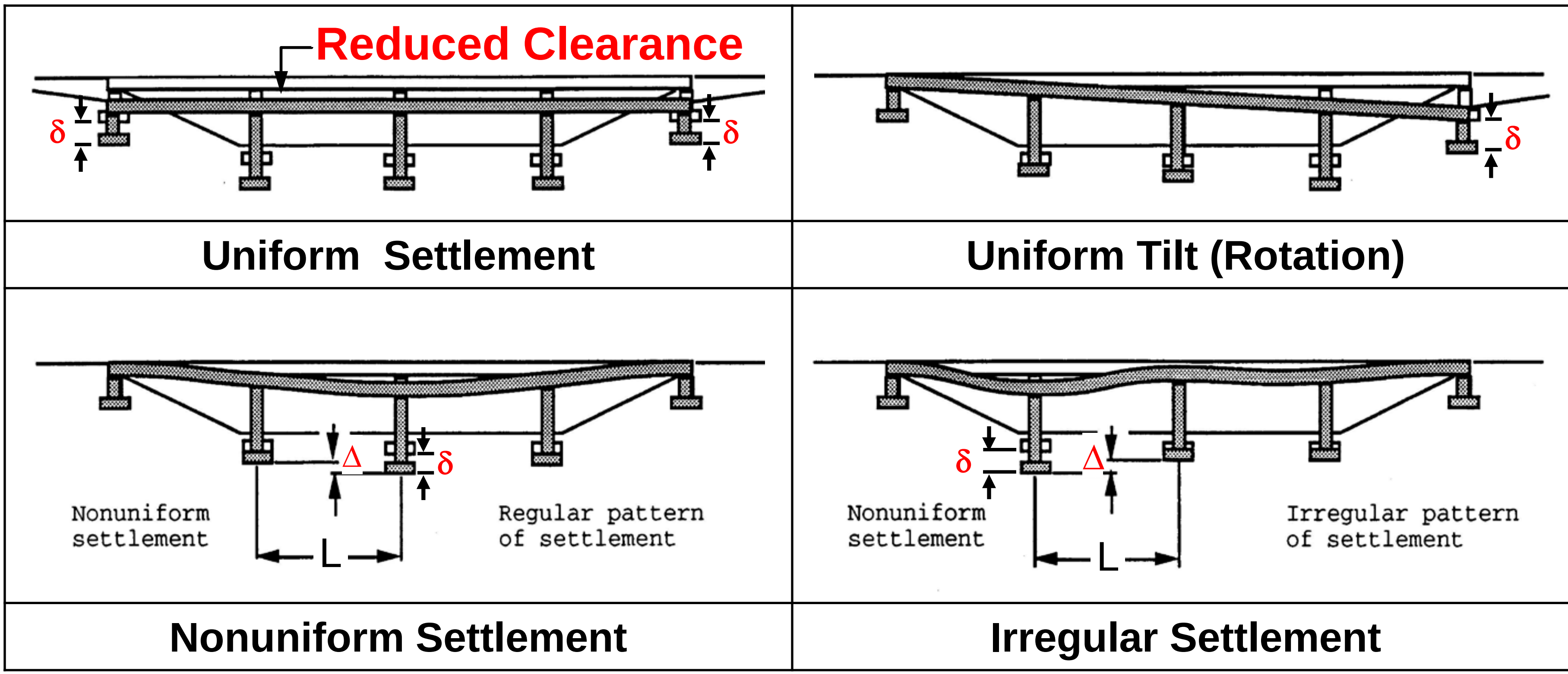
- In LRFD platform,
  - Category of superimposed deformations
  - The g_{SE} load factor appears in both strength and service limit state load combinations.

- The uncertainty of predicted deformations needs to be calibrated for the g_{SE} load factor within the overall framework of limit state design.

Nomenclature

Symbol	Meaning
δ	Total deformation at a support element
Δ	Differential deformation between two adjacent support elements
A	Angular distortion = Δ/L, where L is the distance between two adjacent support elements over which Δ is calculated

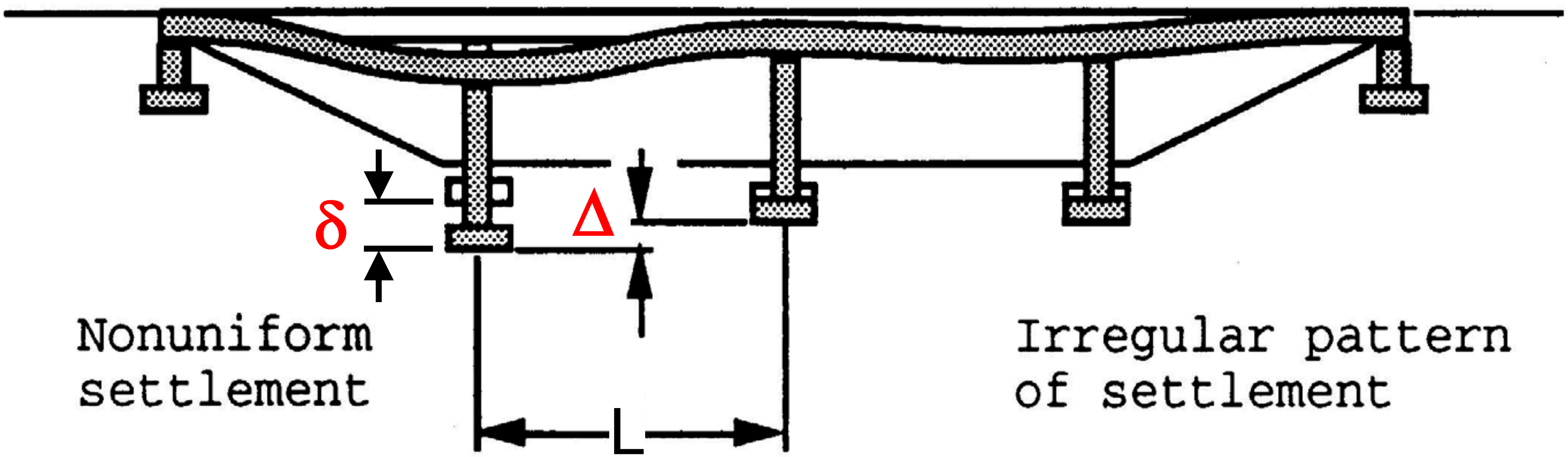
Idealized Deformation Patterns



Reference: After Duncan and Tan (1991)

Differential Settlement

- Difference in settlement between two support elements, Δ
- Induces force effects within superstructure



Induced Moments in Continuous Span Bridges

EXAMPLE

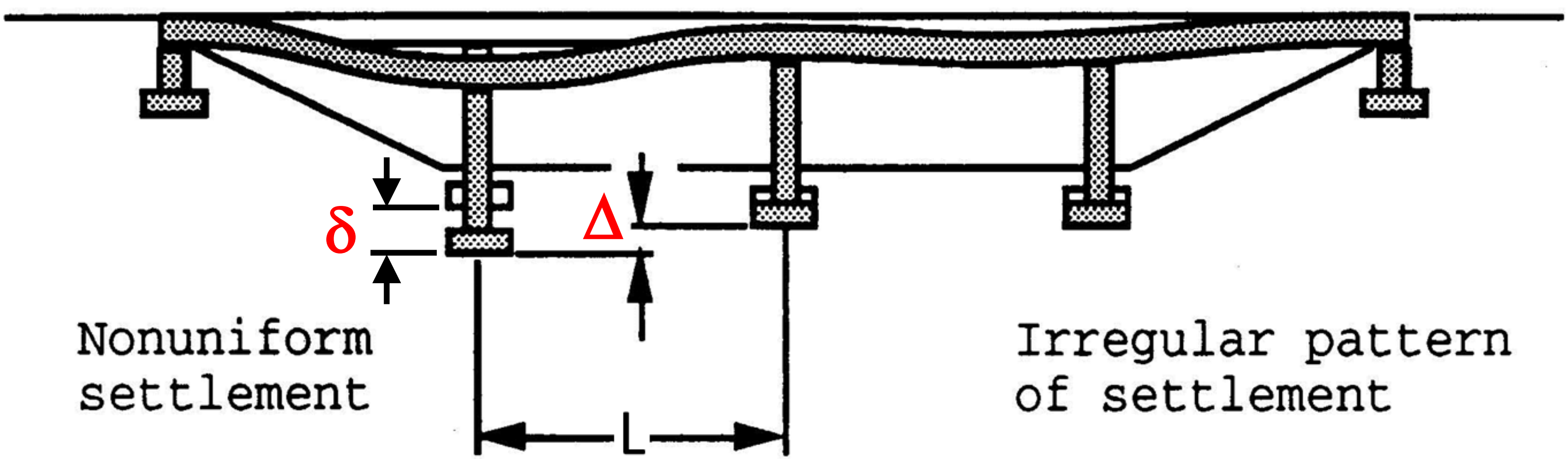
$$FEM = \frac{6EI\Delta}{L^2} = 6\left(\frac{EI}{L}\right)\left(\frac{\Delta}{L}\right)$$

→ **Force Effect = *f* (EI/L, Δ/L)**

EI/L is a representation of **Structure Stiffness**

Δ/L is **Angular Distortion** (dimensionless)

Settlement, δ, and Angular Distortion, A = Δ/L



- What is a ***tolerable*** value of Δ/L ?
- How ***reliable*** is the value of δ ?

Limiting (Tolerable) Angular Distortion

- Moulton et al. (1985) – For FHWA
- AASHTO – Standard (ASD) and LRFD Specifications

Type of Bridge	Limiting Angular Distortion, Δ/L	
	Moulton et al. (1985)	**AASHTO**
Continuous Span	**0.004** (4.8" in 100')	**0.004** (4.8" in 100')
Simple Span	**0.005** (6.0" in 100')	**0.008** (9.6" in 100')
For rigid frames, perform case-specific analysis		

Use of AASHTO Limiting Values

Arbitrary (no consistency in application)

- 0.004 → 0.0004 or 0.008 → 0.0008
- I-25/I-40 TI (BIG-I), NM: 0.004 → 0.002, 0.008 → 0.004
- WSDOT (From Chapter 8 of Geotech Design Manual)

Total Settlement, δ, at Pier or Abutment	Differential Sett over 100 ft within pier or abut & diff sett between piers	Action
$\delta \le 1''$	$\Delta_{100\ ft} \le 0.75''$ **[0.000625]**	Design & Construct
$1'' < \delta \le 4''$	$0.75'' < \Delta_{100\ ft} \le 3''$ **[0.000625-0.0025]**	Ensure structure can tolerate settlement
$\delta > 4''$	$\Delta_{100\ ft} > 3''$ **[> 0.0025]**	Need Dept approval

Definition of Intolerable Movement in Moulton's Study

- Per TRB Committee A2K03 (mid 1970s)
  - "***Movement is <u>not</u> tolerable if damage requires costly maintenance and/or repairs <u>and</u> a more expensive construction to avoid this would have been preferable.***"

- Definition is somewhat subjective and needs to be revisited in stochastic (reliability) context of LRFD, which is what was done by SHRP2 – Project R19B

Evaluation by Moulton et al. (1985)

Basis

- 1977 – 12th Edition of Standard Specifications
- HS20-44 wheel loading or its equivalent lane loading

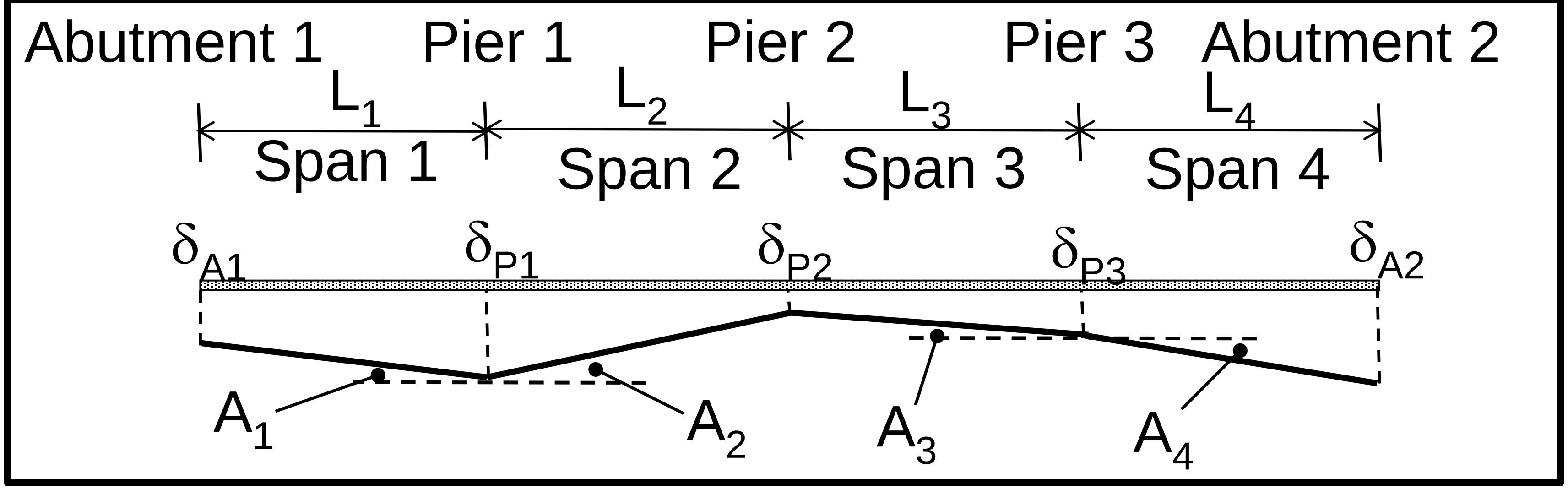
Key observation of 1985 study

- Attempts to establish tolerable movements from analyses of the effects of differential settlement on the stresses in bridges significantly underestimated the criteria established from field observations
- Analytical evaluation leads to overly conservative angular distortion criteria

A Rational Approach – FHWA 2010

Step 1 – Estimate Total/Diff Settlements and Angular Distortions

Example profile of settlement, δ, along a bridge



Span	Differential Settlement	Angular Distortion
1	$\lvert\delta_{A1} - \delta_{P1}\rvert$	$A_1 = (\lvert\delta_{A1} - \delta_{P1}\rvert)/L_1$
2	$\lvert\delta_{P1} - \delta_{P2}\rvert$	$A_2 = (\lvert\delta_{P1} - \delta_{P2}\rvert)/L_2$
3	$\lvert\delta_{P2} - \delta_{P3}\rvert$	$A_3 = (\lvert\delta_{P2} - \delta_{P3}\rvert)/L_3$
4	$\lvert\delta_{P3} - \delta_{A2}\rvert$	$A_4 = (\lvert\delta_{P3} - \delta_{A2}\rvert)/L_4$

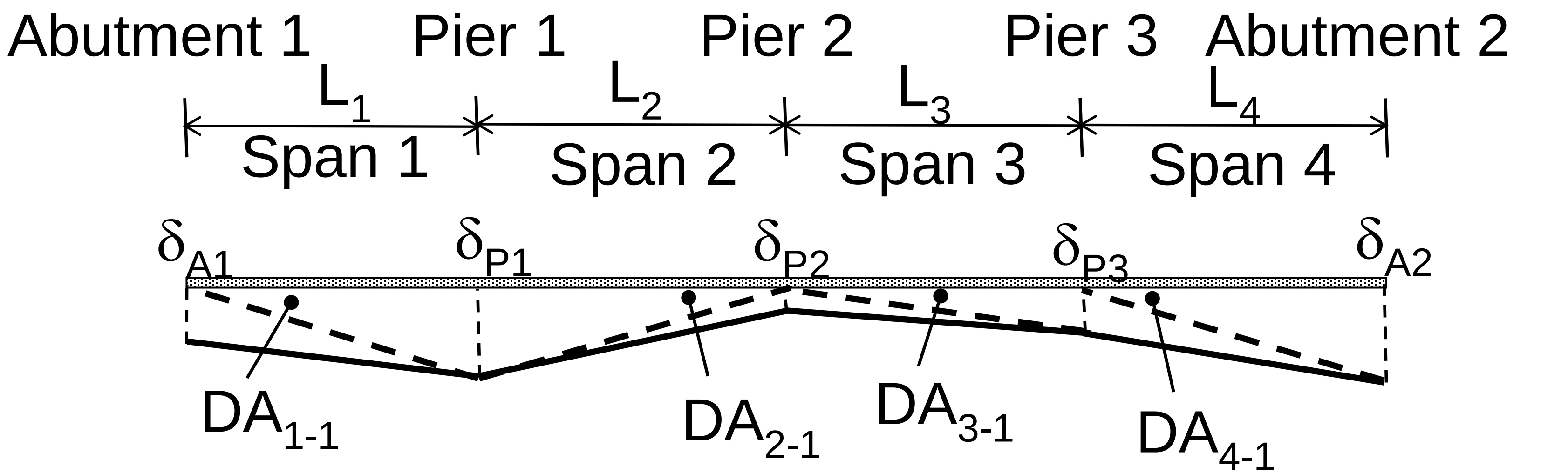
Nomenclature

Symbol	Meaning
Dδ	Design differential deformation based on δ-0 concept
DA	Design Angular distortion = Dδ/L, where L is the distance between two adjacent support elements over which Dδ is calculated based on δ-0 concept

A Rational Approach – FHWA 2010

Step 2 – Estimate *Design* Values Based on δ-0 Concept – Mode 1

Mode 1

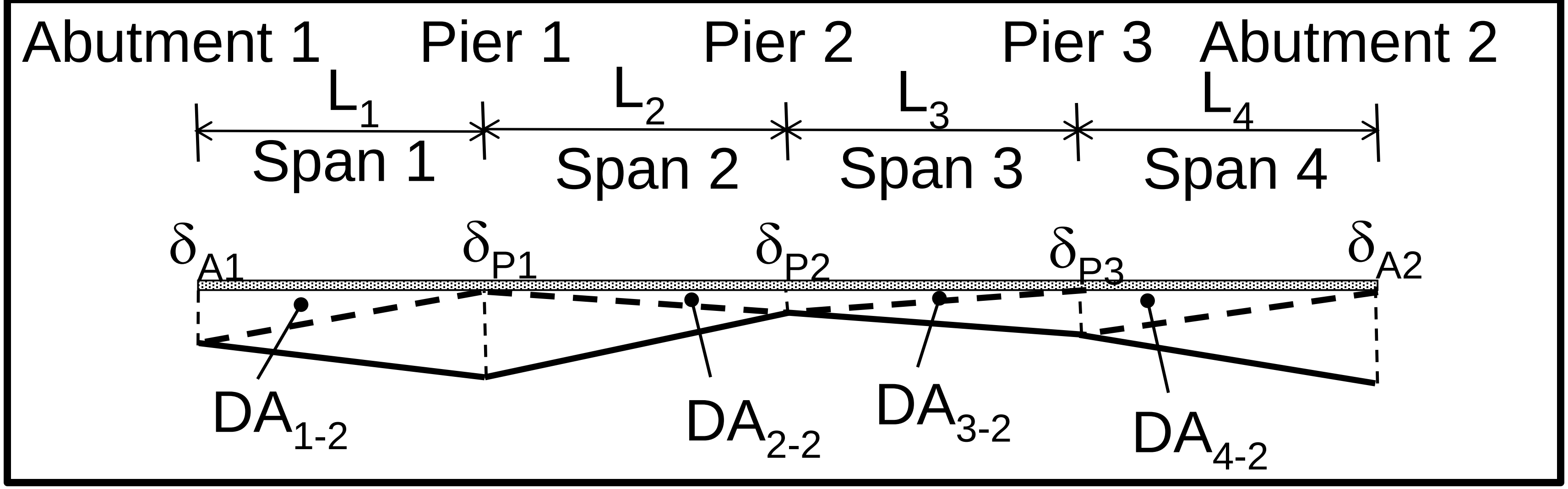


Span	Design Differential Settlement	Design Angular Distortion
1	$D\delta_{P1} = \delta_{P1}$ (assume $\delta_{A1} = 0$)	$DA_{1\text{-}1} = D\delta_{P1}/L_1$
2	$D\delta_{P1} = \delta_{P1}$ (assume $\delta_{P2} = 0$)	$DA_{2\text{-}1} = D\delta_{P1}/L_2$
3	$D\delta_{P3} = \delta_{P3}$ (assume $\delta_{P2} = 0$)	$DA_{3\text{-}1} = D\delta_{P3}/L_3$
4	$D\delta_{A2} = \delta_{A2}$ (assume $\delta_{P3} = 0$)	$DA_{4\text{-}1} = D\delta_{A2}/L_4$

A Rational Approach – FHWA 2010

Step 2 – Estimate *Design* Values Based on δ-0 Concept – Mode 2

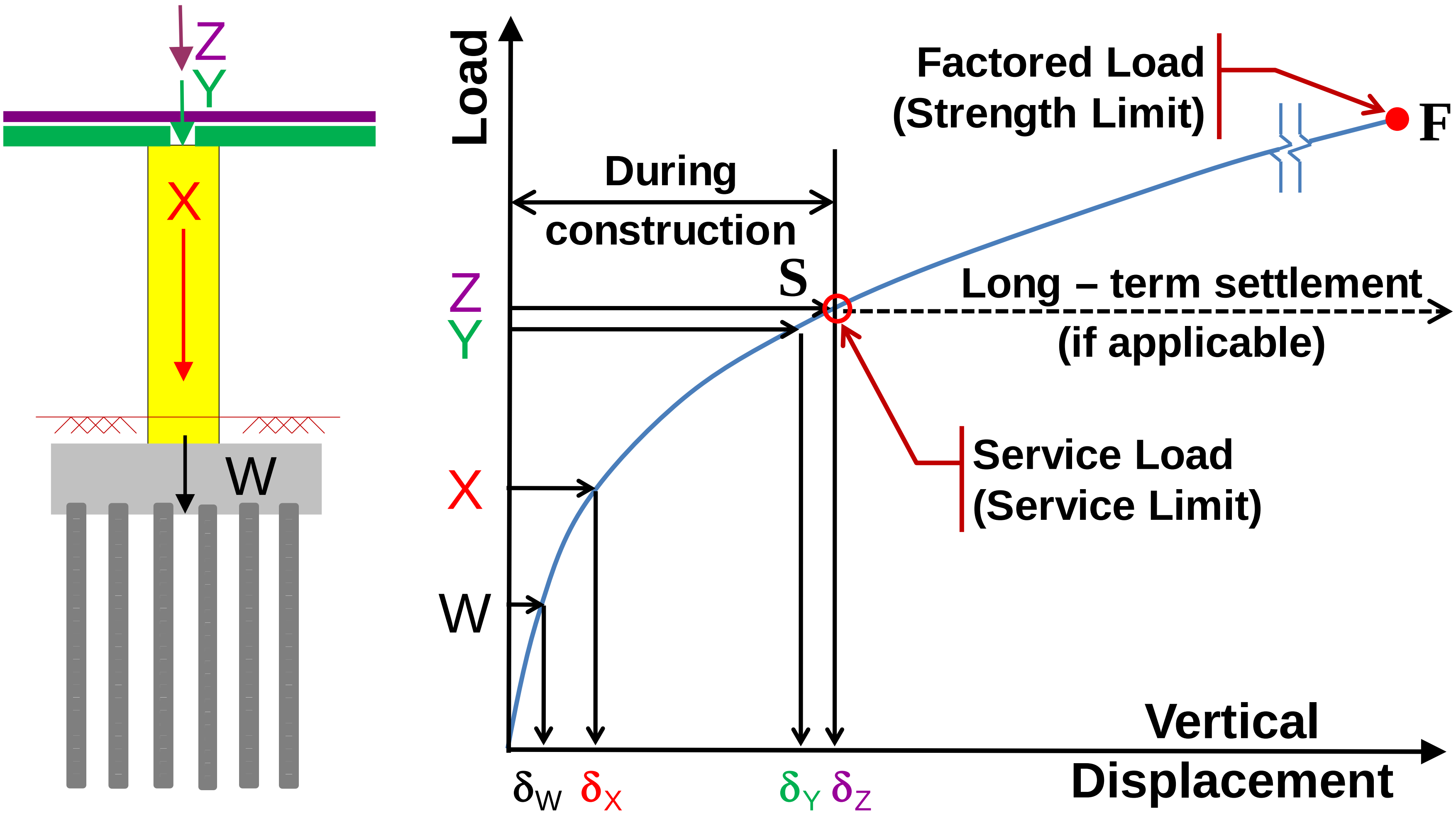
Mode 2



Span	Design Differential Settlement	Design Angular Distortion
1	$D\delta_{A1} = \delta_{A1}$ (assume $\delta_{P1} = 0$)	$DA_{1\text{-}2} = D\delta_{A1}/L_1$
2	$D\delta_{P2} = \delta_{P2}$ (assume $\delta_{P1} = 0$)	$DA_{2\text{-}2} = D\delta_{P2}/L_2$
3	$D\delta_{P2} = \delta_{P2}$ (assume $\delta_{P3} = 0$)	$DA_{3\text{-}2} = D\delta_{P2}/L_3$
4	$D\delta_{p3} = \delta_{p3}$ (assume $\delta_{A2} = 0$)	$DA_{4\text{-}2} = D\delta_{p3}/L_4$

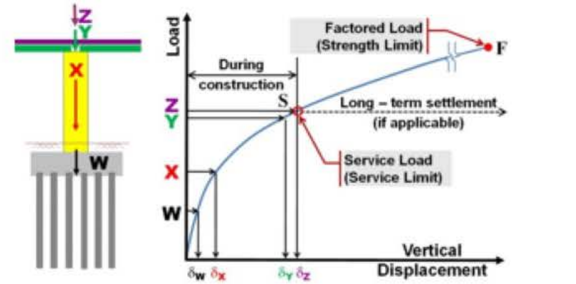
When is a Bridge Structure Affected?

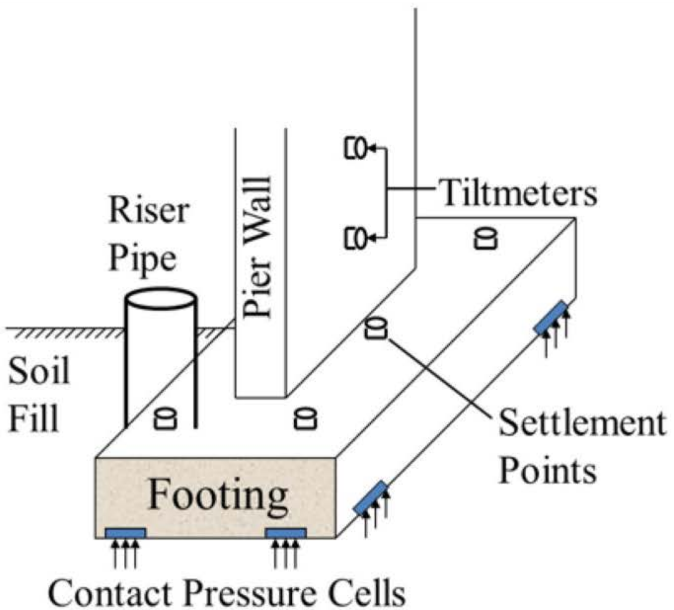
Foundation could be shallow (spread footings) or deep (piles, shafts, etc.)



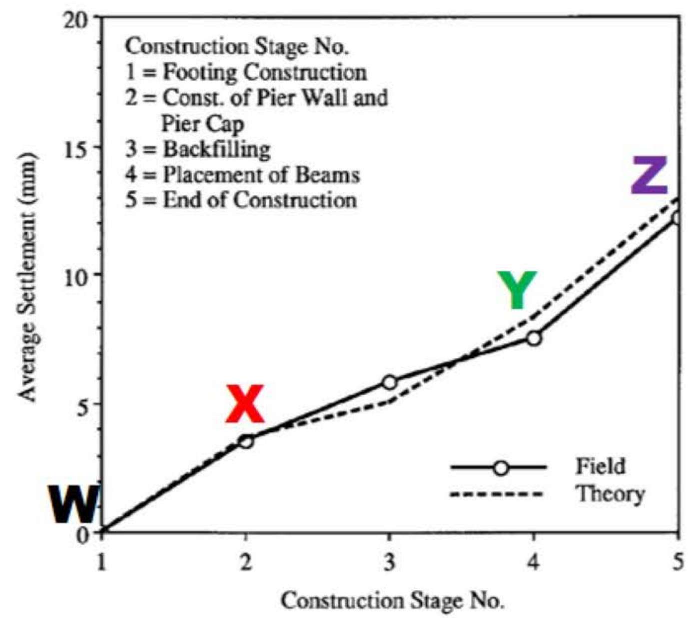
When is a Bridge Structure Affected?

Construction Point Concept





Instrumentation



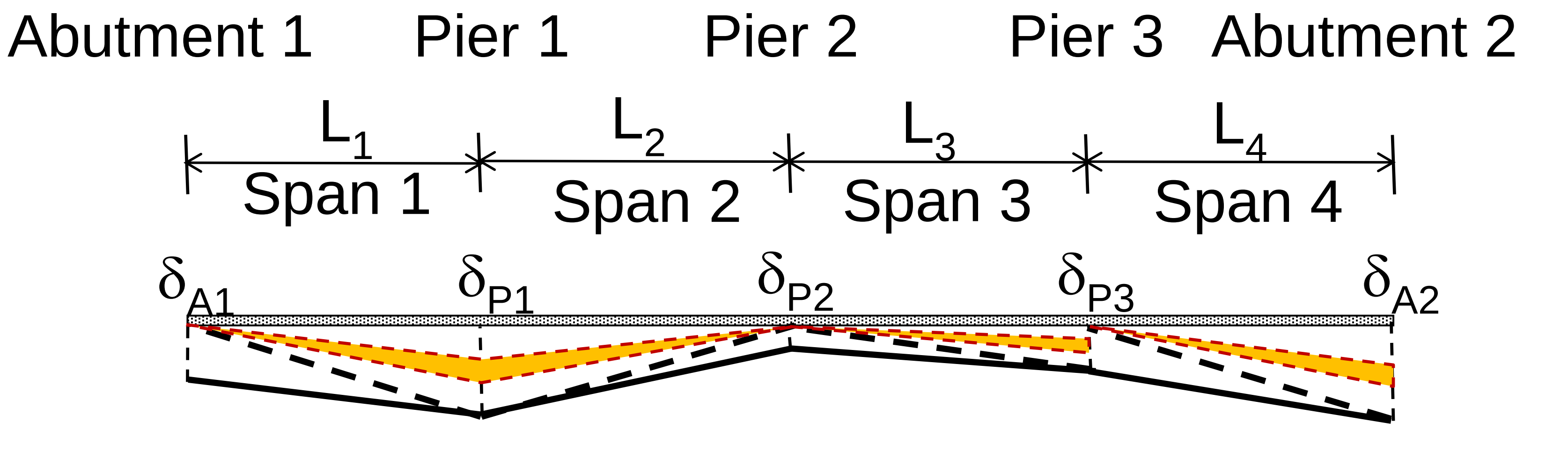
Example Data (Pier)

Reference: Sargand, et al., (1999); Ohio DOT

A Rational Approach – FHWA 2010
Step 3 – Estimate *Relevant* Values

- Based on construction point concept, estimate ***relevant*** deformation values (which can be up to half of the values based on assumption of instantaneous placement of entire structure)

Mode 1

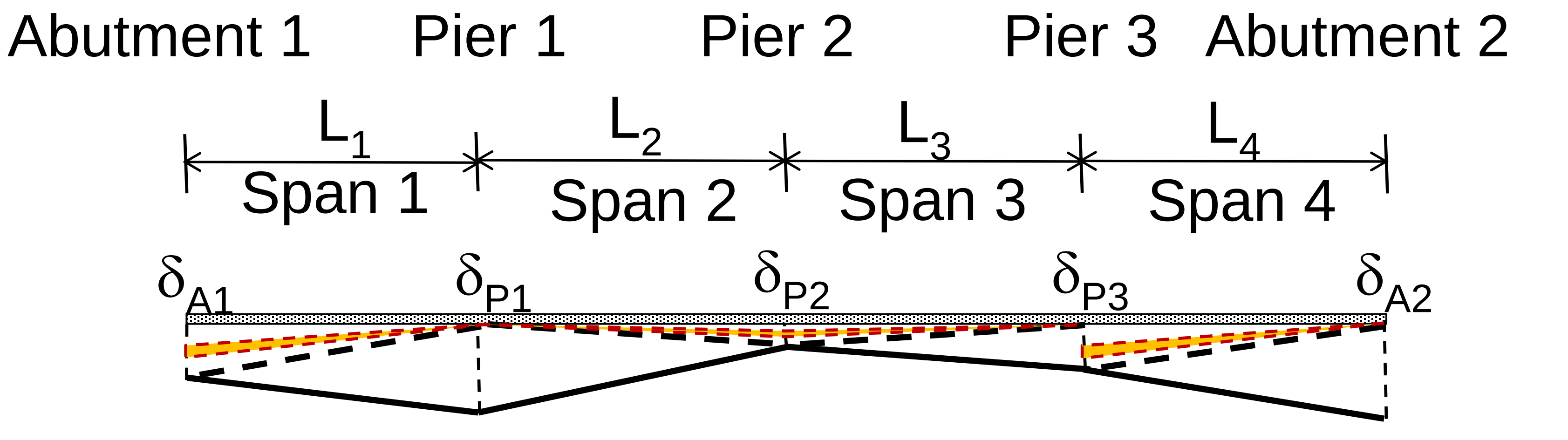


A Rational Approach – FHWA 2010

Step 3 – Estimate *Relevant* Values

- Based on construction point concept, estimate ***relevant*** deformation values (which can be up to half of the values based on assumption of instantaneous placement of entire structure)

Mode 2



What Does All of This Mean?

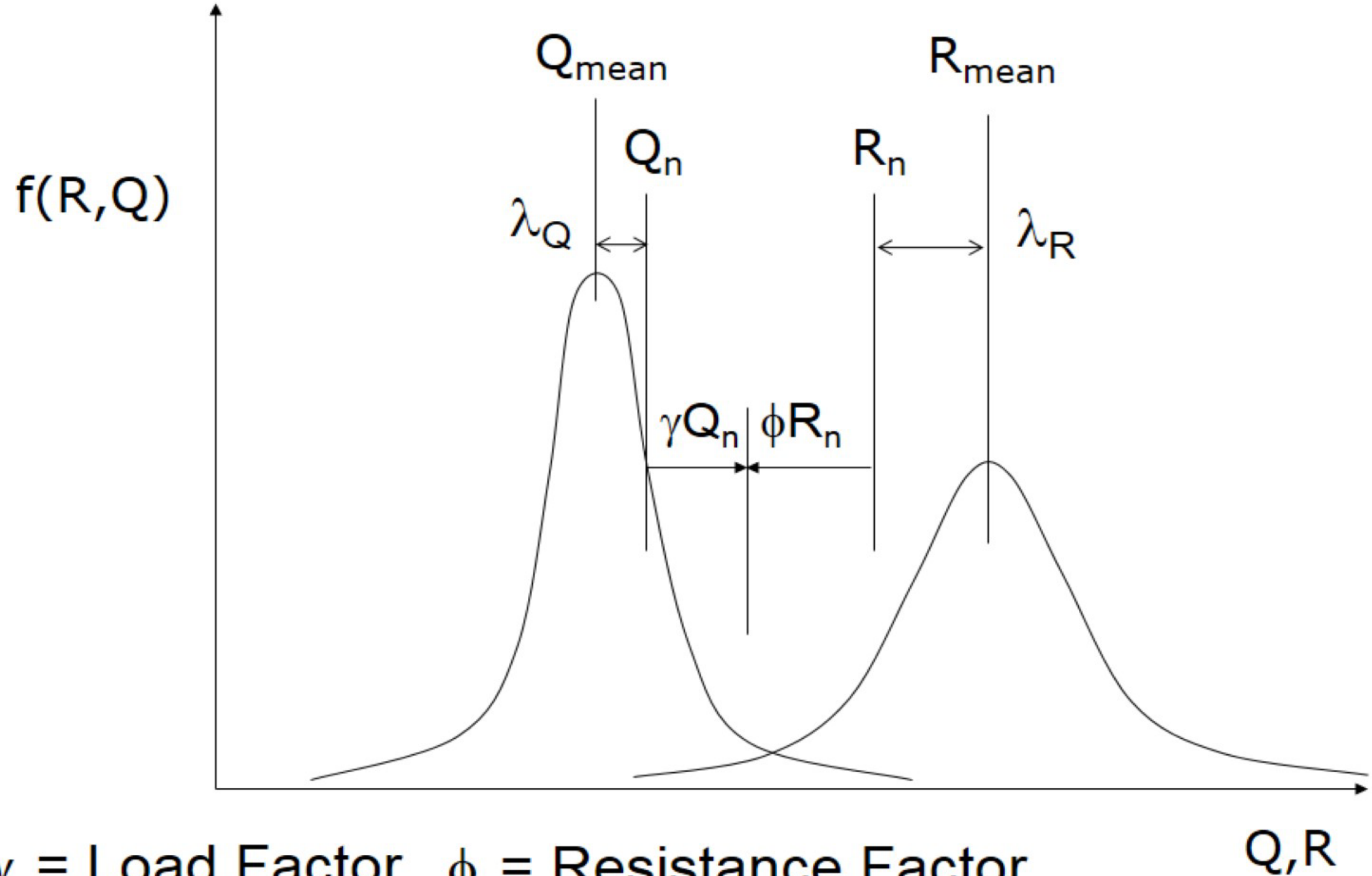
Need to:

1. **Re-evaluate** past data in LRFD framework
2. **Re-survey** using revised definition of intolerable movements in LRFD context
3. Using reliability considerations, **evaluate** foundation/soil response with substructure/superstructure interaction

Calibration Approach

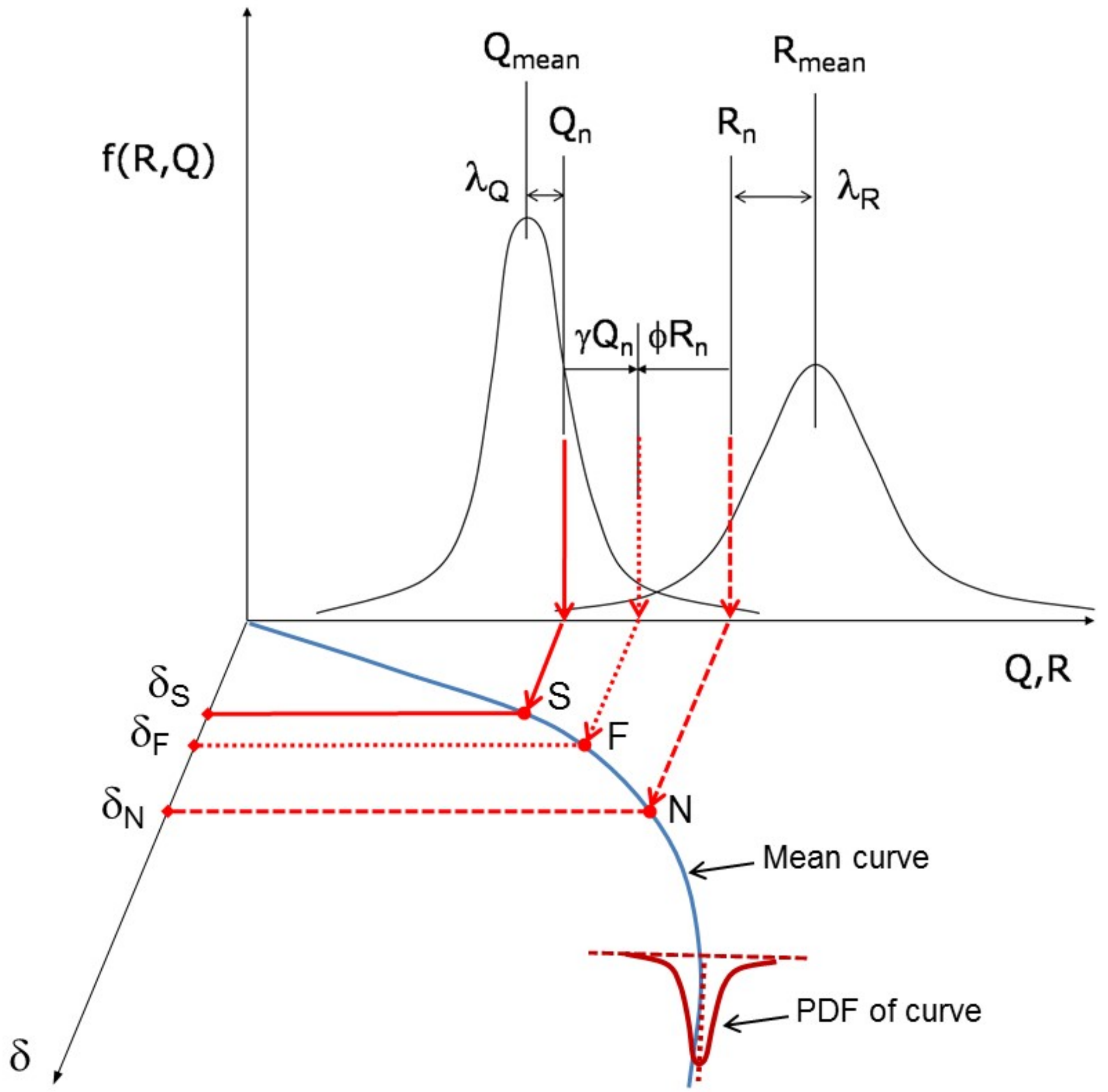
Incorporating reliability into evaluation of foundation deformations

Basic LRFD Concept



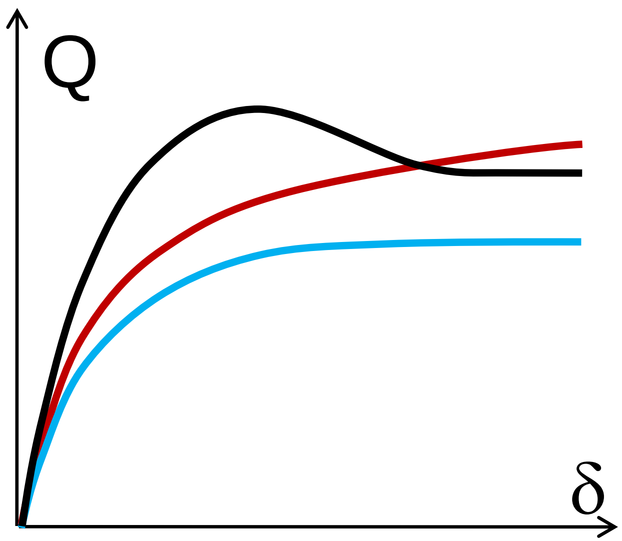
γ = Load Factor ϕ = Resistance Factor

The Q-δ Dimension



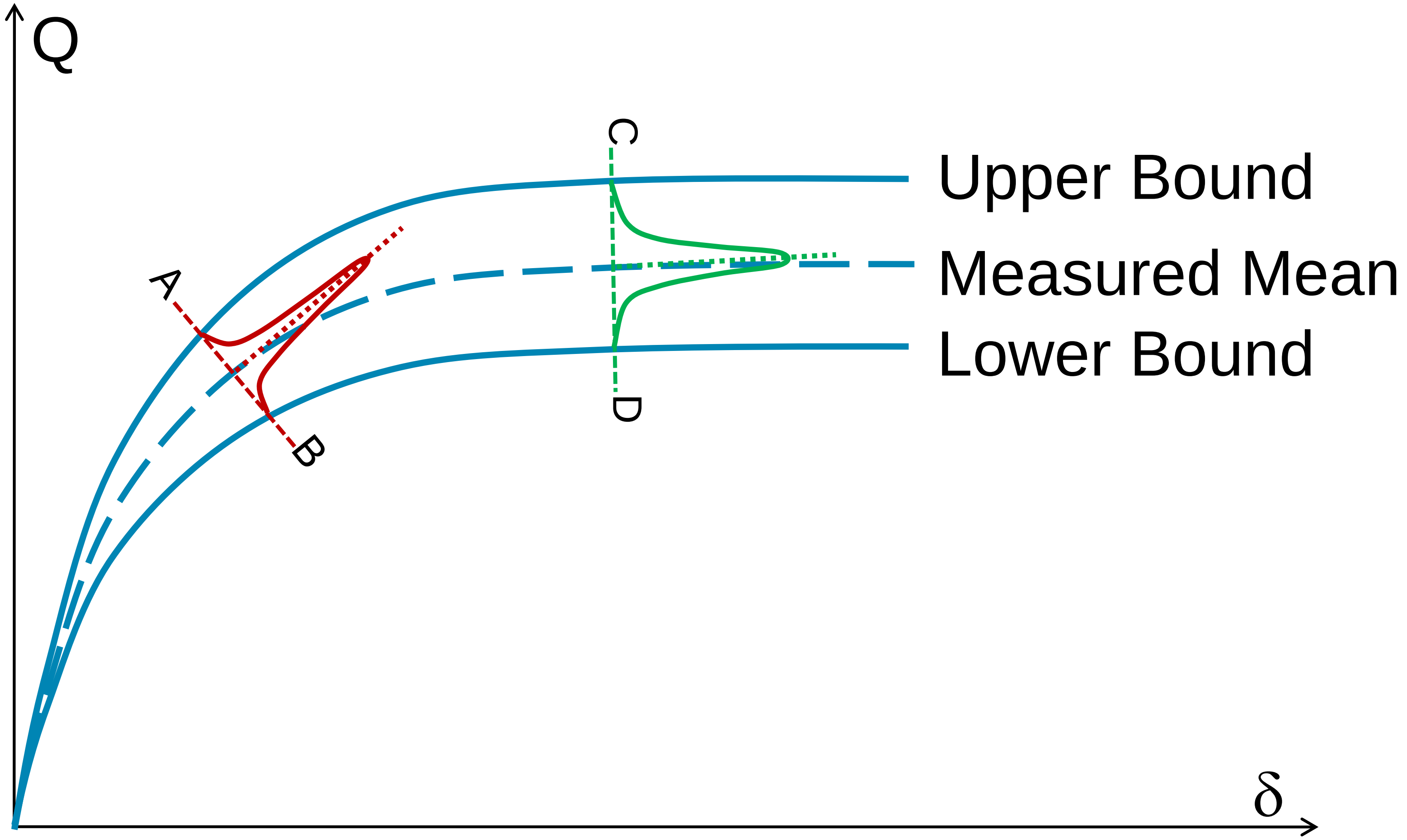
Q-δ Model

- Q is force effect such as applied load, induced stress, moment, shear, etc.
  - Could be expressed as resistance, R
- δ is deformation such as settlement, rotation, strain, curvature, etc.
- Q-δ curves can have many shapes
  - Only 3 shapes are shown in the figure as examples

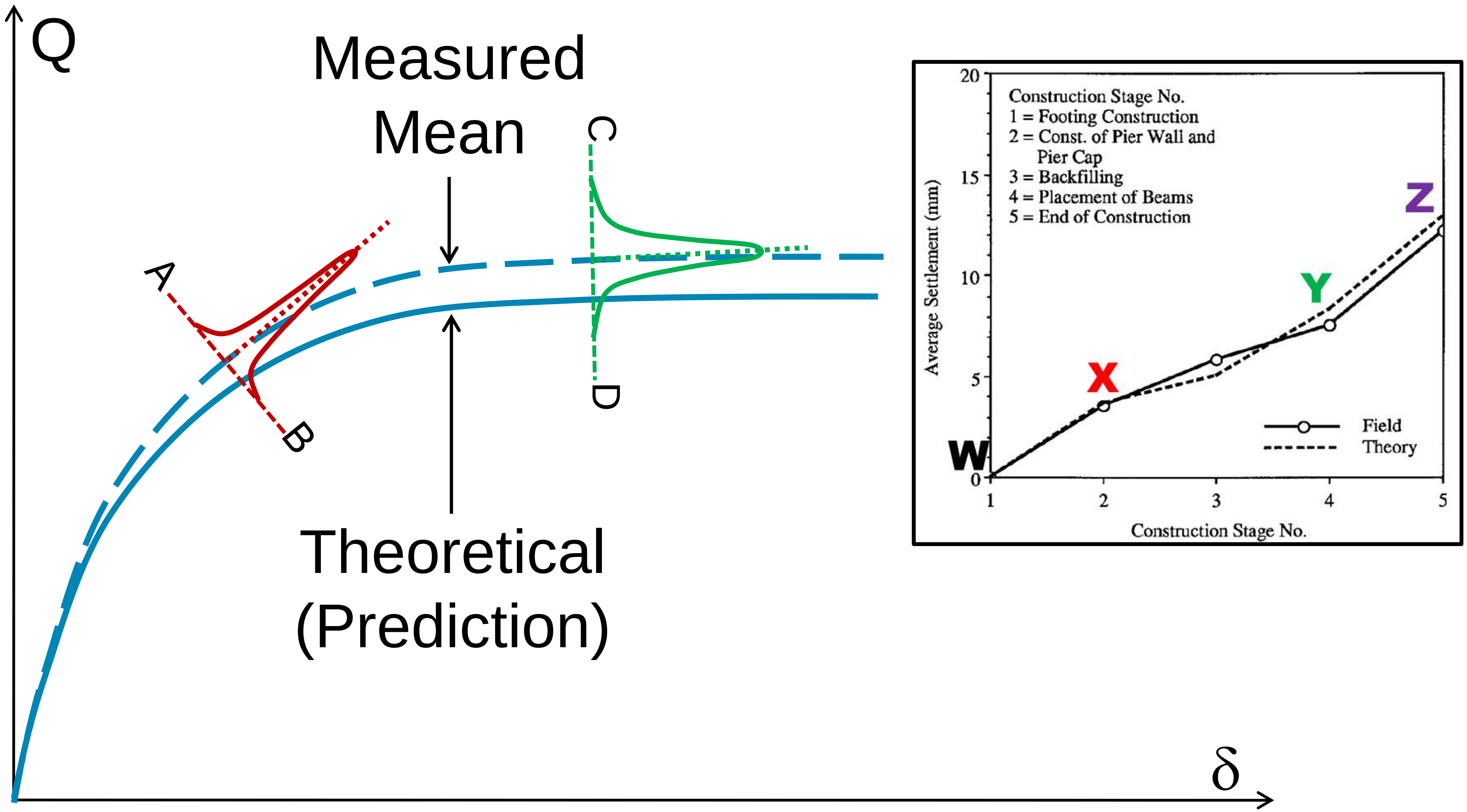


- **Formulation is general and applies to both geotechnical and structural aspects.** Some examples are as follows:
  - Lateral load – lateral displacement (P-y) curves
  - Moment-curvature (M-ϕ) curves
  - Shear force-shear strain curves

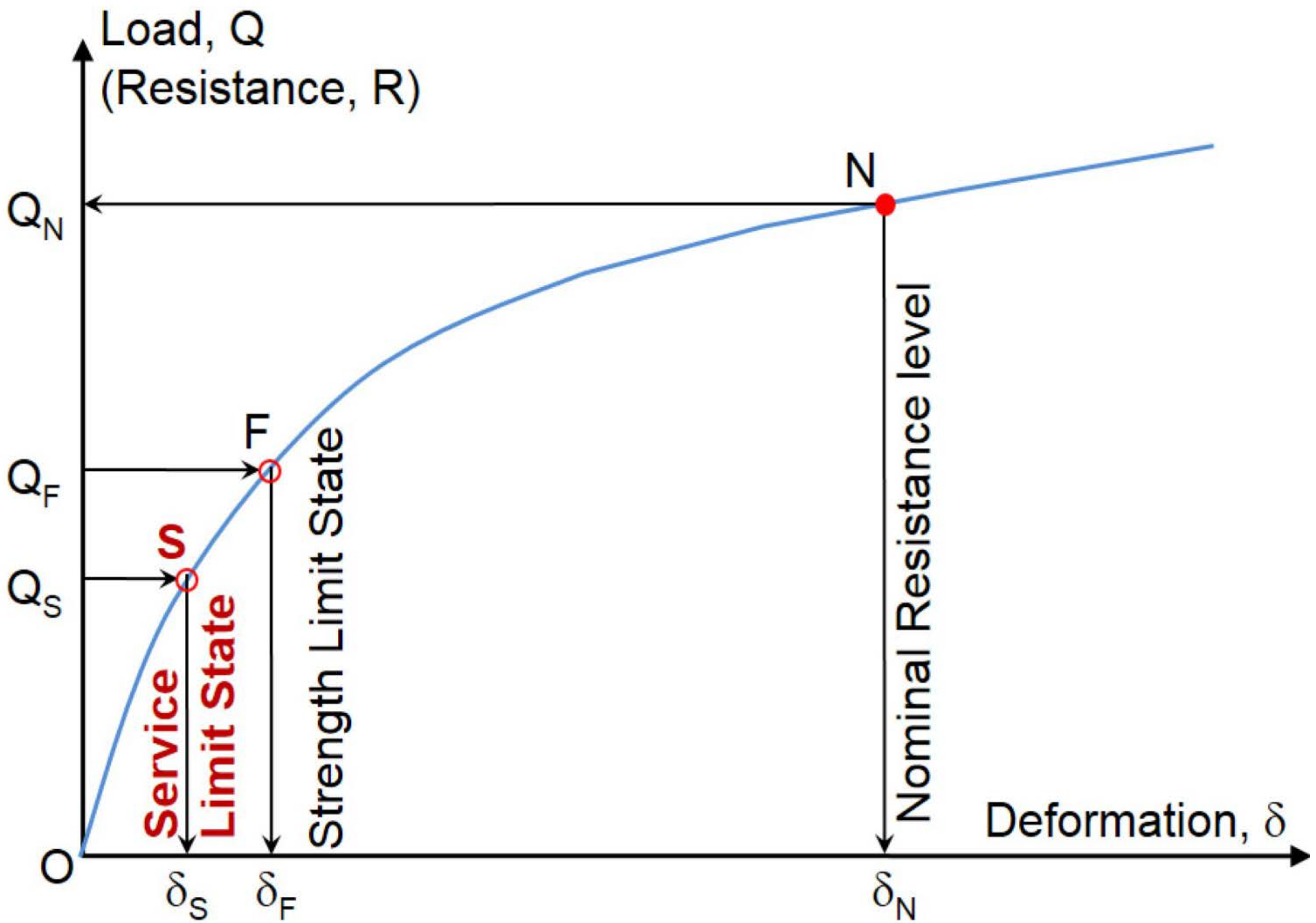
Range and Distribution of Q-δ



Correlation of Measured Mean With Theoretical Prediction



Q-δ Model and Limit States



Serviceability Limit State(s)

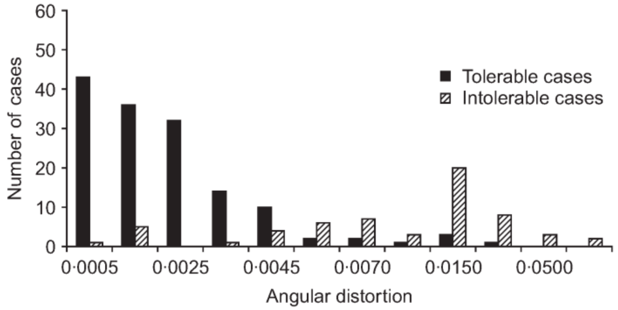
- For strength limit state, common expression is $g = R - Q$
- For service limit state, the expression can be

$$g = \delta_T - \delta_P \quad \begin{cases} \delta_T = \text{target (design or tolerable)} \\ \delta_P = \text{predicted (estimated)} \end{cases}$$

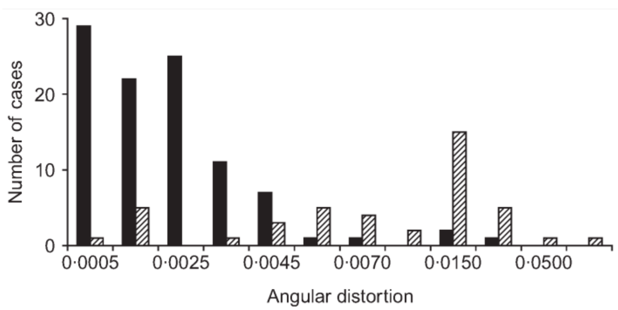
- δ_T is Resistance and δ_P is Load
- Need statistics for δ_T and δ_P

Data from Moulton et al. (1985)

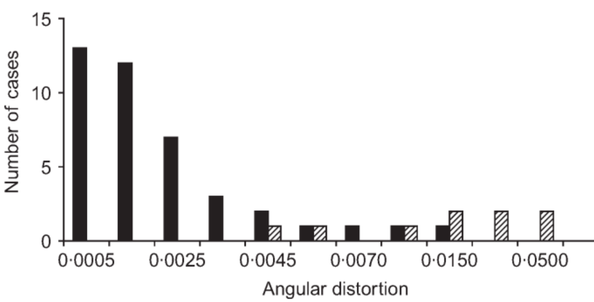
Angular distortion interval	All bridges*		Steel bridges		Concrete bridges	
	Tolerable cases	Intolerable cases	Tolerable cases	Intolerable cases	Tolerable cases	Intolerable cases
0–0·001	43	1	29	1	13	0
0·0011–0·002	36	5	22	5	12	0
0·0021–0·003	32	0	25	0	7	0
0·0031–0·004	14	1	11	1	3	0
0·0041–0·005	10	4	7	3	2	1
0·0051–0·006	2	6	1	5	1	1
0·0061–0·008	2	7	1	4	1	0
0·0081–0·010	1	3	0	2	1	1
0·011–0·020	3	20	2	15	1	2
0·021–0·040	1	8	1	5	0	2
0·041–0·060	0	3	0	1	0	2
0·061–0·080	0	2	0	1	0	0
	144	60	99	43	41	9



All Bridges



Steel Bridges



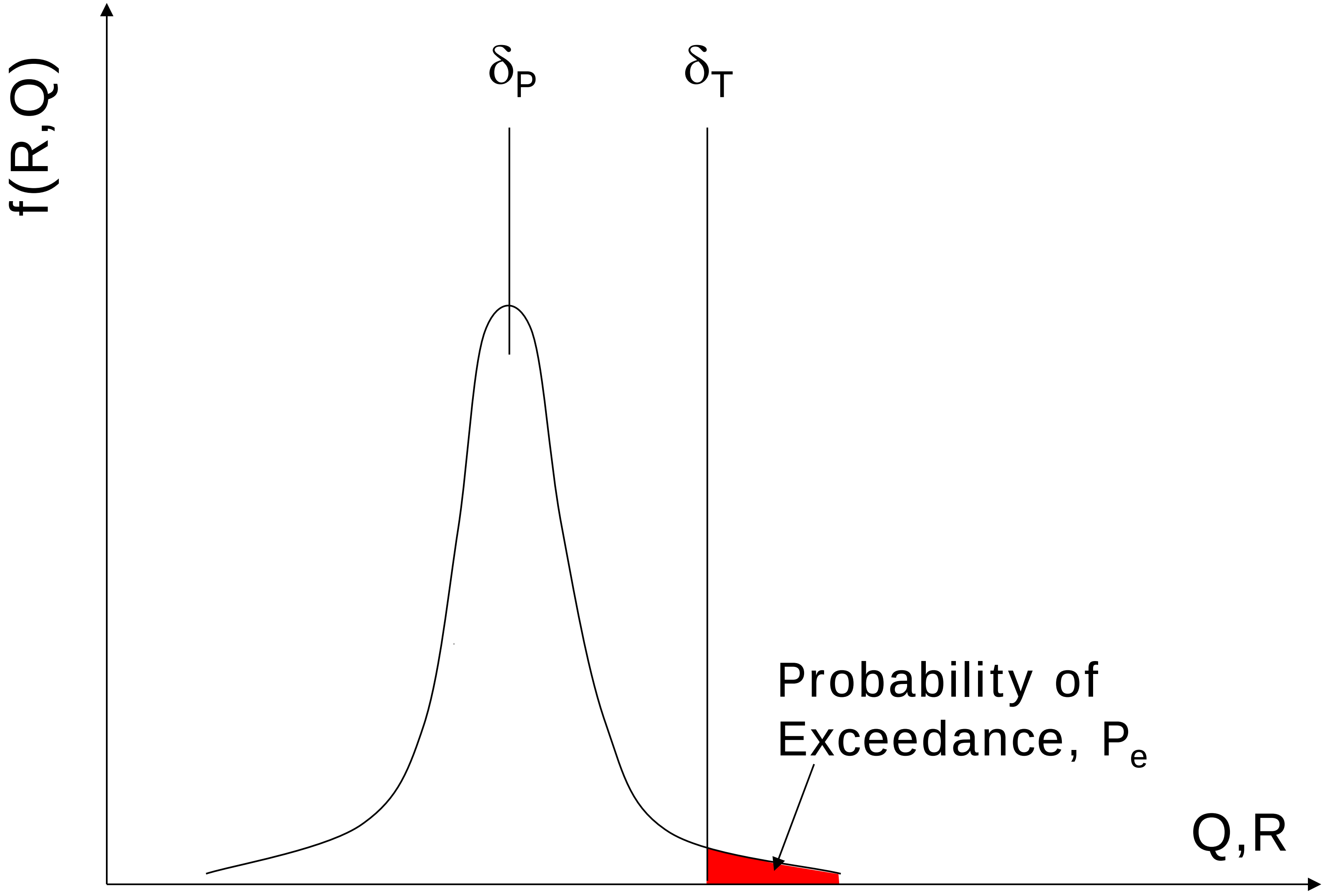
Concrete Bridges

Reference: Zhang and Ng (2005)

Statistics for δ_T (Resistance)

- No consensus on δ_T
- No standard deviation (σ), Bias (or Accuracy) data available at this time using LRFD specifications
  - Long Term Bridge Performance Program (LTBPP) may offer future data
- Use of deterministic value of δ_T by bridge designer
  - Varies based on type of bridge structure, joints, design of specific component, ride quality, deck drainage, aesthetics, public perception, etc.

Adaptations



Statistics for δ_P (Load)

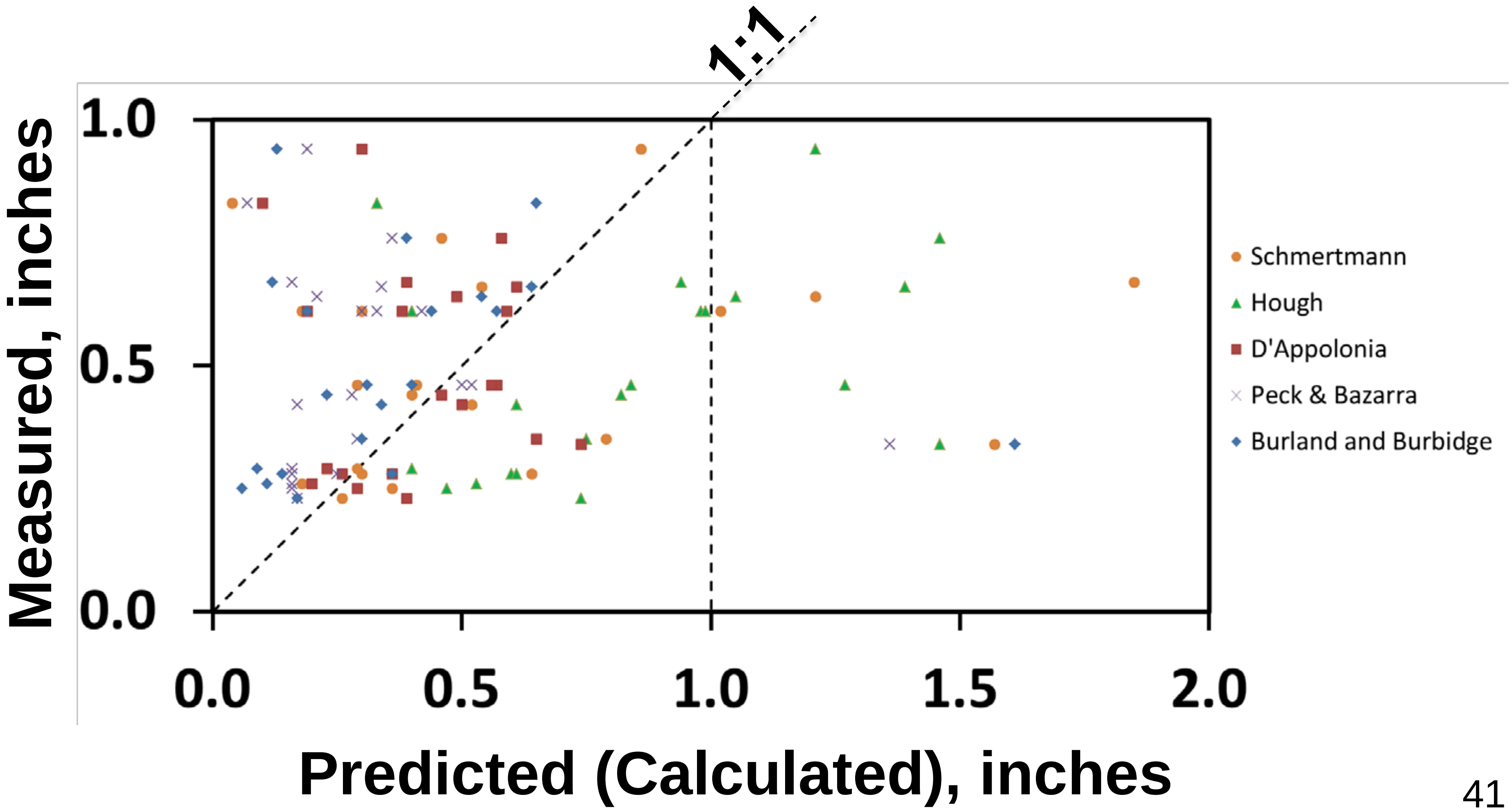
- Can be developed based on deformation data from monitoring of ***bridge*** construction and/or load tests of ***bridge*** foundations

- Example: Immediate Settlement of Spread Footings

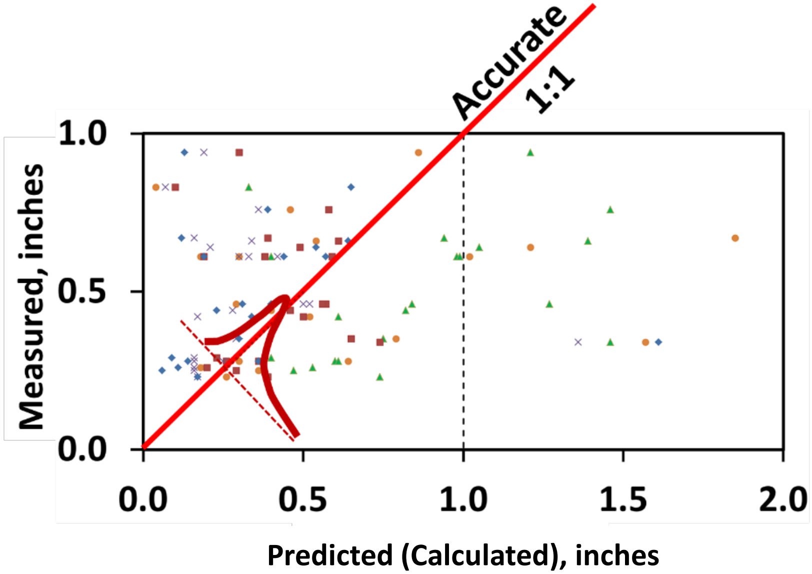
Immediate settlement of spread footings is used to explain concepts. All discussions apply to other foundation/wall types and deformations, e.g., lateral movements, MSE wall deformations, etc.

Data for Immediate Settlement of Spread Footings

Data from FHWA (1987)



Concept of Accuracy and Bias



- Accurate method: $\delta_P = \delta_M \rightarrow \delta_P / \delta_M = 1.0$
- Accuracy, $X = \delta_P / \delta_M$ Bias, $\lambda = 1/X = \delta_M / \delta_P$
- Concept of Accuracy is used herein
- Accuracy, X, is a random variable

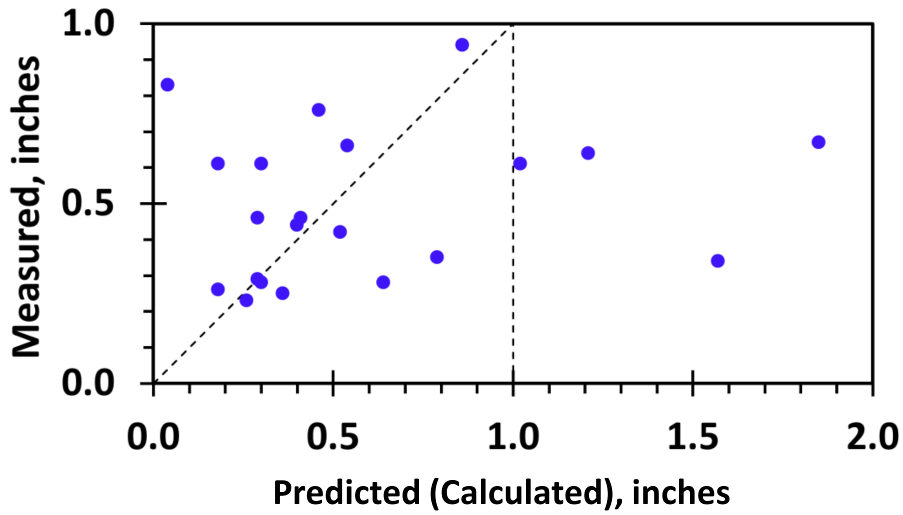
Statistics of Accuracy, X (= δ_P/δ_M)

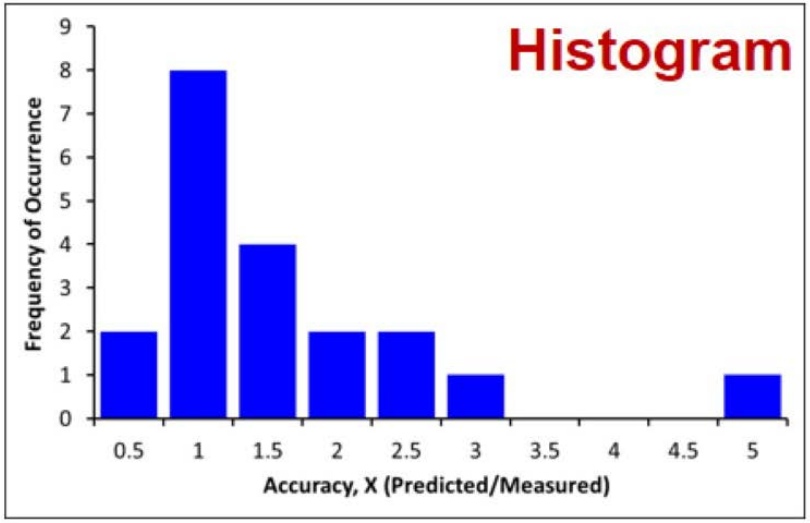
Statistic	Schmertmann	Hough	D'Appolonia	Peck & Bazzara	Burland & Burbridge
Count	20	20	20	20	20
Min	0.295	0.656	0.311	0.202	0.138
Max	4.618	4.294	2.176	4.000	4.735
μ	1.381	1.971	1.031	0.779	0.829
σ	1.006	0.769	0.476	0.796	0.968
CV	0.729	0.390	0.462	1.022	1.168

Legend:
μ = Mean
σ = Standard Deviation
CV = Coefficient of Variation (= σ/μ)

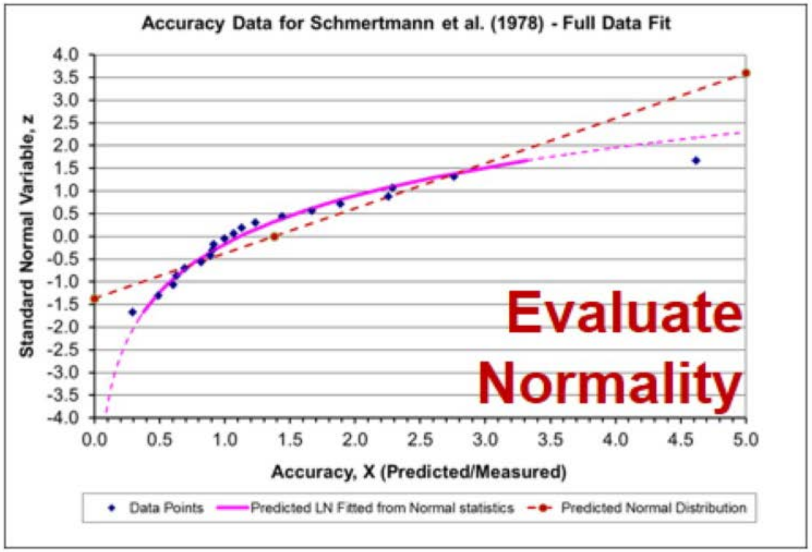
Statistics based on data in FHWA (1987)

Schmertmann Data

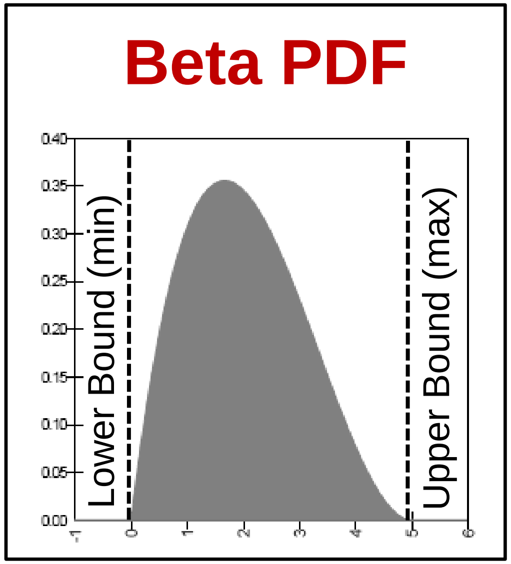


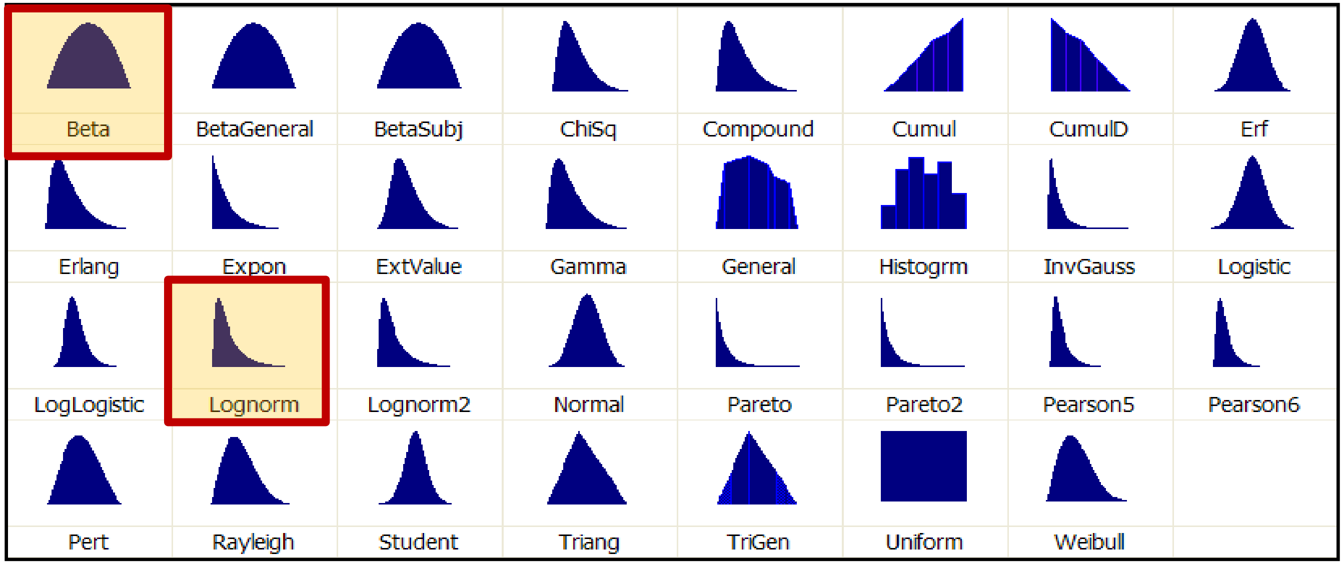


- Data are non-normal
- Which **Probability Distribution Function** (PDF) is the best to represent non-normal data?



Probability Distribution Functions (PDFs)





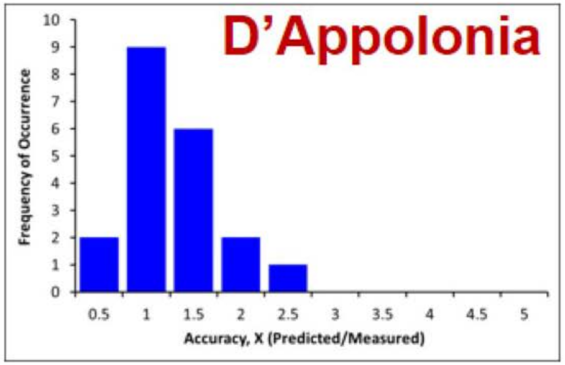
Reference for PDF Schematics: @Risk by Palisade Corporation

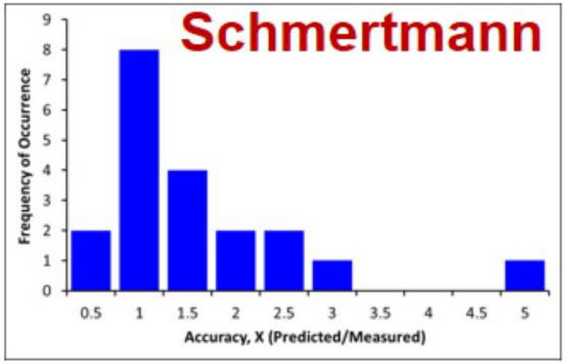
Calibration concept applies regardless of PDF chosen

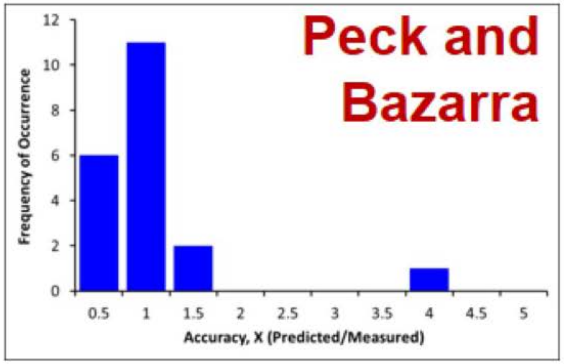
Non-Normal Data

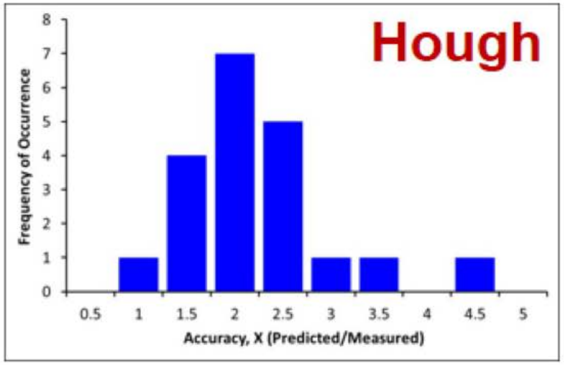
Histograms for
Various Methods

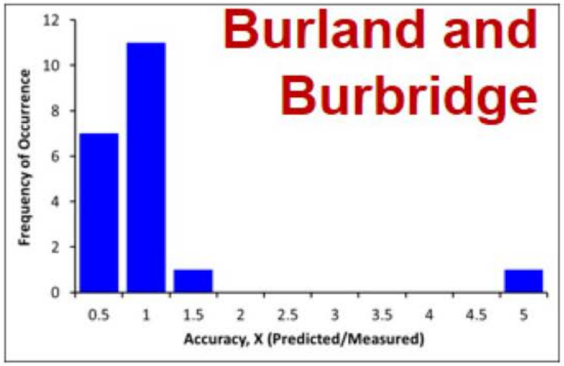
Skewed to the right







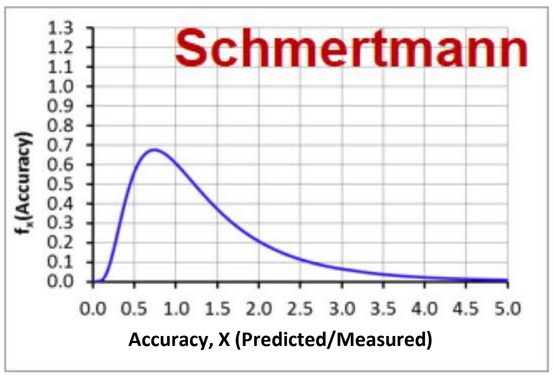


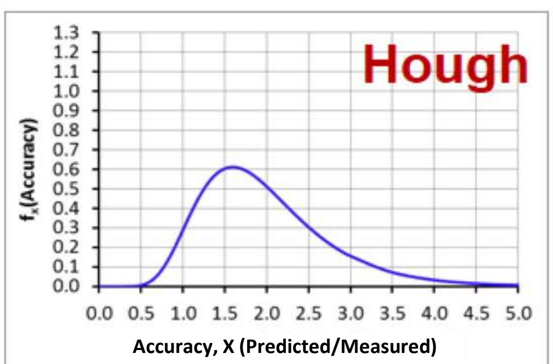


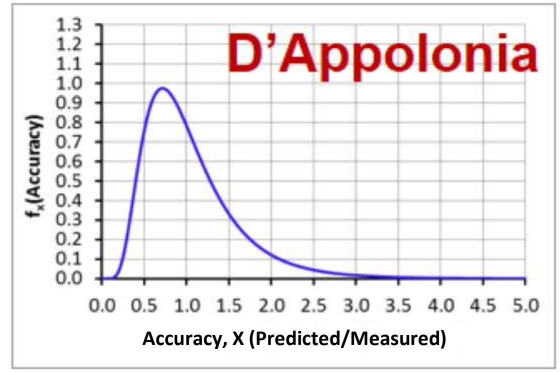
Non-Normal Data

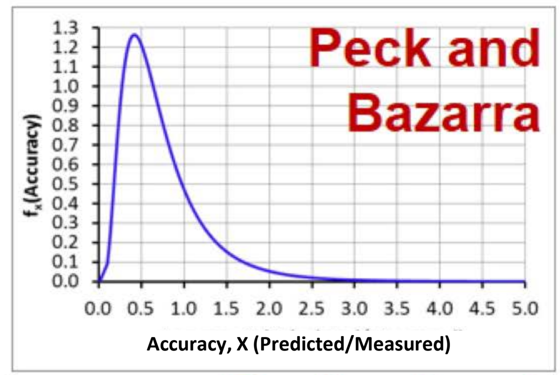
PDF's skewed to the right (reverse-J)

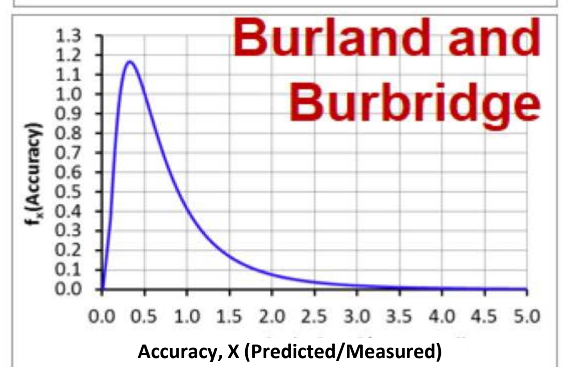
Use Lognormal PDF to be consistent with LRFD practice thus far





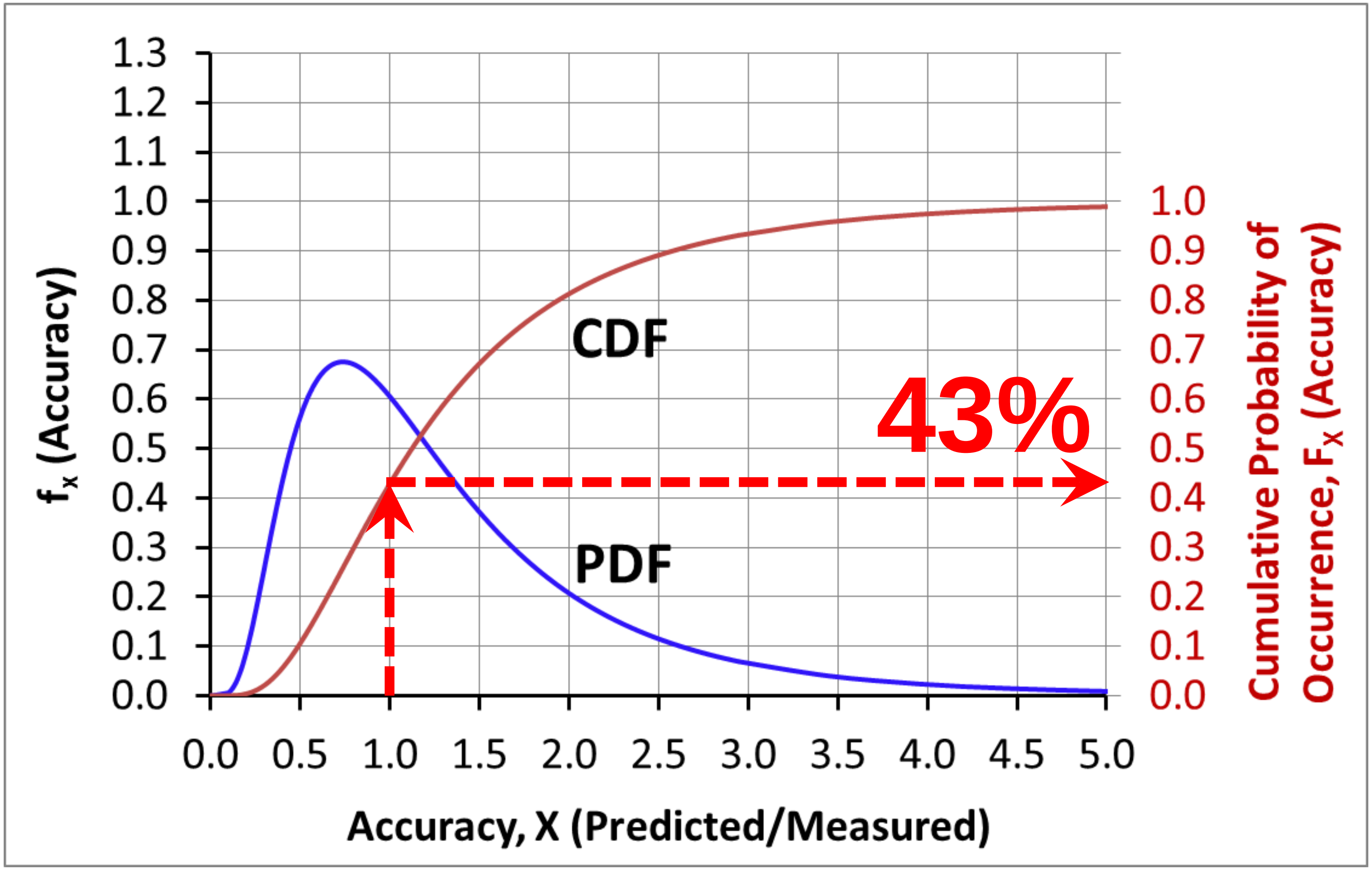






Convert PDF to CDF

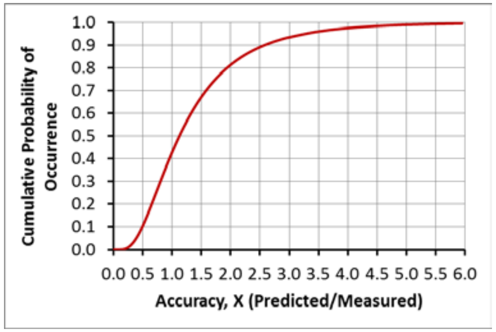
Example: Schmertmann

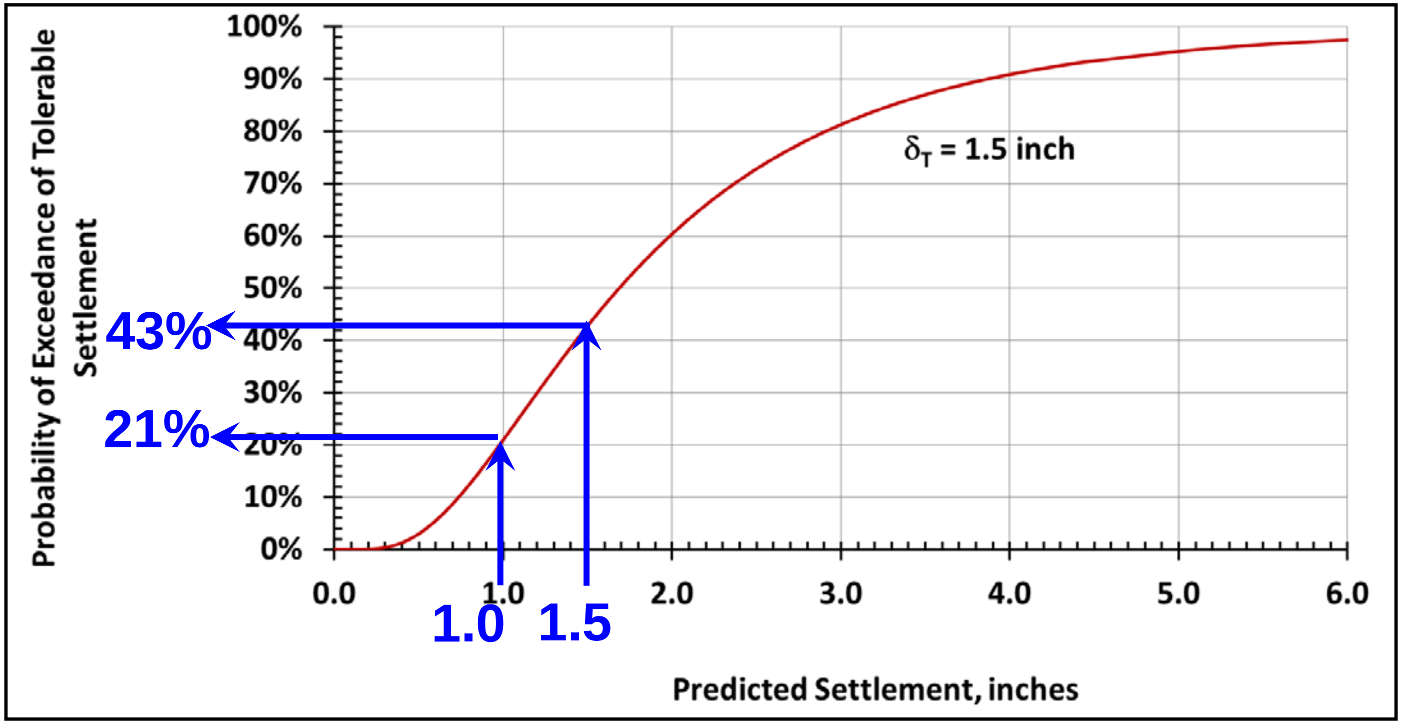


PDF: Probability Distribution Function; CDF: Cumulative Distribution Function

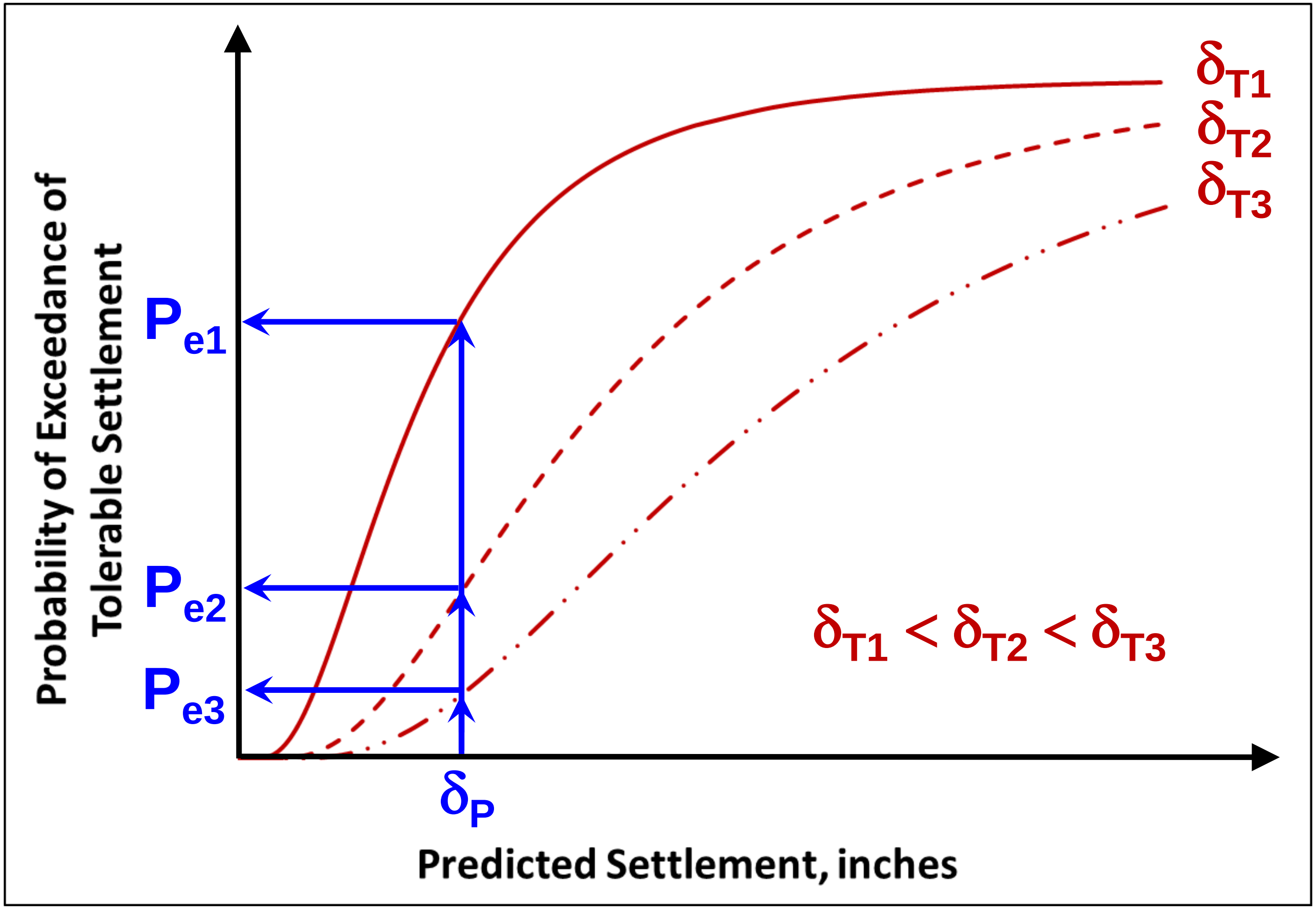
Generate Probability Exceedance Chart (PEC) from CDF

Example: Schmertmann





PEC with Family of Curves



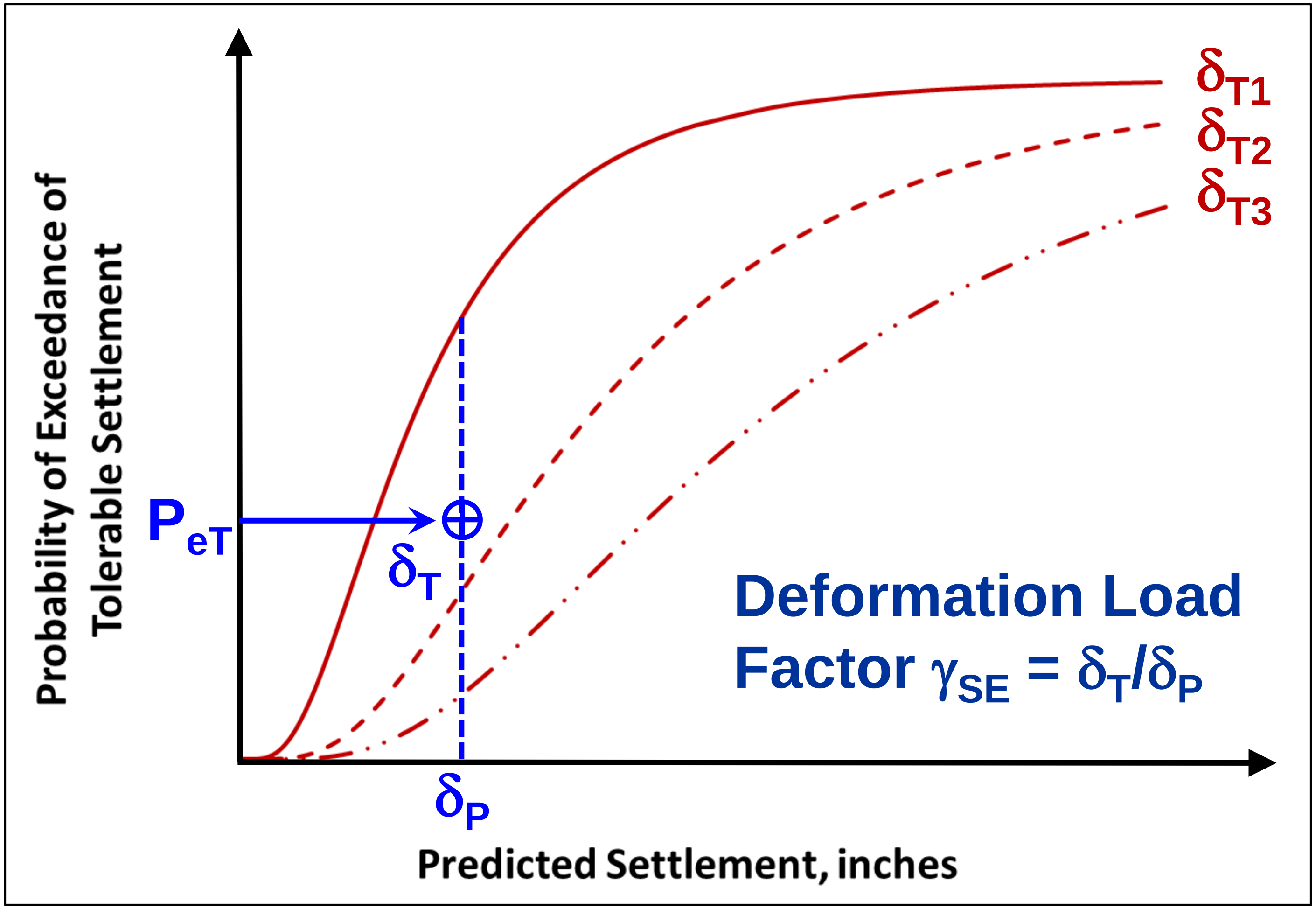
Probability of Exceedance, P_e, For Structural Limit States

Limit State	**Target Reliability Index, β_T**	**Approx P_e (Note 1)**
Fatigue I and Fatigue II limit states for steel components	1.0	16%
Fatigue I for compression in concrete and tension in reinforcement	0.9 (Compression) 1.1 (Tension)	18% 14%
Tension in prestressed concrete components	1.0 (Normal environment) 1.2 (Severe environment)	16% 11%
Crack control in decks*	1.6 (Class 1) 1.0 (Class 2)	5% 16%
Service II limit state for yielding of steel and for bolt slip*	1.8	4%

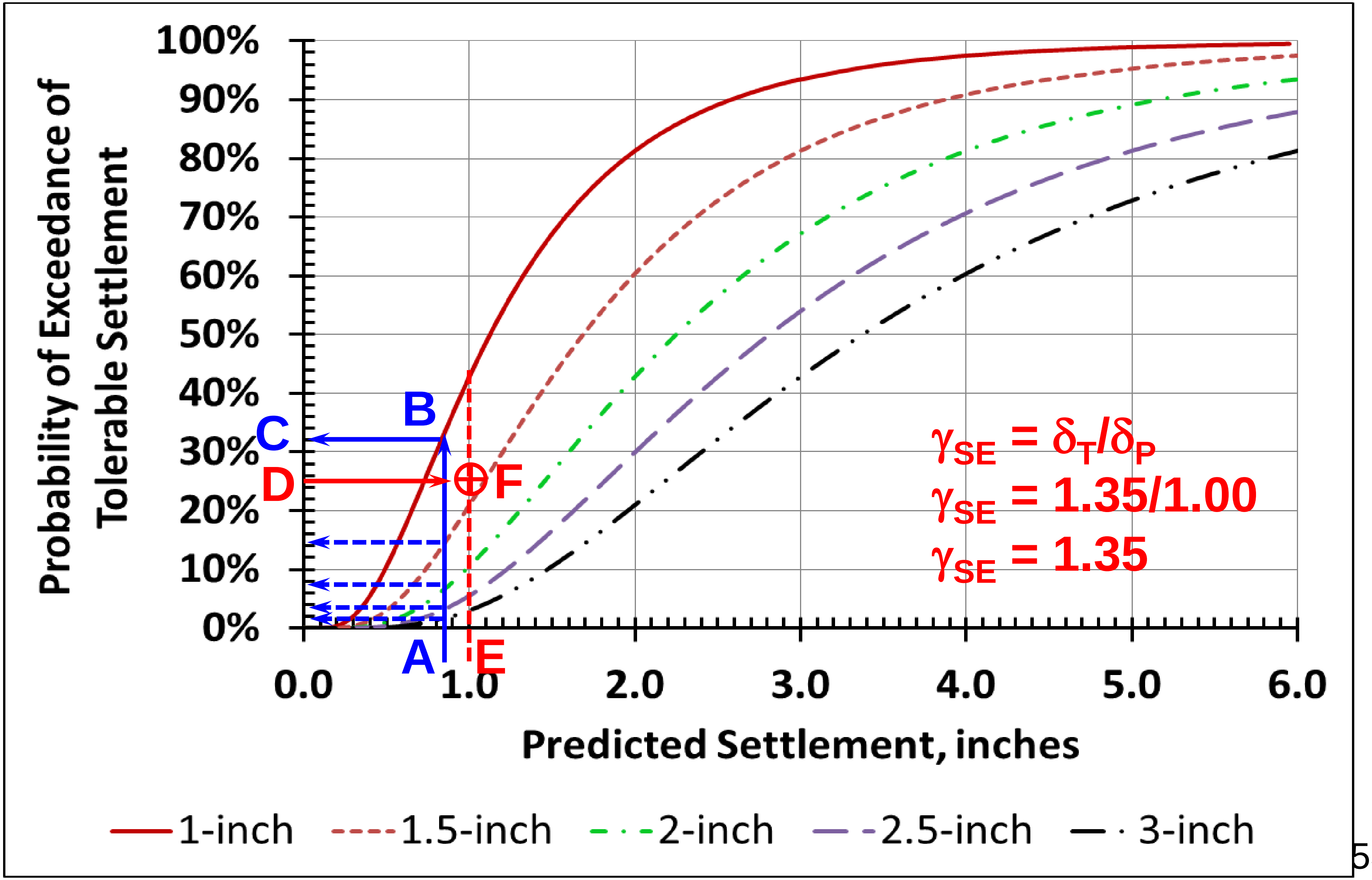
Note 1: P_e is based on “Normal” Distribution

* No desire to change

Load Factor γ_{SE}



For Schmertmann Method



Express β in Terms of P_e

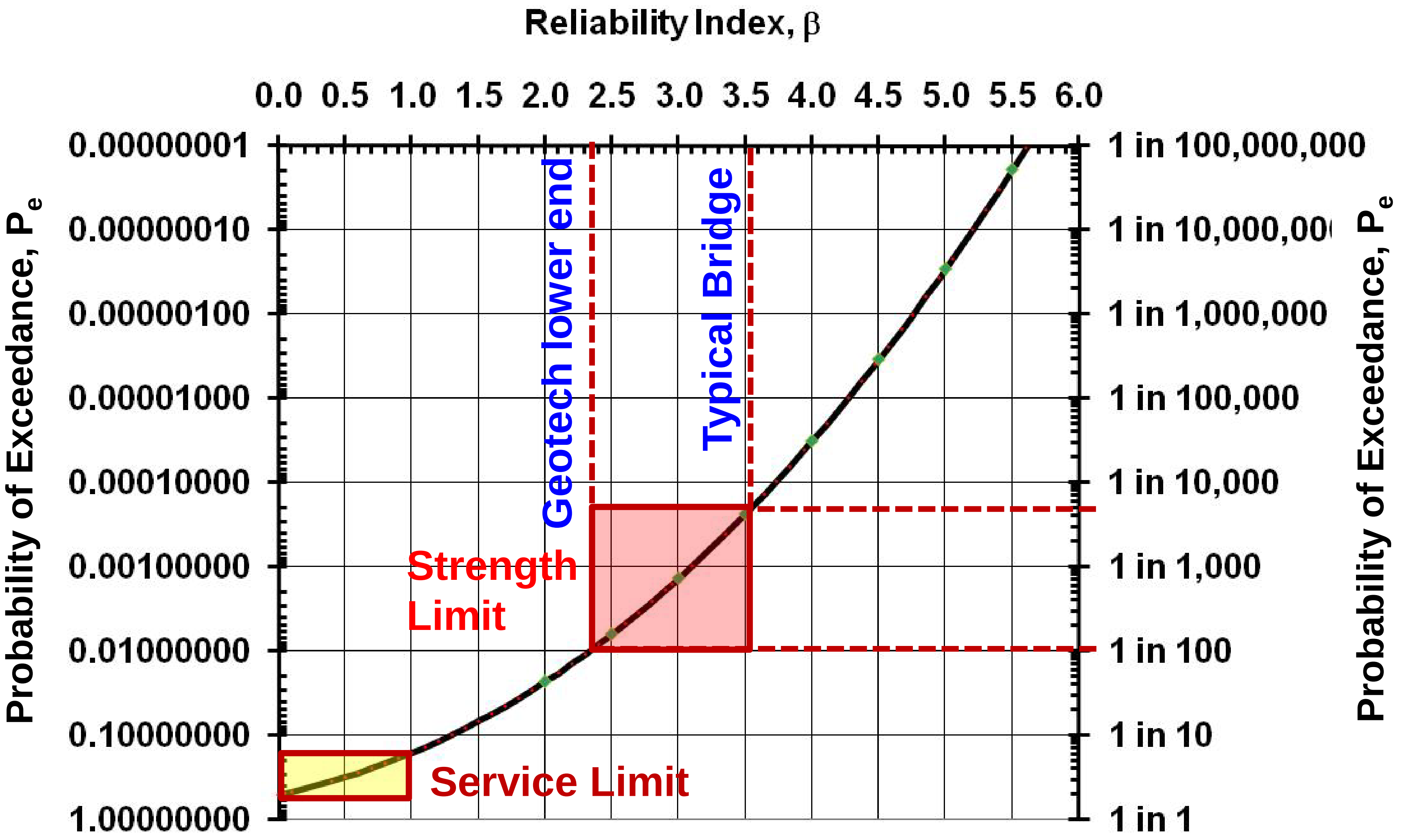
- Conventional definition of β

$$\beta = \frac{R_{mean} - Q_{mean}}{\sqrt{\sigma_R^2 + \sigma_Q^2}}$$

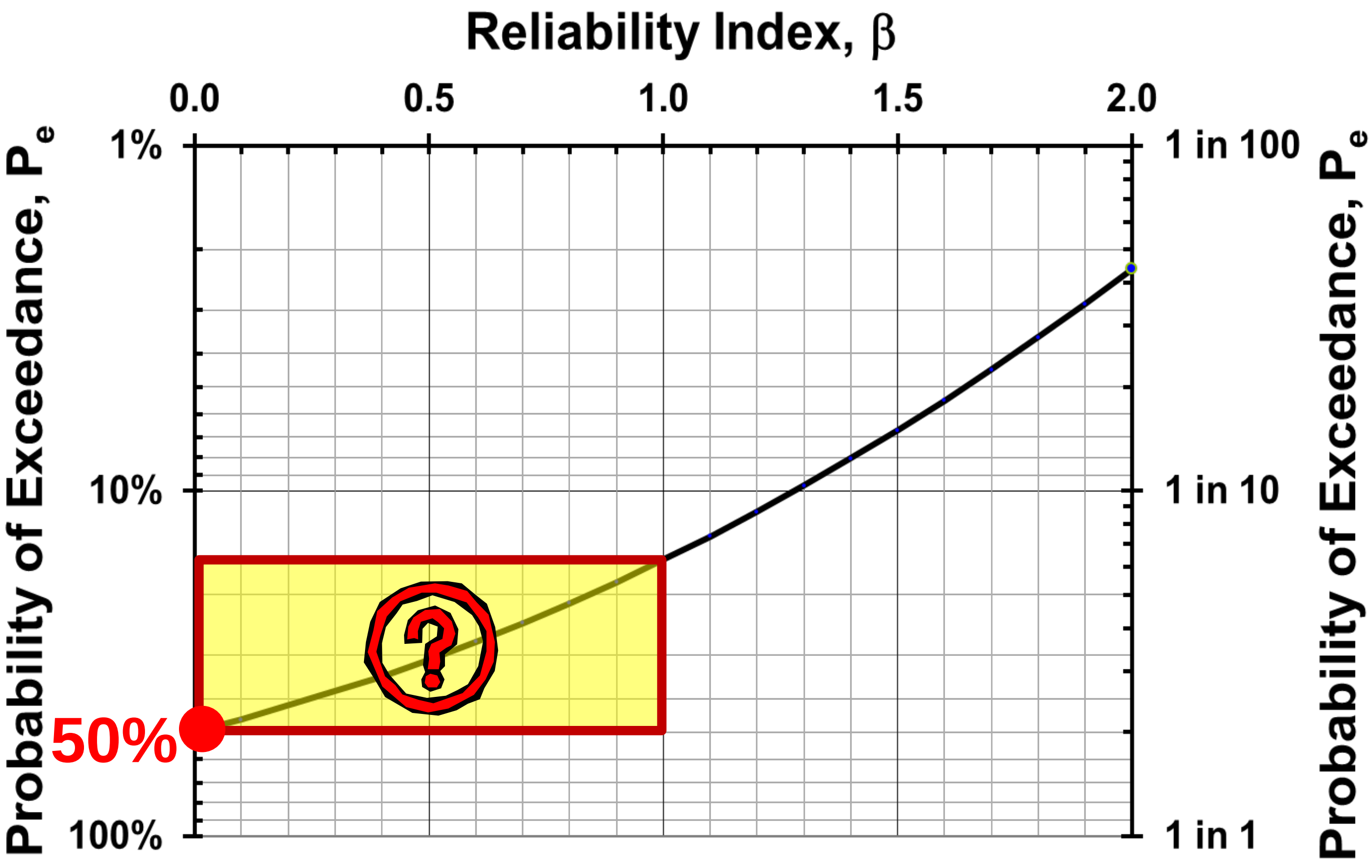
- Using Microsoft Excel, the relationship can be expressed as follows:

$$\beta = \text{NORMSINV}(1-P_e)$$

Reliability Index β vs P_e for "Normal" Distribution



What Value of β to Use?



What about consequences?

What Value of β to Use?

P_e, %	β	P_e, %	β	P_e, %	β	P_e, %	β
0.01	3.719	11	1.227	25	0.674	39	0.279
0.02	3.540	12	1.175	26	0.643	40	0.253
0.05	3.291	13	1.126	27	0.613	41	0.228
0.1	3.090	14	1.080	28	0.583	42	0.202
1	2.326	15	1.036	29	0.553	43	0.176
2	2.050	16	0.994	30	0.524	44	0.151
3	1.875	17	0.954	31	0.496	45	0.126
4	1.750	18	[illegible]	32	0.468	46	0.100
5	1.645	[illegible]	[illegible]	33	0.440	47	0.075
6	1.555	20	0.842	[illegible]	[illegible]	48	0.050
7	1.476	21	0.806	[illegible]	[illegible]	49	0.025
8	1.405	22	0.772	36	0.358	50	0.000
9	1.341	23	0.739	37	0.332		
10	1.282	24	0.706	38	0.305		

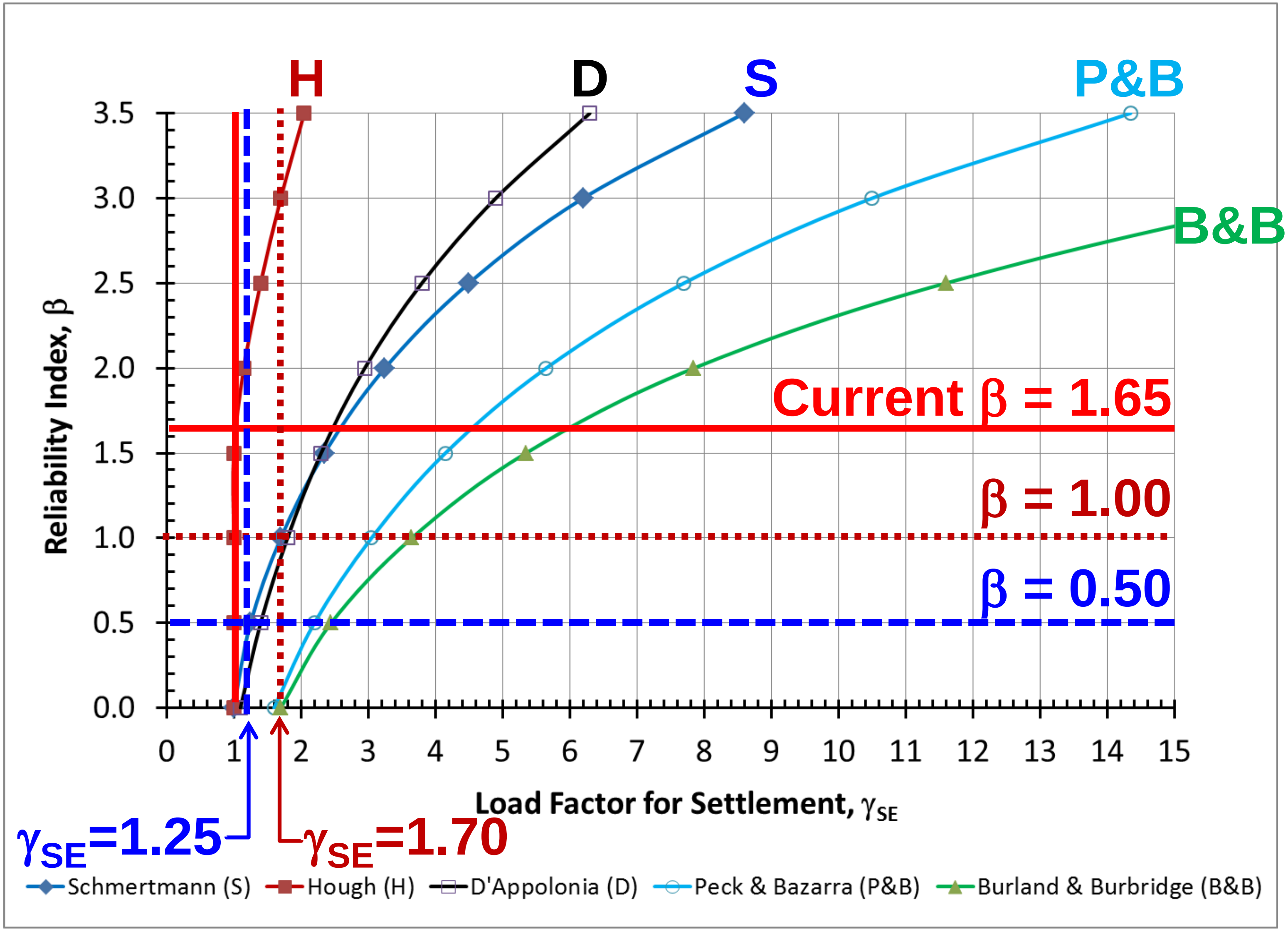
B

G

Irreversible

Reversible
Irreversible

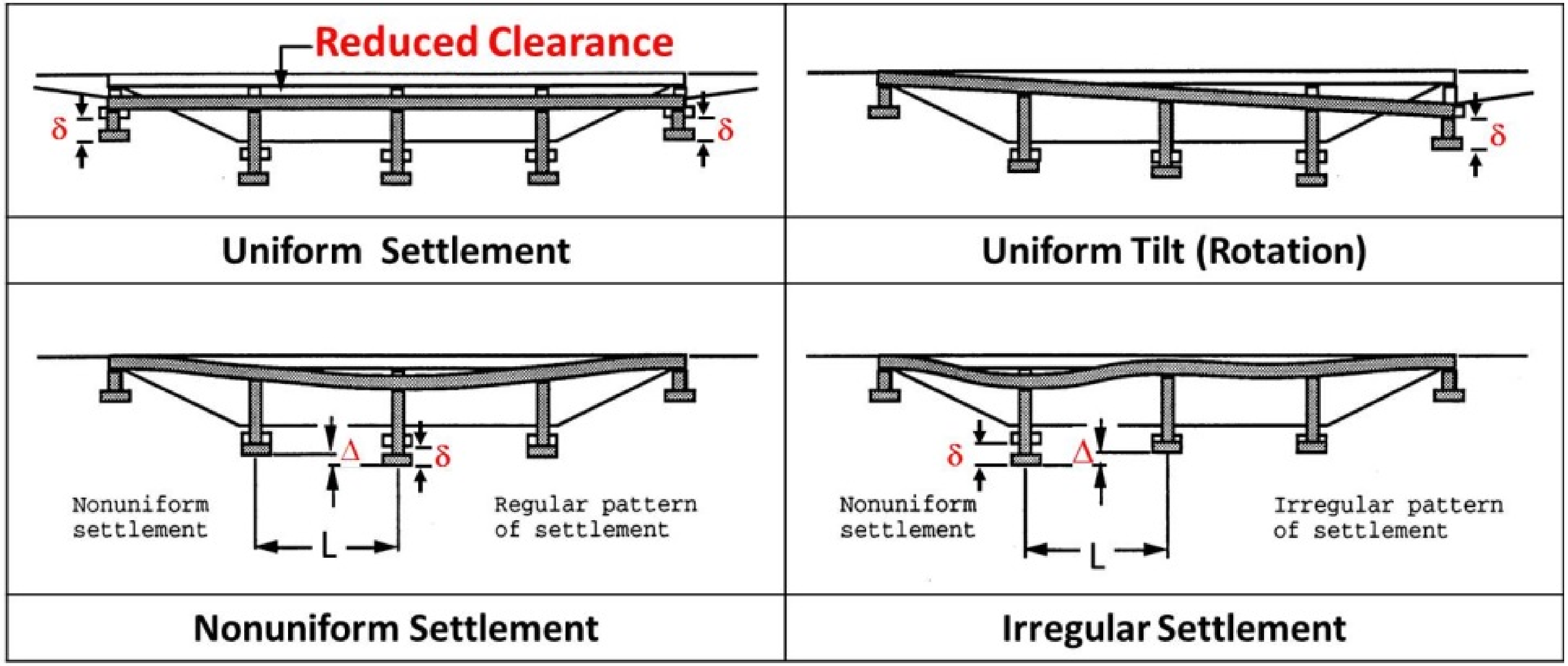
Selection of γ_{SE} Based on β Value



β Versus γ_{SE} for Various Methods

β	γ_{SE}				
	S	H	D	P&B	B&B
0.00	1.00	1.00	1.10	1.60	1.70
0.50	1.25	1.00	1.40	2.20	2.45
1.00	1.70	1.00	1.80	3.05	3.65
1.50	2.35	1.00	2.30	4.15	5.35
2.00	3.25	1.15	2.95	5.65	7.85
2.50	4.50	1.40	3.80	7.70	11.60
3.00	6.20	1.70	4.90	10.50	17.05
3.50	8.60	2.05	6.30	14.35	25.10

Meaning and Use of γ_{SE}



- Bridge deck (superstructure) implications
  - Force effect = *f* (EI/L, Δ/L)
- Implications for facilities at abutments (e.g., joints, approach slabs, utilities, etc.), roadway grade, and vertical clearance

Steps to Apply γ_{SE} in Design Process

1. Calculate δ at each substructure/foundation location using Service I load combination.

2. Select γ_{SE} based on the specific method used for calculation of δ at each substructure/foundation location

3. Compute factored deformation, δ_f, at each substructure/foundation location. $\delta_f = \gamma_{SE} (\delta)$

5. Use δ -0 and construction point concept as applicable to determine factored angular distortion, A_{df}, within each span, L. All viable deformed shapes should be evaluated.

6. Are δ_f and A_{df} acceptable?

7. Continue bridge analysis by incorporating the induced force effects due to factored deformation, δ_f.

Induced Force Effects Due to γ_{SE}

- Deformations generate additional force effects (moments)
  - Load factor of SE is similar to PS, CR, SH, TU, and TG
- The value of γ_{SE} must not be taken literally
  - $\gamma_{SE} = 1.25$ does not mean that the total force effects will increase by 25%
  - γ_{SE} is only one component in a load combination
- The additional moments due to effect of deformations are very dependent on the stiffness of the bridge (EI/L) as well as the angular distortion (Δ/L)

Results of Limited Parametric Study

- Several 2- and 3-span steel and pre-stressed concrete continuous bridges from NCHRP Project 12-78.
  - Considered full angular distortion (Moulton's criteria)
- Finding: An increase in factored Strength I moments on the order of as little as 10% for the more flexible units to more than double the moment from only factored dead and live load moments for the stiffer units.
  - Finding is based on elastic analysis and without consideration of creep, which could significantly reduce the moments, especially for relatively stiff concrete bridges.
  - Additional examples will be developed.

Effect of Foundation Deformations On Superstructures

- For all bridges, stiffness should be appropriate to considered limit state.
- The effect of continuity with the substructure should be considered.
- Consider all viable deformation shapes.
- For concrete bridges, the determination of the stiffness of the bridge components should consider the effect of cracking, creep, and other inelastic responses.

Proposed Modifications To AASHTO

- Article 10.5.2 – “Service Limit States”

- Article 10.5.2 is cross-referenced in articles for various foundations types such as spread footings, driven piles, drilled shafts, micropiles, retaining walls, joints, etc.

- Making change in Article 10.5.2 will permeate through all the relevant sections of AASHTO.

Section 3, Table 3.4.1-3

Bridge Component	PS	CR, SH
Superstructures—Segmental Concrete Substructures supporting Segmental Superstructures (see 3.12.4, 3.12.5)	1.0	See γ_P for DC, Table 3.4.1-2
Concrete Superstructures—Non-Segmental	1.0	1.0
Substructures supporting Non-Segmental Superstructures • using I_g • using $I_{effective}$	 0.5 1.0	 0.5 1.0
Steel Substructures	1.0	1.0

- Include the γ_{SE} in above table or develop a similar table

Section 3, New Table 3.4.1-4 for γ_{SE}

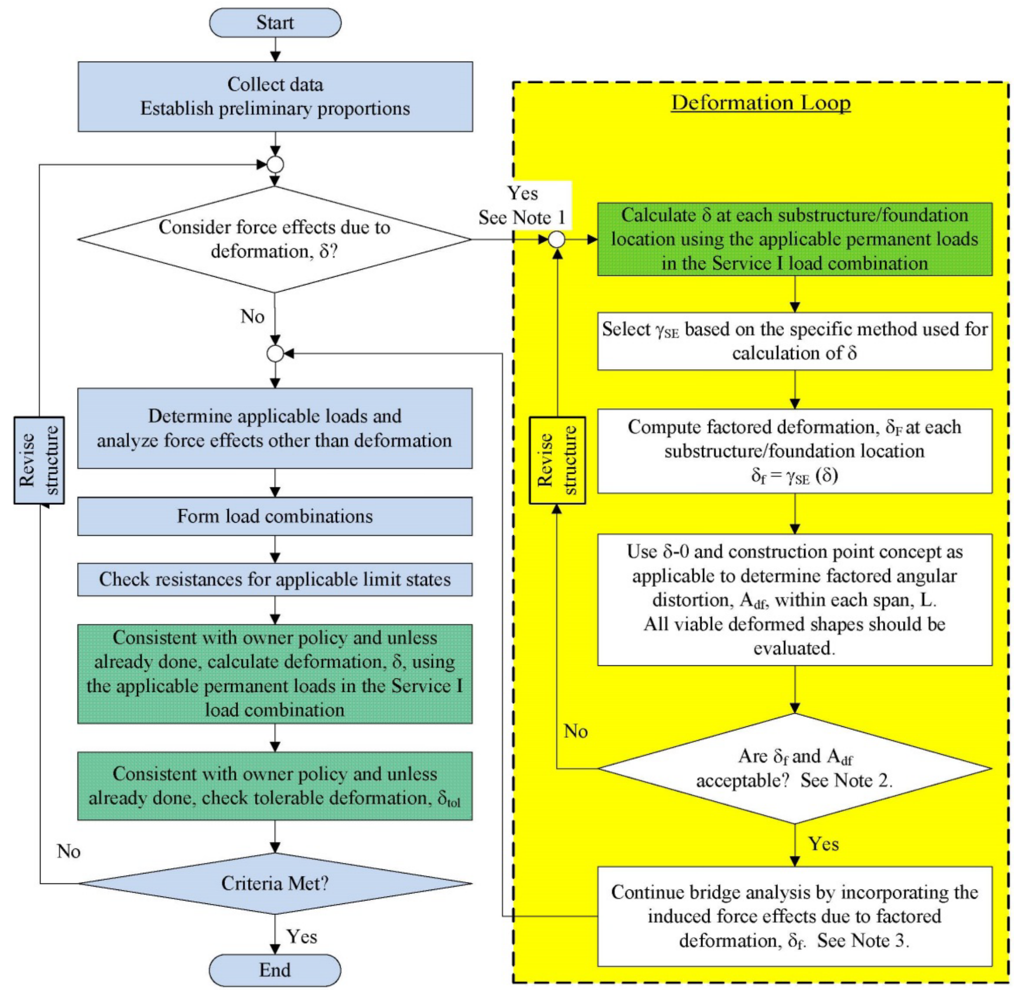
Deformation	SE (Note 1)
Immediate Settlement • Hough method • Schmertmann method • Local method	 1.00/1.00 1.25/1.70 *
Consolidation settlement	1.00/1.00
Lateral deformation • P-y or SWM soil-structure interaction method • Local method	 1.25/1.70 *
Note 1: Smaller value used when deformation is easily reversible. Larger value used when structures are difficult to either modify or adjust to re-establish roadway grade. *To be determined by the Owner based on local geologic conditions and calibration using a target reliability index of 0.50 and 1.00 for Service I limit state.	

For Consideration by T-5/T-15

- Modification to Sections 3 and 10 to implement recommendations ready for:
  - Deformation Load factors, γ_{SE}
  - δ – 0 concept with construction point and estimation of ***relevant*** deformation values
  - Schmertmann method
  - Commentaries
  - Updated references

Implementation Tools

- Several examples
- White paper
- Flow Chart
- Proposed LRFD specification revisions and commentaries
- SHRP2 Round 7 Implementation Assistance Program (IAP)

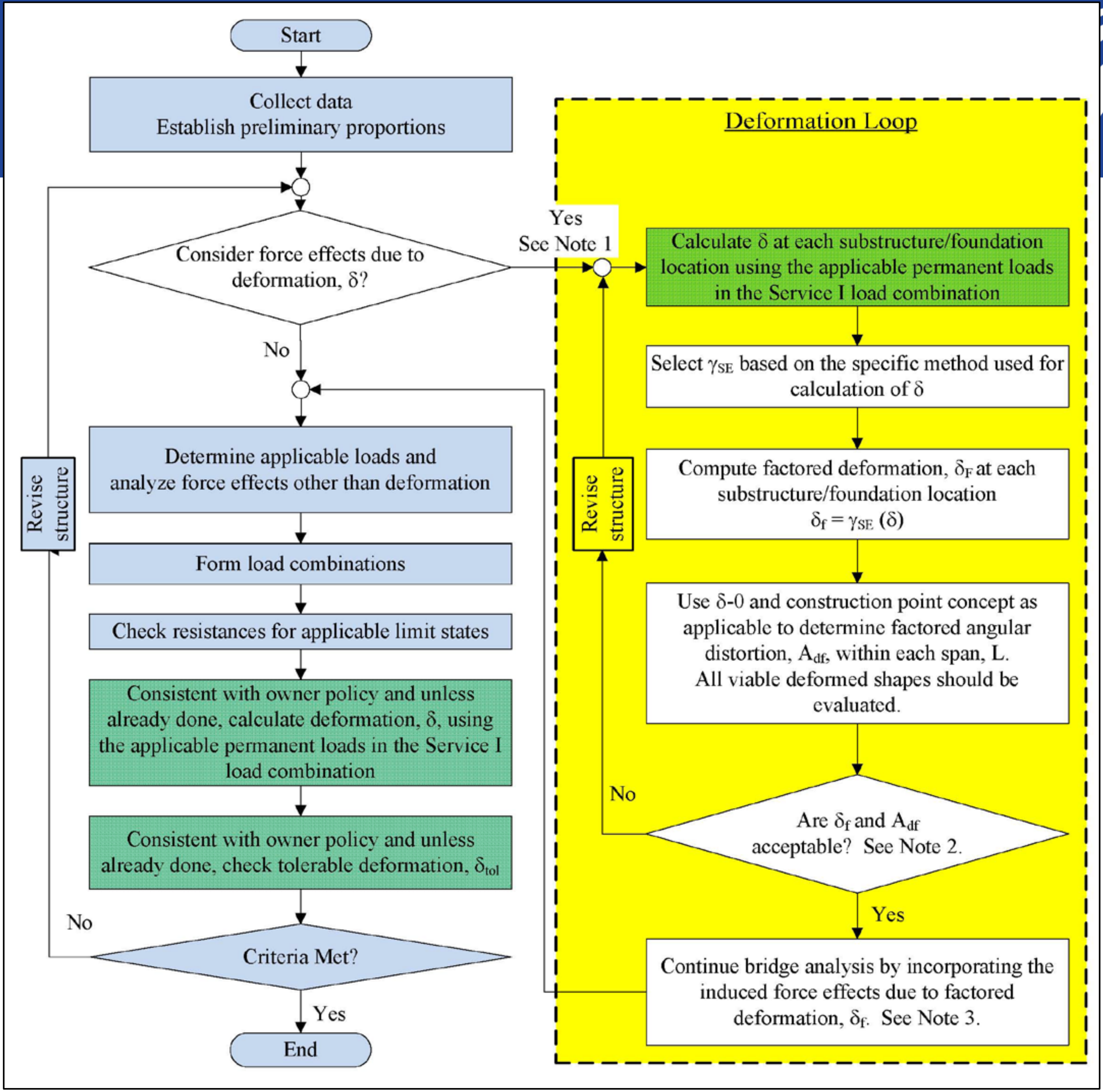


Note 1: It may be efficient to run some early design iterations without including this loop until the proportions of the bridge are well developed, and then include this loop to consider the force effects from differential deformations.

Note 2: Compare A_{df} to permissible angular distortion criteria and δ_f to permissible values at abutment interfaces and within spans in terms of vertical clearance under bridge. Guidance in Article 10.5.2 may be used to establish permissible values. Owner may establish other permissible values.

Note 3: Note that the γ_{SE} is used to factor the deformations as shown in this flow chart. γ_{SE} also appears in Table 3.4.1-1 (Load Combinations and Load Factors). This does not imply a second application of γ_{SE} in the load combinations but rather it is an acknowledgement that the deformations have already been factored. Use of the factored deformations in a structural analysis program ensures that the output is factored value.

Flow Chart



Start
Collect data
Establish preliminary proportions
Consider force effects due to deformation, δ?
Yes
See Note 1
No
Determine applicable loads and analyze force effects other than deformation
Form load combinations
Check resistances for applicable limit states
Consistent with owner policy and unless already done, calculate deformation, δ, using the applicable permanent loads in the Service I load combination
Consistent with owner policy and unless already done, check tolerable deformation, δ_{tol}
Criteria Met?
No
Yes
End
Revise structure
Deformation Loop
Calculate δ at each substructure/foundation location using the applicable permanent loads in the Service I load combination
Select γ_{SE} based on the specific method used for calculation of δ
Compute factored deformation, δ_F at each substructure/foundation location
$\delta_f = \gamma_{SE}$ (δ)
Use δ-0 and construction point concept as applicable to determine factored angular distortion, A_{df}, within each span, L.
All viable deformed shapes should be evaluated.
Are δ_f and A_{df} acceptable? See Note 2.
No
Yes
Revise structure
Continue bridge analysis by incorporating the induced force effects due to factored deformation, δ_f. See Note 3.

Closing Comments

- Consideration of foundation deformations in bridge design is not new.
- The uncertainty in predicted deformations can now be quantified through the mechanism of SE load factor, γ_{SE}.
- The calibration process is general and can be applied to any foundation or wall type and any type of deformation.
- Microsoft Excel®-based calibration processes have been developed.
- Framework for inclusion of future calibrations is provided through proposed Table 3.4.1-4 for γ_{SE}.

Closing Comments

- Tools for implementation are available.
  - SHRP2 Round 7 Implementation Assistance Program (IAP)
    - Application period, April 1 – 29, 2016
    - Informational webinars, February – March 2016
  - Training seminars, TBD

Questions and Contacts

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http://SHRP2.transportation.org or https://www.fhwa.dot.gov/goshrp2