


SHRP2 SOLUTIONS
STRATEGIC HIGHWAY RESEARCH PROGRAM

Service Limit State Design for Foundations
— Impact on Bridge Design

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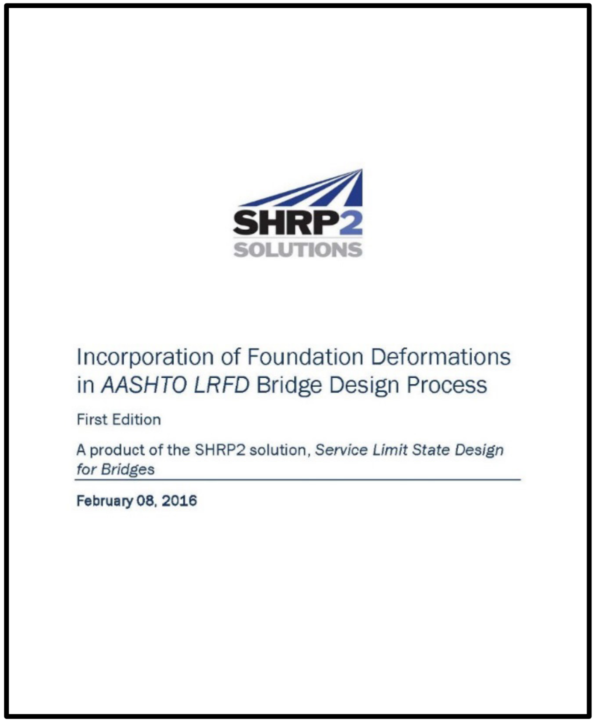
U.S. Department of Transportation
Federal Highway Administration

American Association of State Highway and Transportation Officials
AASHTO

FHWA/AASHTO Implementation

- TRB Project R19B final report published in 2015
- Implementation work began in Fall 2015
- Presentations at AASHTO SCOBS Annual T-15 Committee Meetings
  - 2012, Austin, TX
  - 2014, Columbus, OH
  - 2015, Saratoga Springs, NY
- Presentation at AASHTO SCOBS Mid Year Joint Meeting of T-15 and T-5 committees on October 28, 2015, in Chicago, IL; included a flow chart
- Development of examples, draft agenda items for T-15 and T-5 committees, and a white paper
- 2 Round 7 awards in June 2016 – California and Federal Lands Highway


SHRP2 SOLUTIONS

Incorporation of Foundation Deformations in *AASHTO LRFD* Bridge Design Process

First Edition

A product of the SHRP2 solution, *Service Limit State Design for Bridges*

February 08, 2016

R19B Product Page

http://shrp2.transportation.org/Pages/R19B_ServiceLimitStateDesignforBridges.aspx

AASHTO Table 3.4.1-1

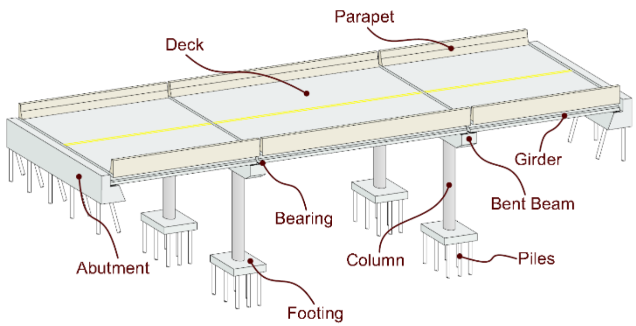
Superimposed Deformations

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."



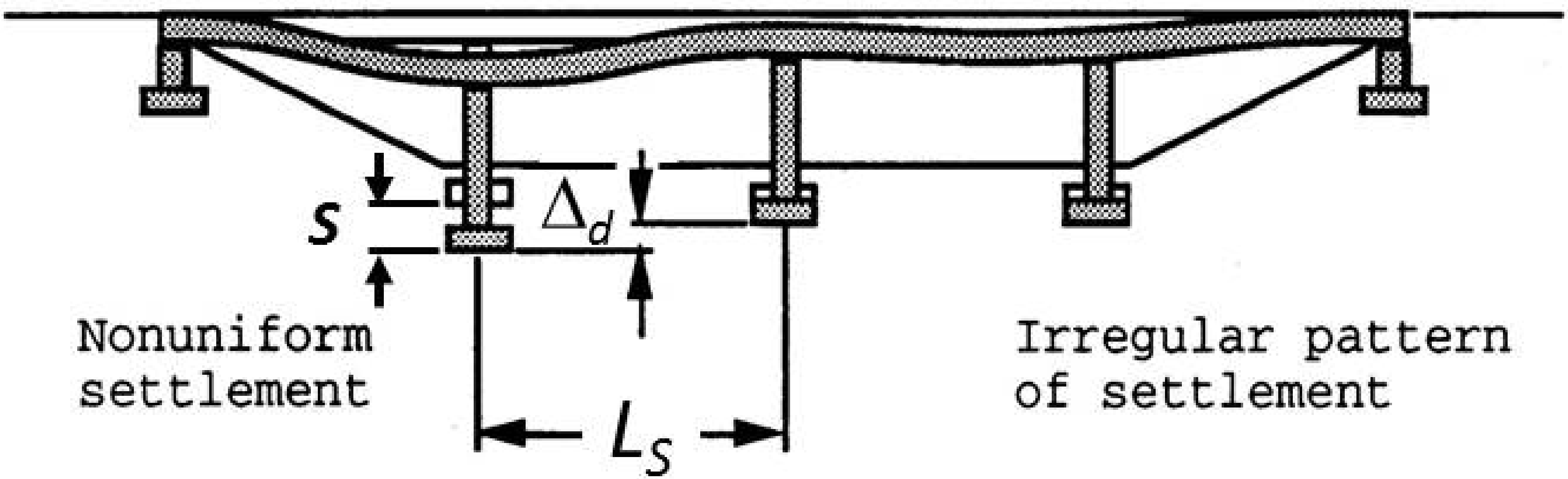
Commentary

- "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."

Key Points

- Evaluation of differential deformation is mandated by AASHTO bridge design specifications regardless of design platform (ASD, LFD, or LRFD).
  - It is not a new requirement.
- In LRFD platform,
  - Category of superimposed deformations
  - The γ_{SE} load factor appears in both strength and service limit state load combinations.
- The uncertainty of predicted deformations needs to be calibrated for the γ_{SE} load factor within the overall framework of limit state design.

Settlement, *S*, and Angular Distortion, $A_d = \Delta_d / L_S$



- What is a ***tolerable*** value of Δ_d / L_S ?
- How ***reliable*** is the value of *S* ?

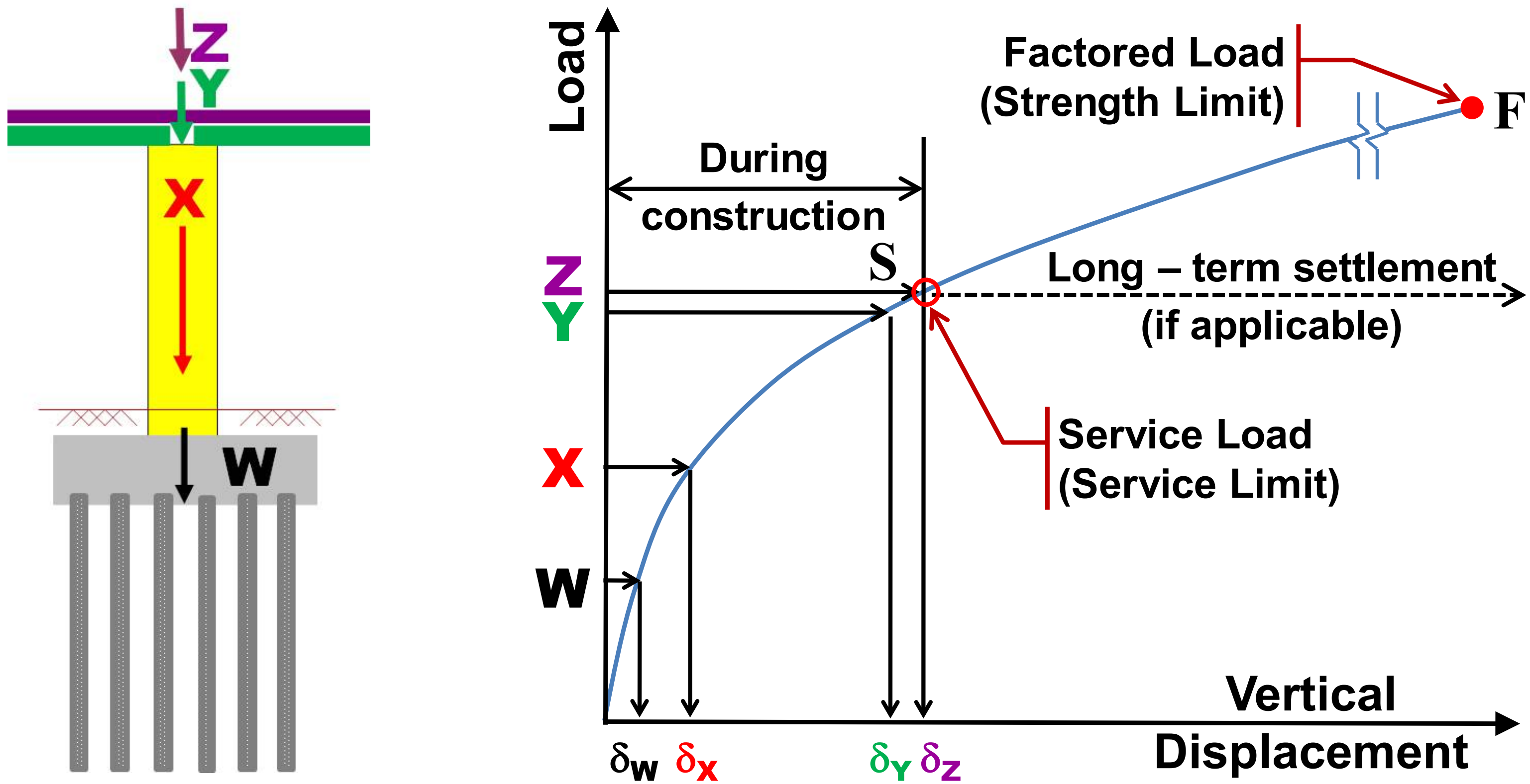
Limiting (Tolerable) Angular Distortion

- 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		

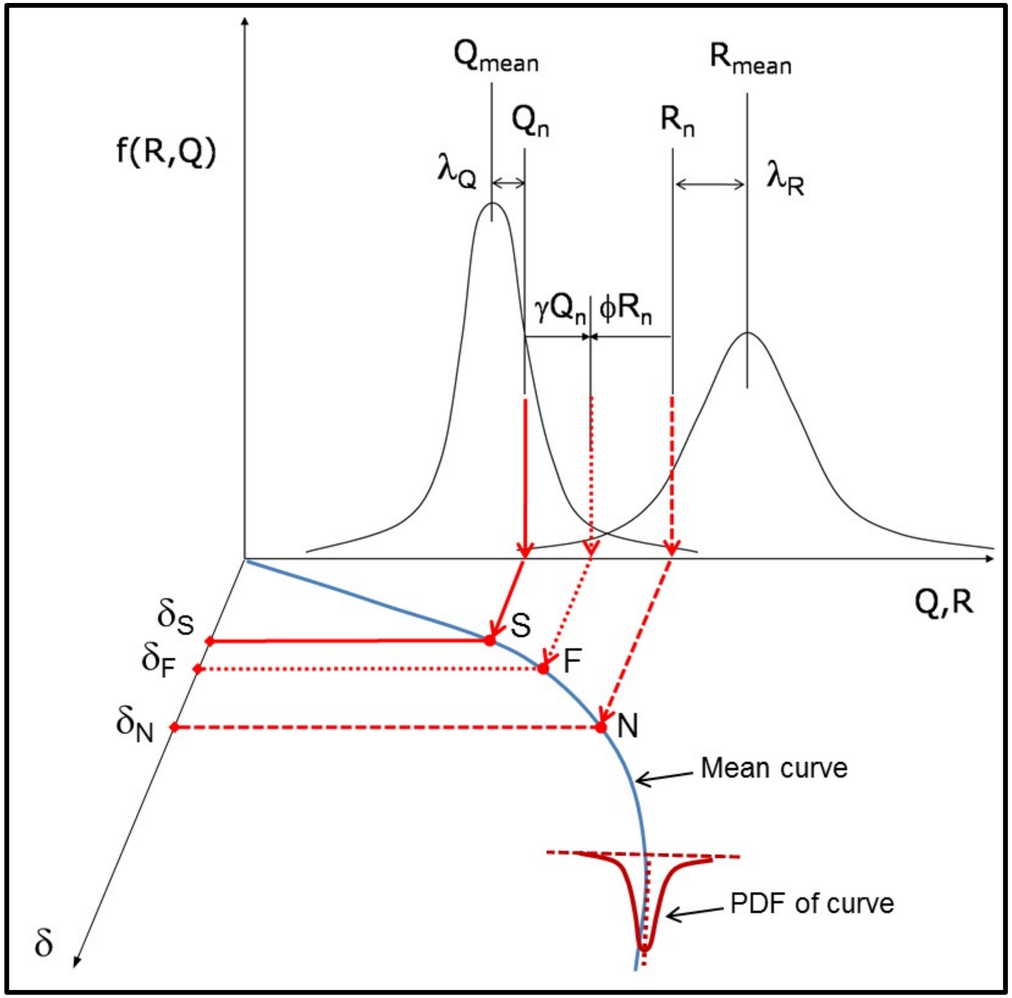
When is a Bridge Structure Affected?

CONSTRUCTION POINT CONCEPT

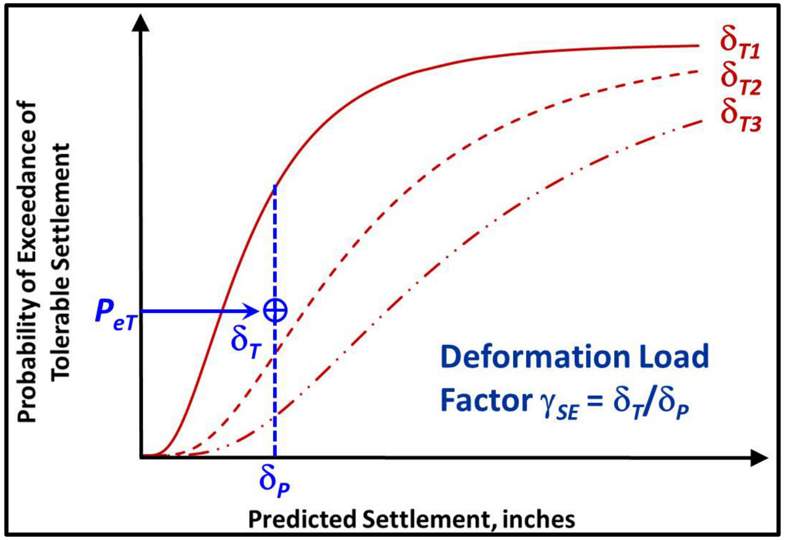


Foundation could be shallow (spread footings) or deep (piles, shafts, etc.)

Calibration Process for Load Factor γ_{SE}



- What is the uncertainty in estimated values of foundation deformation, δ?
- Need to express γ_{SE} in terms of probability of exceedance (or reliability index)



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

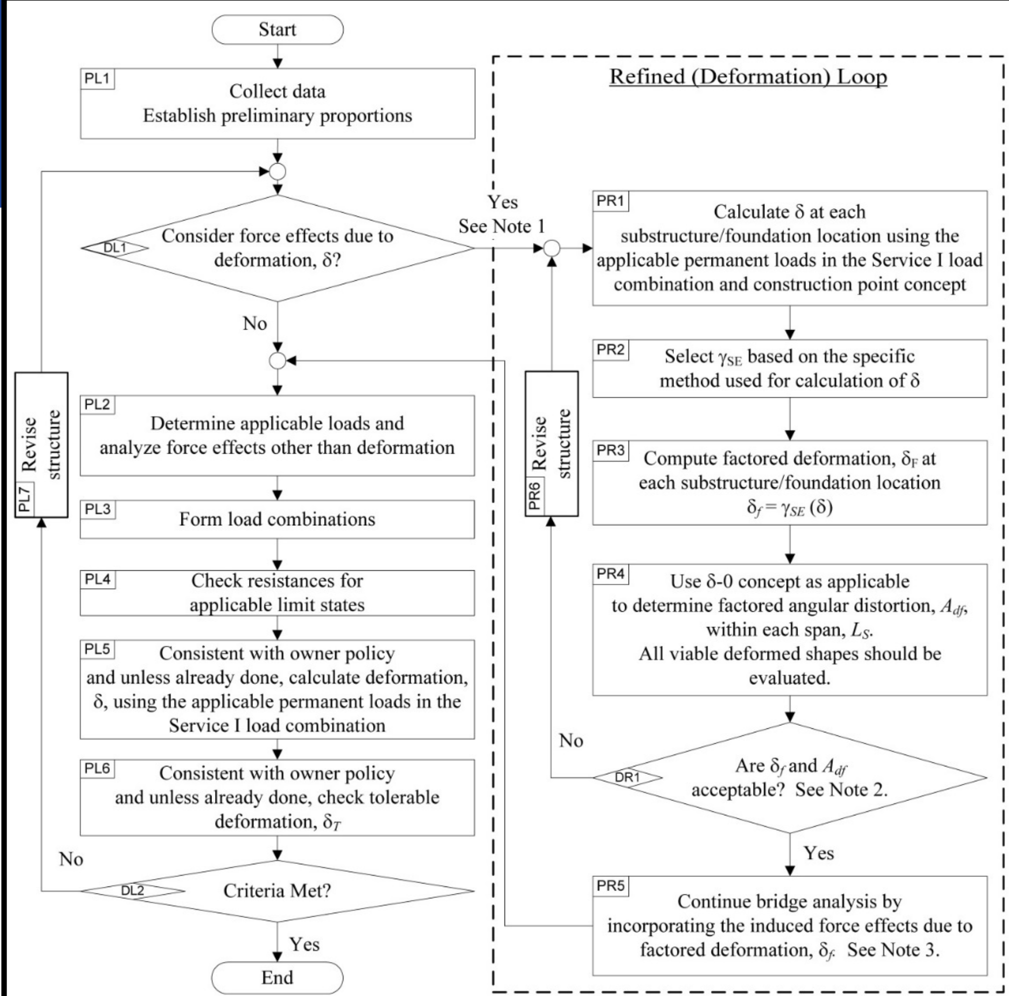
- Include the γ_{SE} in above table or develop a similar table

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

Deformation	γ_{SE}
Immediate settlement • Hough method • Schmertmann method • Local method	 1.00 1.25 *
Consolidation settlement	1.00
Lateral deformation • P-y or SWM soil-structure interaction method • Local method	 1.00 *
*To be determined by the owner based on local geologic conditions.	

Implementation Tools

- White paper
  - Flow Chart
  - Several examples
- Proposed LRFD specification revisions and commentaries
- SHRP2 Round 7 Implementation Assistance Program (IAP) – 2 User Incentives



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.

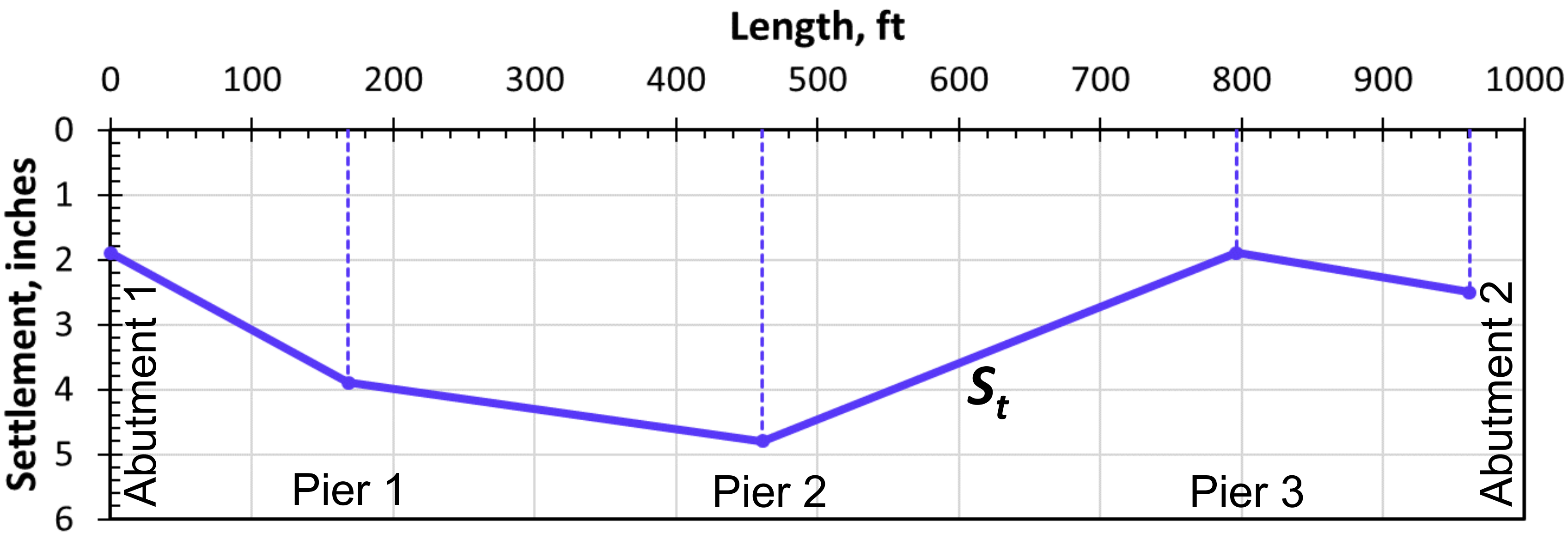
Impact on Bridge Design

- Three examples in White Paper
  - With input and assistance from Dr. Wagdy Wassef (AECOM)
- Example 1
  - Two span bridge, 100 ft long
  - Span lengths: 50 ft, 50 ft
- Example 2
  - Four span bridge, 961 ft long
  - Span lengths: 168 ft, 293 ft, 335 ft, 165 ft
- Example 3
  - Five span bridge, 660 ft long
  - Span lengths: 120 ft, 140 ft, 140 ft, 140 ft, 120 ft

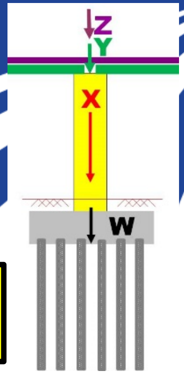
Predicted Unfactored Total Settlements, S_t

S_t based on Service I load combination (TOTAL)

Predicted Unfactored Total Settlements, S_t (in.)				
Abutment 1	Pier 1	Pier 2	Pier 3	Abutment 2
1.90	3.90	4.80	1.90	2.50

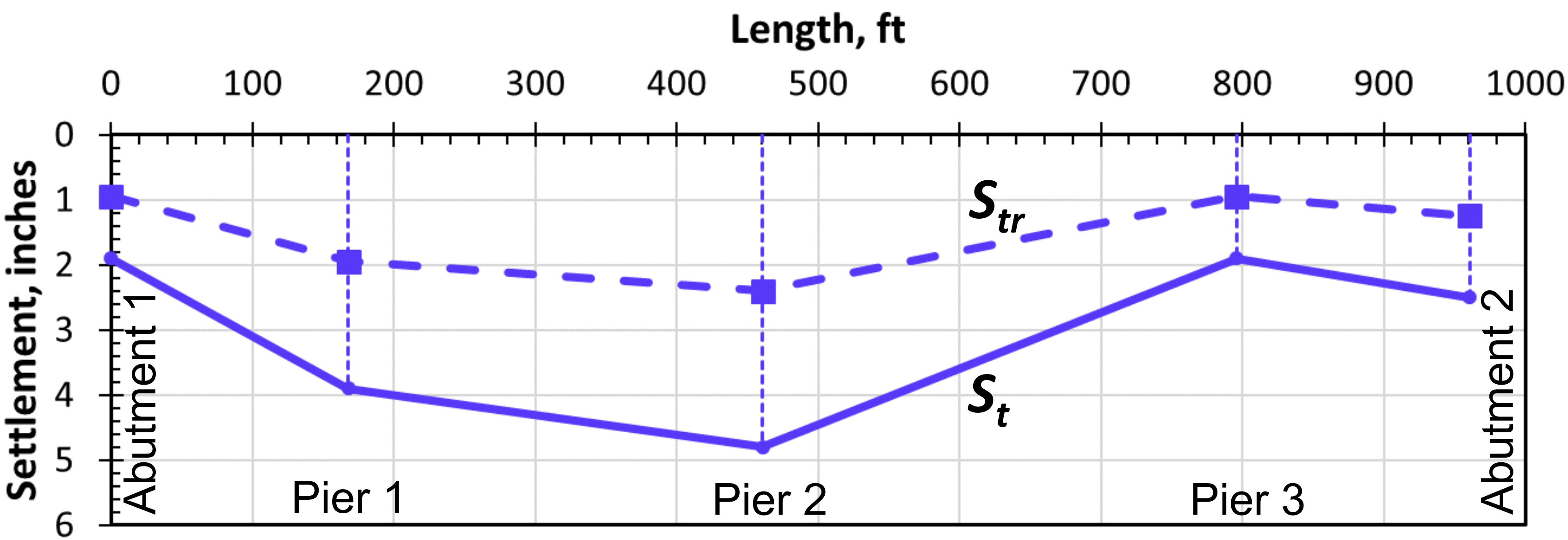


Estimated Unfactored Relevant Settlements, S_{tr}



S_{tr} based on construction point concept

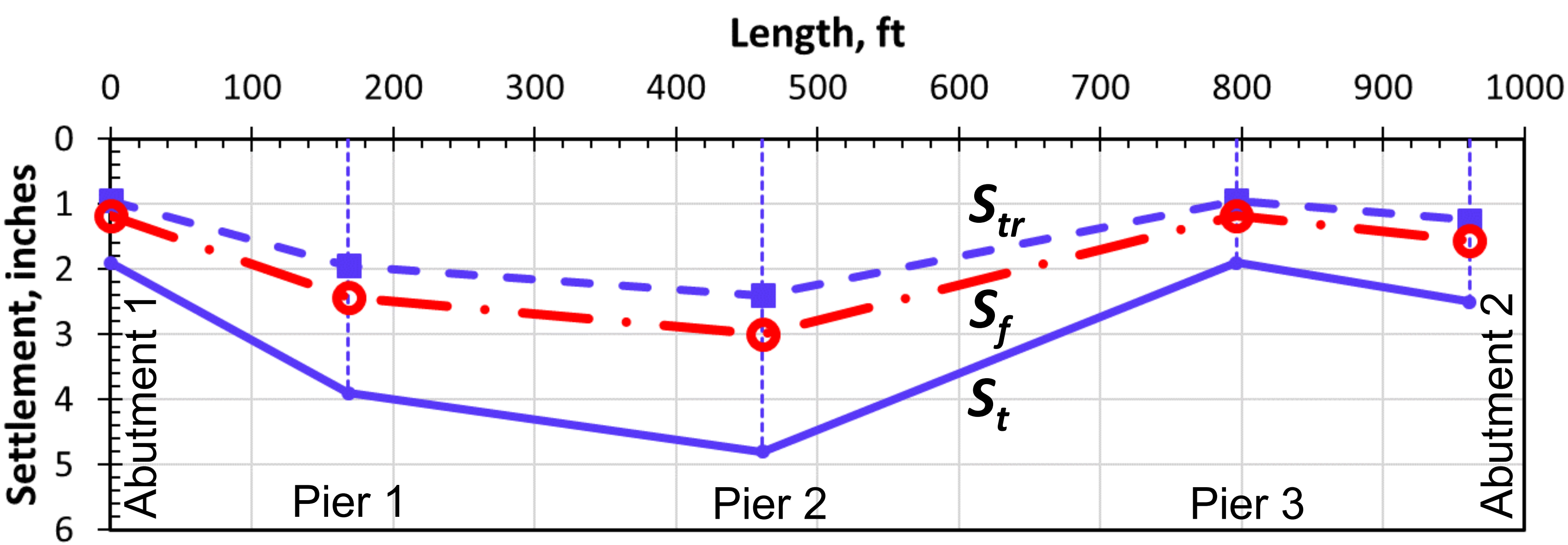
Estimated Unfactored Relevant Settlements, S_{tr} (in.)				
Abutment 1	Pier 1	Pier 2	Pier 3	Abutment 2
0.95	1.95	2.40	0.95	1.25



Factored Relevant Settlements, S_f

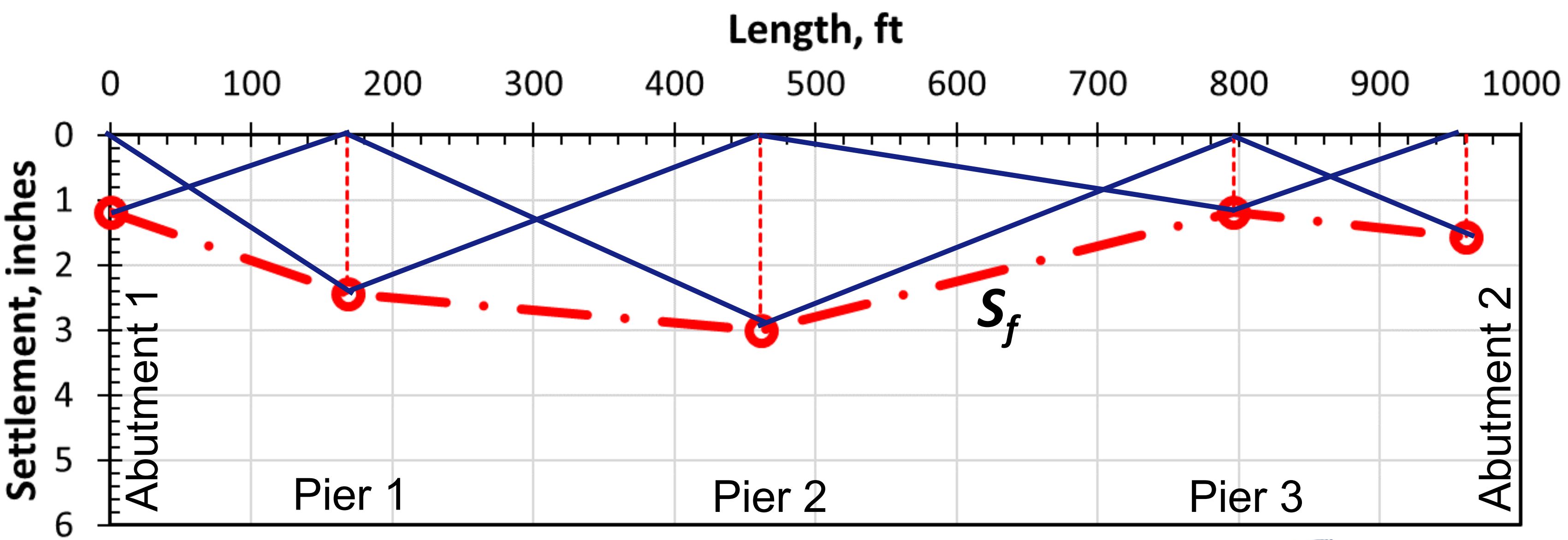
$$S_f = \gamma_{SE}\,(S_{tr})$$

Factored Relevant Settlements, S_f (in.) using γ_{SE} = 1.25				
Abutment 1	Pier 1	Pier 2	Pier 3	Abutment 2
1.19	2.44	3.00	1.19	1.56



Evaluate Factored Angular Distortions, A_{df}

Factored Angular Distortion, A_{df} (rad.)			
Mode 1: S_f at the left end of the span divided by the span length			
Span 1	**Span 2**	**Span 3**	**Span 4**
0.0006	0.0007	0.0007	0.0006
Mode 2: S_f at the right end of the span divided by the span length			
Span 1	**Span 2**	**Span 3**	**Span 4**
0.0012	0.0009	0.0003	0.0008



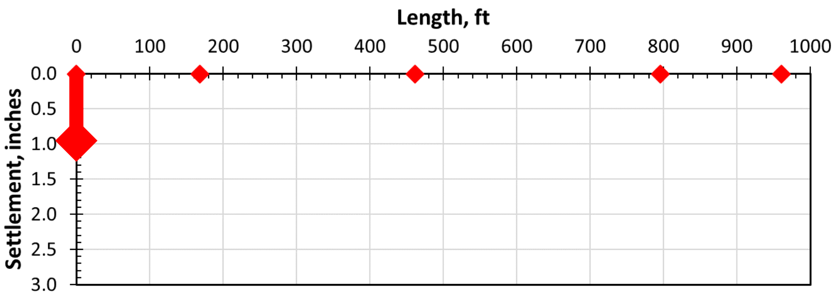
Example 2: Four-Span Bridge

Table E2-M1

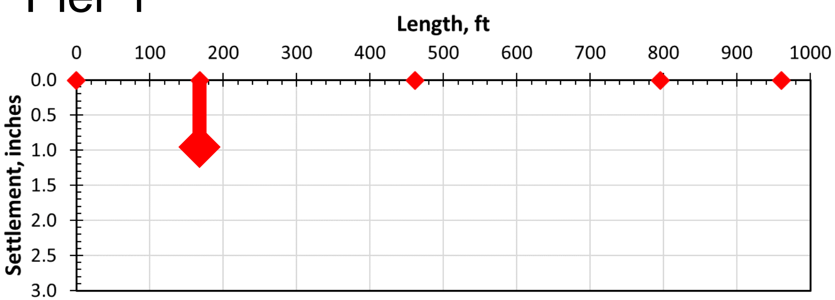
Moment (kip-ft)								
		Span 1 - 0.4L	Pier 1	Span 2 - 0.5L	Pier 2	Span 3 - 0.5L	Pier 3	Span 4 - 0.8L
Unfactored DL moment (No Settlement)		3884	-15561	8001	-33891	13513	-25824	1651
Unfactored LL moment	+ve	6401	2807	8639	1166	9741	2662	4379
	-ve	-3171	-10609	-3174	-13208	-2257	-14582	-2270
Unfactored effect of 1 in. settlement at Abutment 1		-329	-822	-273	278	84	-110	-22
Unfactored effect of 1 in. settlement at Pier 1		702	1753	609	-534	-161	212	43
Unfactored effect of 1 in. settlement at Pier 2		-469	-1174	-79	1016	344	-328	-65
Unfactored effect of 1 in. settlement at Pier 3		192	452	-479	-1409	321	2050	411
Unfactored effect of 1 in. settlement at Abutment 2		-82	-208	221	651	-587	-1825	-364

Unit Settlements at Supports

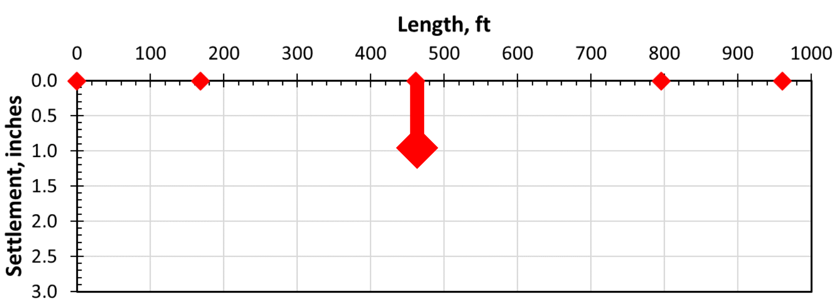
Abutment 1



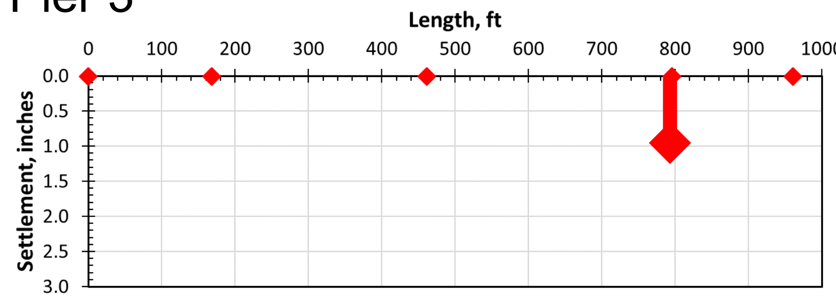
Pier 1



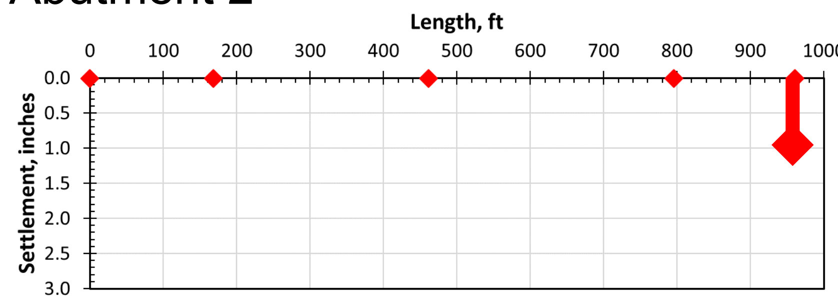
Pier 2



Pier 3



Abutment 2



- Use linear scaling and superposition to develop force effects (moments and shears) due to settlements

Service I Comparison

Case 1: Not consider settlement
Case 2: Consider full settlement with γ_{SE} = 1.0 (current AASHTO)
Case 3: Consider uncertainty in settlement and construction-point concept

Service I Comparison		Moment (kip-ft) Span 1 - 0.4L	Pier 1	Span 2 - 0.5L	Pier 2	Span 3 - 0.5L	Pier 3	Span 4 - 0.8L
Case 1: 1.0 DL + 1.0 LL without SE	Max	10285	-12754	16640	-32725	23254	-23162	6030
	Min	713	-26170	4827	-47099	11256	-40406	-619
Case 2: 1.0 DL + 1.0 LL + γ_{SE} SE (use γ_{SE} = 1.00 and S_t)	Max	13388	-5059	19568	-25693	25675	-18440	6979
	Min	-2368	-33887	3019	-51859	9161	-46752	-1883
Case 3: 1.0 DL + 1.0 LL + γ_{SE} SE (use γ_{SE} = 1.25 and S_{tr})	Max	12224	-7944	18470	-28330	24767	-20211	6623
	Min	-1213	-30993	3697	-50074	9946	-44372	-1409
Ratio of Case 3 to Case 1	Max	**1.189**	0.623	**1.110**	0.866	**1.065**	0.873	**1.098**
	Min	-1.701	**1.184**	0.766	**1.063**	0.884	**1.098**	2.276
Ratio of Case 3 to Case 2	Max	***0.913***	*1.570*	***0.944***	*1.103*	***0.965***	*1.096*	***0.949***
	Min	*0.512*	***0.915***	*1.225*	***0.966***	*1.086*	***0.949***	*0.748*

Strength I Comparison

Case 1: Not consider settlement
Case 2: Consider full settlement with γ_{SE} = 1.0 (current AASHTO)
Case 3: Consider uncertainty in settlement and construction-point concept

Strength I Comparison		Moment (kip-ft) Span 1 - 0.4L	Pier 1	Span 2 - 0.5L	Pier 2	Span 3 - 0.5L	Pier 3	Span 4 - 0.8L
Case 1: 1.25 DL + 1.75 LL without SE	Max	16057	-14539	25120	-40323	33938	-27622	9727
	Min	-694	-38017	4447	-65478	12942	-57799	-1909
Case 2: 1.25 DL + 1.75 LL + γ_{SE} SE (use γ_{SE} = 1.00 and S_t)	Max	19159	-6844	28047	-33291	36359	-22900	10676
	Min	-3776	-45734	2639	-70237	10846	-64144	-3173
Case 3: 1.25 DL + 1.75 LL + γ_{SE} SE (use γ_{SE} = 1.25 and S_{tr})	Max	17996	-9729	26949	-35928	35451	-24670	10320
	Min	-2620	-42840	3317	-68453	11632	-61765	-2699
Ratio of Case 3 to Case 1	Max	**1.121**	0.669	**1.073**	0.891	**1.045**	0.893	**1.061**
	Min	3.774	**1.127**	0.746	**1.045**	0.899	**1.069**	1.414
Ratio of Case 3 to Case 2	Max	***0.939***	*1.422*	***0.961***	*1.079*	***0.975***	*1.077*	***0.967***
	Min	*0.694*	***0.937***	*1.257*	***0.975***	*1.072*	***0.963***	*0.851*

Some Observations

- Deformations generate additional force effects.
  - Load factor of SE is similar to PS, CR, SH, TU, and TG
- The value of γ_{SE} must not be taken literally
  - γ_{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.
- Use of construction point concept in conjunction with γ_{SE} incorporates force effects related to expected sequence of construction along with quantification of uncertainty in predicted deformations.

Benefits of Using Calibrated Foundation Deformations

- Consideration of calibrated foundation deformations in the bridge design process can lead to use of cost-effective structures with more efficient foundation systems.
  - Permit enhanced use of cost-effective spread footings and true bridge abutments (spread footing on top of MSE wall).

- The proposed revisions provide a more rational basis to compare alternatives

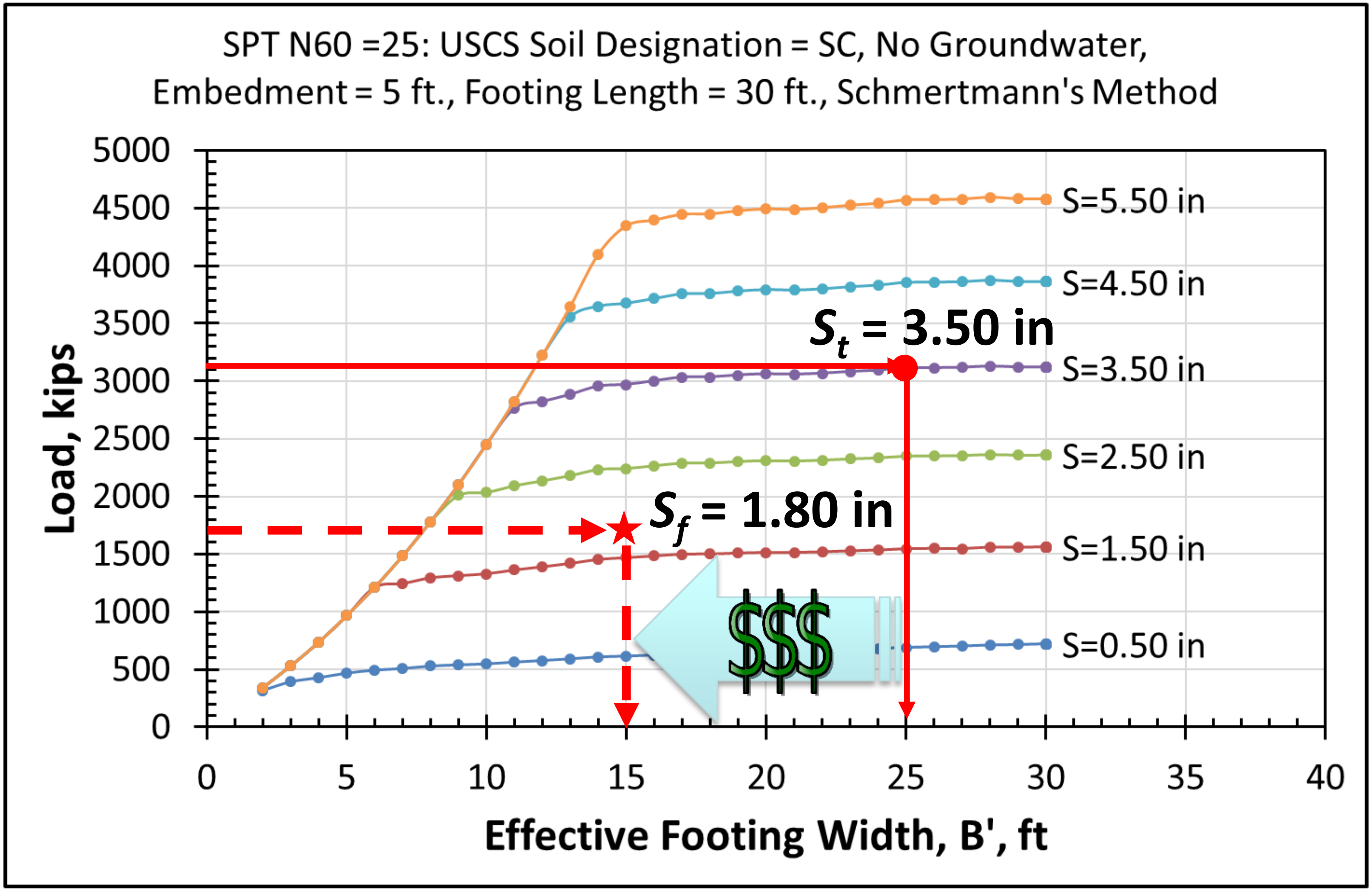
Benefits of Using Calibrated Foundation Deformations

- Approach and modifications will help avoid overly conservative criteria that can lead to:

  a) foundations that are larger than needed, or

  b) a choice of less economical foundation type (such as, using a deep foundation at a location where a shallow foundation would be adequate).

Example of Foundation Efficiency



FHWA Resources

APPENDIX E – LRFD GUIDANCE FOR SPREAD FOOTINGS

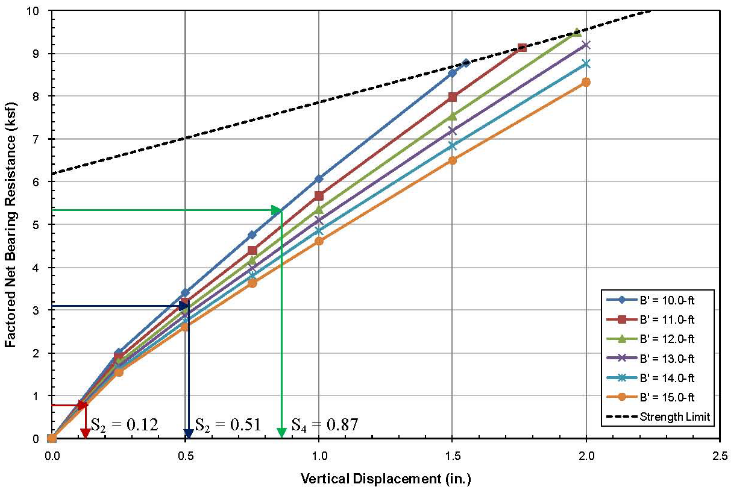


Figure E.4-2. Graph. Example of a factored bearing resistance chart in terms of stress-settlement curves for a range of effective footing widths.

Table E.4-5: Summary of computations of settlements at significant construction points for the example abutment footing.

Quantity	Units	Construction-point			
		1	2	3	4
		End of construction of footing	End of construction of stem, backwall and wingwalls	Completion of earth fill behind abutment	Placement of Superstructure and open to traffic
V	k	1,310	3,310	6,446	9,078
M	k-ft	0	400	6,215	22,720
$L'_f = L_f$	ft	150.00	150.00	150.00	150.00
B_f	ft	15.00	15.00	15.00	15.00
$e_B = M/V$	ft	0.00	0.12	1.93	2.50
$B'_f = B_f - 2e_B$	ft	15.00	14.76	11.14	10.00
$q_{tveu} = V/[(B'_f)(L'_f)]$	ksf	0.58	1.50	3.86	6.05
$\gamma_p(\gamma_s D_f)$	ksf	0.72	0.72	0.72	0.72
$q_{nveu} = q_{tveu} - \gamma_p(\gamma_s D_f)$	ksf	-0.14	0.78	3.14	5.33
S (from Figure E.4-2)	in	$S_1 = 0.00$	$S_2 = 0.12$	$S_3 = 0.51$	$S_4 = 0.87$

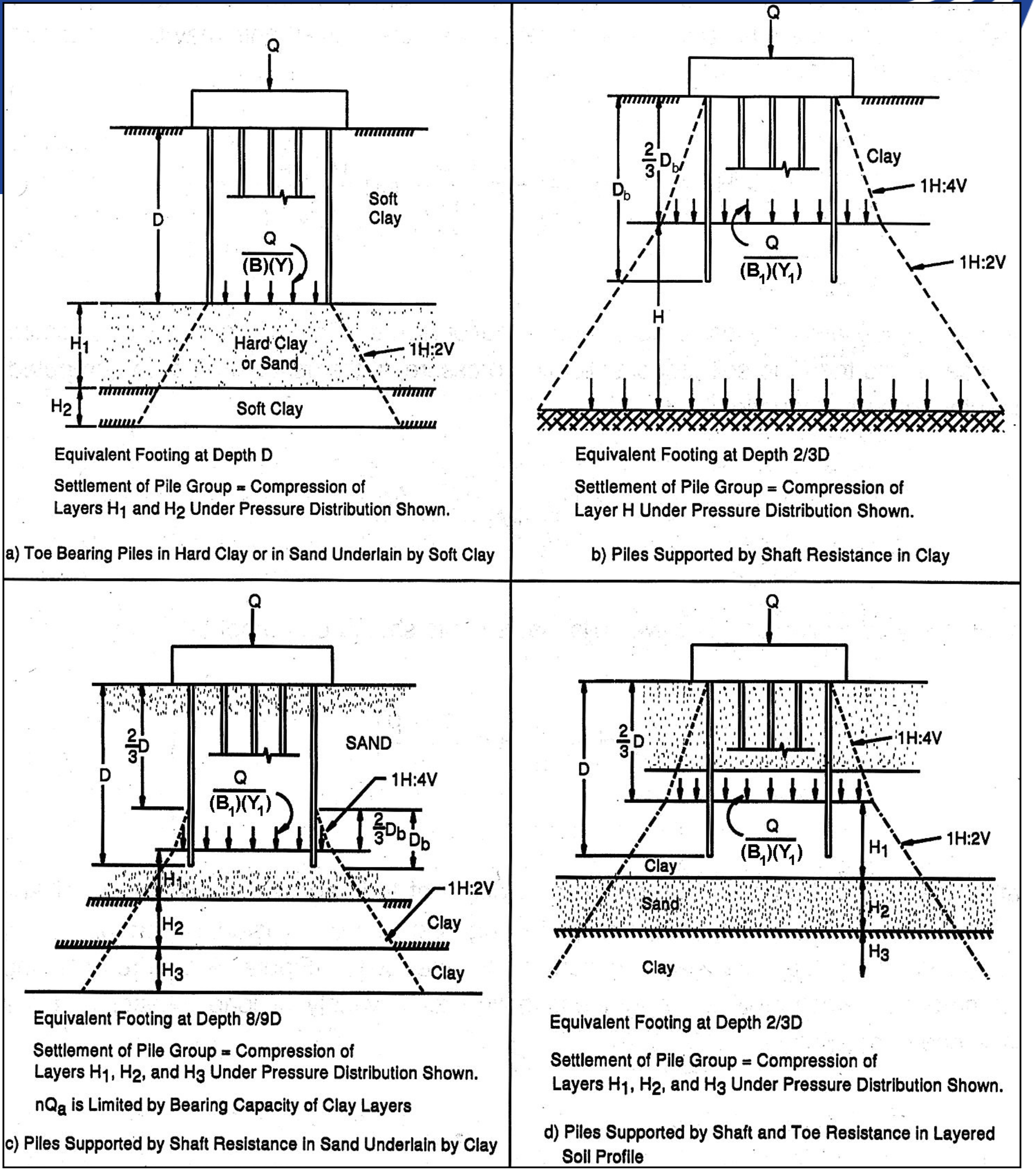
SELECTION OF SPREAD FOOTINGS ON SOILS TO SUPPORT HIGHWAY BRIDGE STRUCTURES

Publication No. FHWA-RC/TD-10-001 — February 2010

U.S. Department of Transportation
Federal Highway Administration

Settlement of Deep Foundations

- Article 10.7.2.3
  - Use equivalent footing
- Can reduce:
  - length of deep foundations
  - plan size of deep foundation system
  - number of deep foundation elements in a group



Closing Comments

- Consideration of foundation deformations in bridge design is not new – **it is in fact required by specifications**
- 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.
- Proposed LRFD specification revisions and commentaries have been developed.
- Significant cost efficiencies can be realized.

Next Steps

- SHRP2 Round 7 IAP User Incentive Awards to California and FHWA Federal Lands Highway
  - (1) Direct technical assistance; (2) Training provided
- FHWA developed training for outreach education
  - (1) Under development; (2) Pilot in Fall 2016
- Technical assistance to AASHTO SCOBS
  - Refinement of ballot item(s)
  - Ballot targeted for 2017 Annual Meeting
- See R19B Product Page for presentations, webinars, tools, and technologies
  - http://shrp2.transportation.org/Pages/R19B_ServiceLimitStateDesignforBridges.aspx

Questions and Contacts

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