SHRP2 SOLUTIONS
STRATEGIC HIGHWAY RESEARCH PROGRAM

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

Naresh C. Samtani, PhD, PE, D.GE, F.ASCE
NCS GeoResources, LLC

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U.S. Department of Transportation
Federal Highway Administration

American Association of State Highway and Transportation Officials
AASHTO

SHRP2 at a Glance

SHRP2 Solutions – 63 products

Solution Development – processes, software, testing procedures, and specifications

Field Testing – refined in the field

Implementation – More than 430 transportation projects; adopt as standard practice

SHRP2 Education Connection – connecting next-generation professionals with next-generation innovations

R19B Product Page
http://shrp2.transportation.org/Pages/R19B_ServiceLimitStateDesignforBridges.aspx

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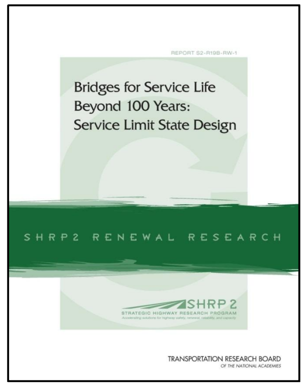
Initial SHRP2-TRB Research Team for R19B

- 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



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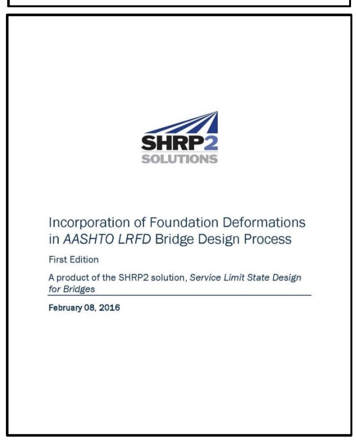
History of Work Related to Foundation Deformations

- Project R19B work started in 2009
  - Final Report published in 2015
- Presentations at AASHTO SCOBS Annual T-15 Committee Meetings
  - 2012, New Orleans, LA
  - 2014, Columbus, OH
  - 2015, Saratoga Springs, NY
  - 2016, Minneapolis, MN
- 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, a white paper, and a training course

Authors: Naresh C. Samtani and John M. Kulicki



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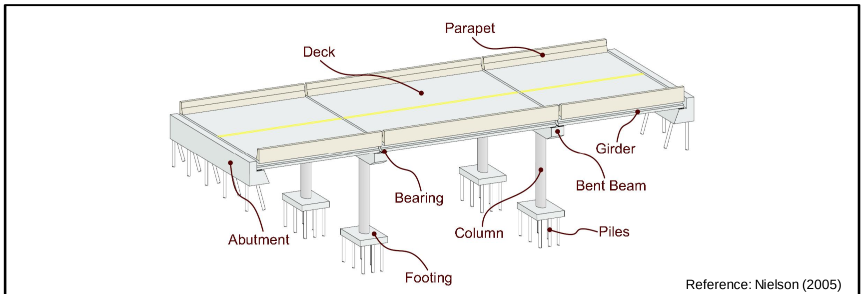
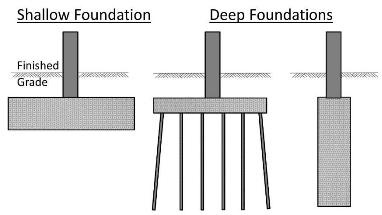
Bridge Configuration and Foundation Types





Foundation Deformations

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

AASHTO Table 3.4.1-1

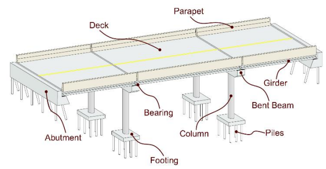
Superimposed Deformations

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."

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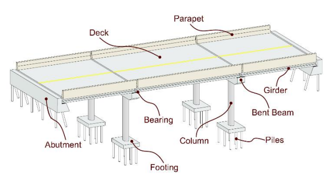
Standard Specifications – 17th Edition (2002)

- **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.

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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 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

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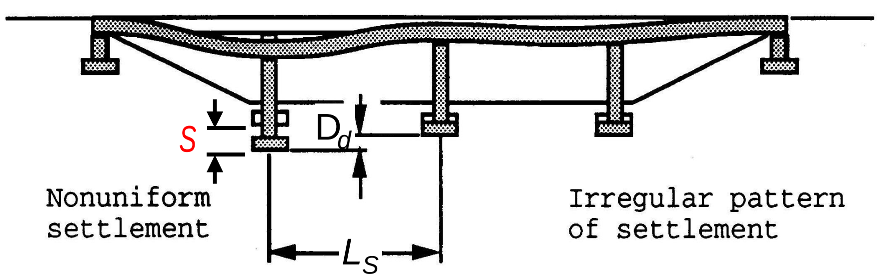
Differential Settlement, D_d



- Differential settlement, D_d, induces force effects within superstructure
- Differential settlement, D_d, when normalized by span length, L_S, is an expression of angular distortion

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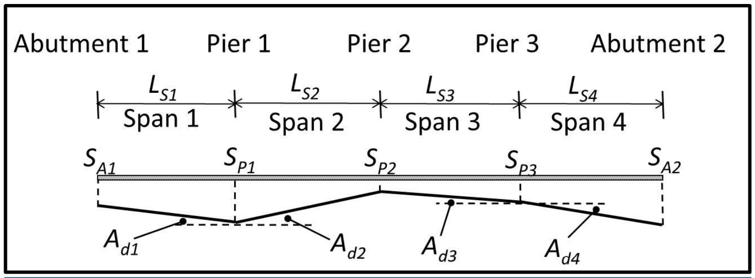
Concept of Differential Settlement and Angular Distortion



Span	Differential Settlement, Δ_d	Angular Distortion, $A_d = \Delta_d / L_S$
1	$\Delta_{d1} = \lvert S_{A1} - S_{P1} \rvert$	$A_{d1} = (\lvert S_{A1} - S_{P1} \rvert)/L_{S1}$
2	$\Delta_{d2} = \lvert S_{P1} - S_{P2} \rvert$	$A_{d2} = (\lvert S_{P1} - S_{P2} \rvert)/L_{S2}$
3	$\Delta_{d3} = \lvert S_{P2} - S_{P3} \rvert$	$A_{d3} = (\lvert S_{P2} - S_{P3} \rvert)/L_{S3}$
4	$\Delta_{d4} = \lvert S_{P3} - S_{A2} \rvert$	$A_{d4} = (\lvert S_{P3} - S_{A2} \rvert)/L_{S4}$

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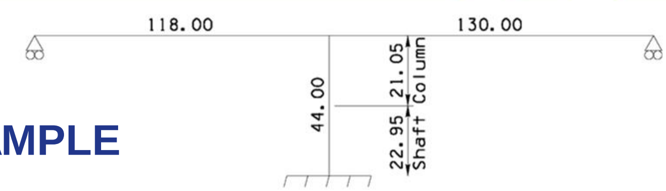
Induced Moments in Continuous-Span Bridges

EXAMPLE



$$M_\Delta = \frac{6EI\Delta_d}{L_S^2} = 6\left(\frac{EI}{L_S}\right)\left(\frac{\Delta_d}{L_S}\right)$$

$$M_\Delta = func\left(\frac{EI}{L_S}, \frac{\Delta_d}{L_S}\right)$$

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

Δ_d/L_S is **Angular Distortion** (dimensionless)

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Limiting (Tolerable) Angular Distortion

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

Type of Bridge	Limiting Angular Distortion, D_d/L_S	
	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		

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Arbitrary Use of AASHTO Limiting Values

Examples of arbitrary (inconsistent) application

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

Total Settlement, d, at Pier or Abutment	Differential Settlement over 100 ft within Pier or Abutments and Differential Settlement Between Piers [Implied Limiting Angular Distortion, radians]	Action
d ≤ 1"	$D_{d100'}$ ≤ 0.75" **[0.000625]**	Design & construct
1" < d ≤ 4"	0.75" < $D_{d100'}$ ≤ 3" **[0.000625-0.0025]**	Ensure structure can tolerate settlement
d > 4"	$D_{d100'}$ > 3" **[> 0.0025]**	Need Dept approval

- Arizona DOT: "The bridge designer should limit the settlement of a foundation per 100 ft span to 0.75 in. Linear interpolation should be used for other span lengths."

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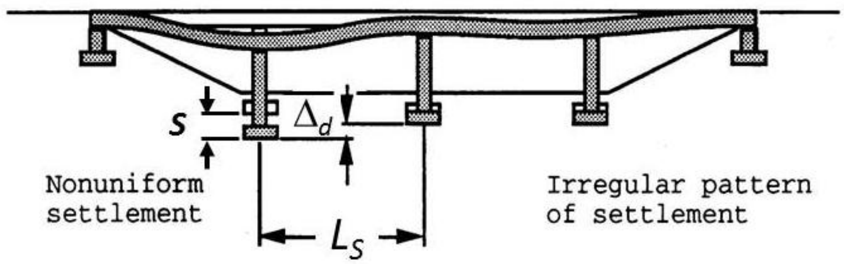
Settlement, *S*, and Angular Distortion, $A_d = D_d/L_S$



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

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Many Methods to Estimate Foundation Movements

- Vertical
  - Immediate settlement
    - Elastic method
    - Hough method
    - Schmertmann
    - Others
  - Long-term settlement
    - Based on 1-D consolidation theory
- Lateral
  - P-y analysis
  - Strain Wedge Method (SWM)
  - Others
- **Are all methods equally reliable?**
- **What is the uncertainty in predicted values?**

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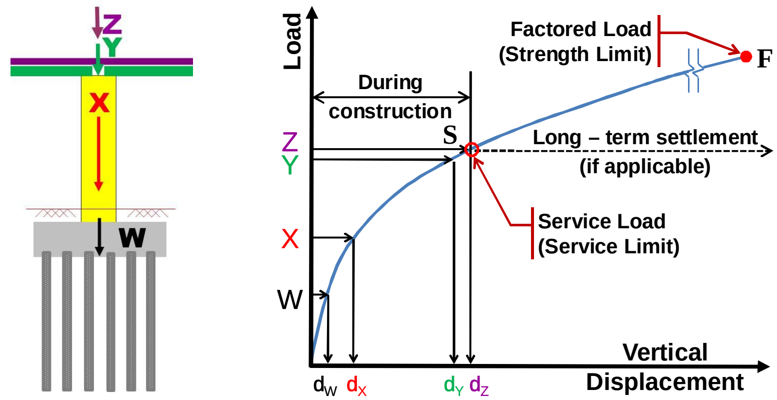
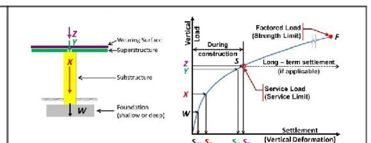
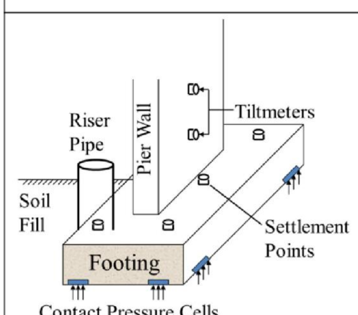
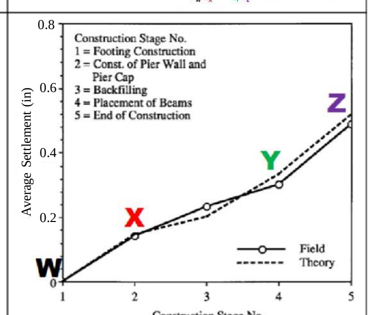
When is a Bridge Structure Affected?

CONSTRUCTION POINT CONCEPT



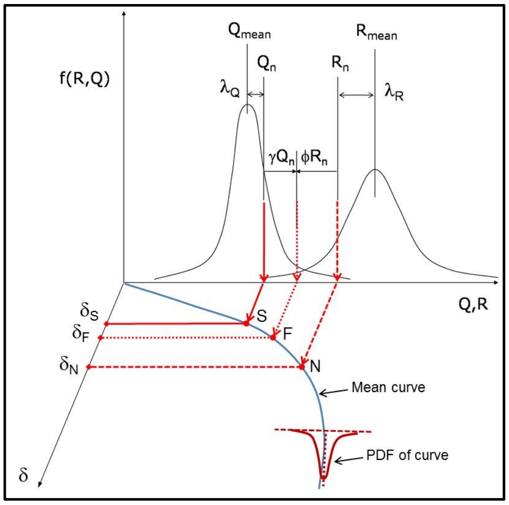
Foundation could be shallow (spread footings) or deep (piles, shafts, etc.)

When is a Bridge Structure Affected?

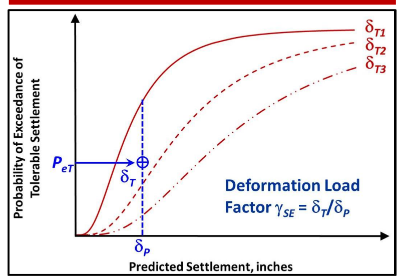
Construction-Point Concept	
	
Instrumentation	Example Data (Pier)

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

Calibration Process for Load Factor g_{SE}



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



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Concept of Reversible-Irreversible Limit States

- Reversible-irreversible limit state is one where the effect of an irreversible limit state may be reversed by intervention.
- Example: Foundation deformation, which is an irreversible limit state with respect to foundation elements but may be reversible in terms of its effect on the bridge superstructure through intervention, e.g., through use of shims or jacking

FHWA (2006)

- **Target reliability index is a function of reversible, irreversible, and reversible-irreversible limit states**

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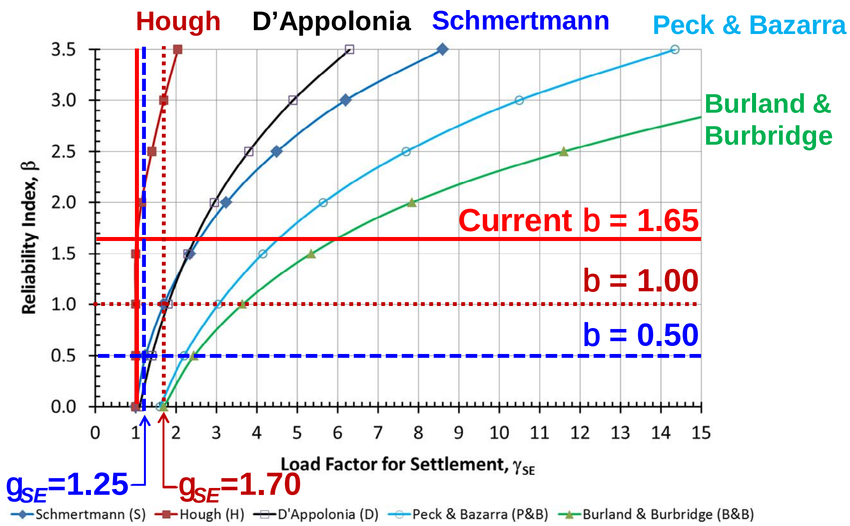
Development of g_{SE} for Different Methods Based on b Value



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 g_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 g_{SE} in above table or develop a similar table

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

Deformation	g_{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 and target reliability index.	

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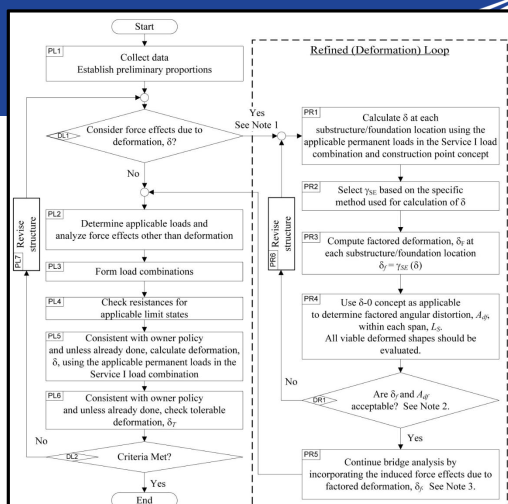
Implementation Tools

- White paper
  - Flow Chart
  - Several examples
- 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.

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Some Observations

- Deformations generate additional force effects.
  - Load factor of SE is similar to PS, CR, SH, TU, and TG
- The value of g_{SE} must not be taken literally
  - g_{SE} = 1.25 does not mean that the total force effects will increase by 25%.
  - g_{SE} is only one component in a load combination.
- Use of construction point concept in conjunction with g_{SE} incorporates force effects related to expected sequence of construction along with quantification of uncertainty in predicted deformations.

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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

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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)

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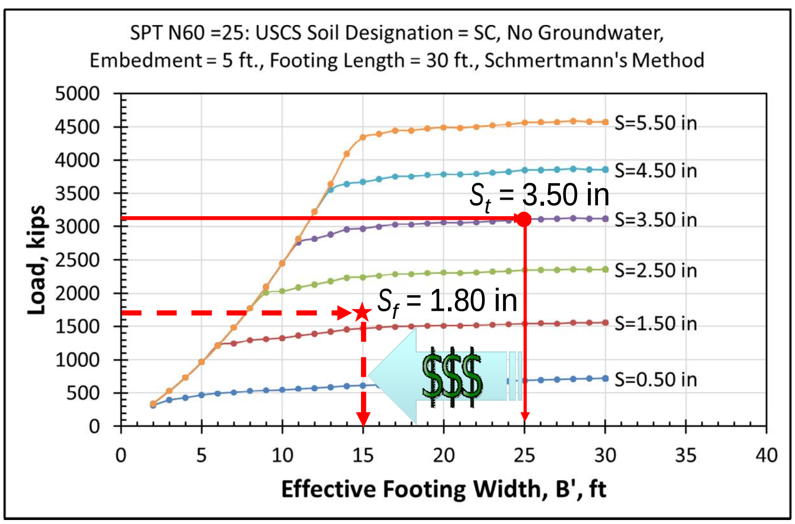
Example of Foundation Efficiency



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FHWA Resources

APPENDIX E – LRFD GUIDANCE FOR SPREAD FOOTINGS

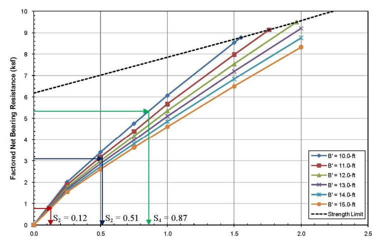

Figure E.4-2. Graph. Example of a factored bearing resistance chart in terms of stress-settlement curves for a range of effective footing widths.

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

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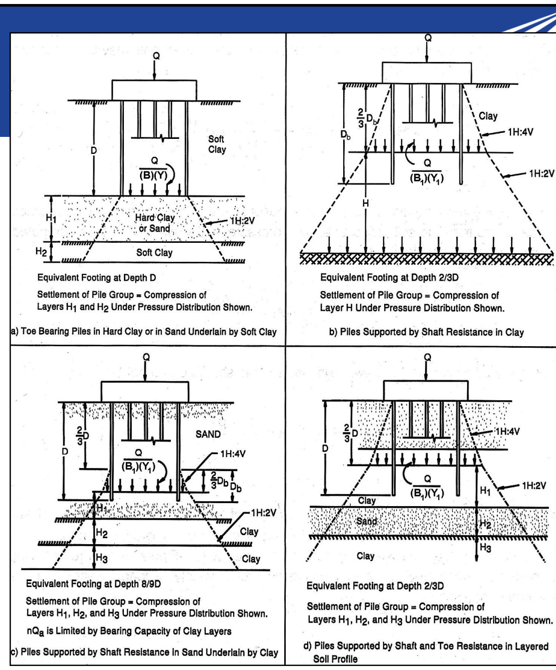
Settlement of Deep Foundations

- 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



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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, $g_{SE.}$
- 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.
- SHRP2 Round 7 Implementation Assistance Program (IAP) and other training opportunities.

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Next Steps

- SHRP2 Round 7 Implementation Assistance Program (IAP) User Incentive Awards
  - Federal Lands Highway
    - Central Division: Denver, CO: May 23 and 24, 2017
    - Eastern Division: Sterling, VA: June 27 and 28, 2017
    - Western Division: Vancouver, WA: July 19 and 20, 2017
  - Caltrans: TBD
- Agenda items under consideration for balloting by AASHTO SCOBS T-15 and T-5 subcommittees
- R19B Product Page
  - http://shrp2.transportation.org/Pages/R19B_ServiceLimitStateDesignforBridges.aspx
  - Presentations, webinars, tools, and technologies

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Questions and Contacts

- FHWA: Silas Nichols, SHRP2 Renewal Program Engineer – Structures, silas.nichols@dot.gov
- AASHTO: Patricia Bush, Program Manager for Engineering, pbush@aashto.org
  Pam Hutton, AASHTO SHRP2 Implementation Manager, phutton@aashto.org
- NCS GeoResources, LLC: Naresh C. Samtani, PhD, PE naresh@ncsgeoresources.com
- Modjeski and Masters, Inc.: John M. Kulicki, PhD, PE JMKulicki@modjeski.com
- AECOM: Wagdy G. Wassef, PhD, PE wagdy.wassef@aecom.com

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

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