Practical Suggestions for Implementation of LRFD Specifications for Geotechnical Features

Naresh C. Samtani, PE, PhD

President, NCS Consultants, LLC

www.ncsconsultants.com

LRFD Implementation Experience

- Teaching NHI's LRFD course on Substructures nationwide
- Contractor for developing and implementing the LRFD action plan for Arizona DOT since 2005

Common Observations

- Why change to LRFD?
  - Fear, confusion and misinformation
- Apply “patches” to mask SLD approach as LRFD by using pseudo load and resistance factors
- Deformations? What is that?
- Structural and geotechnical specialists do not communicate well

Ten Steps for Implementation

1 — 2 — 3 — 4 — 5 — 6 — 7 — 8 — 9 — 10

- Steps followed by an example
- Assumption that AASHTO (2007) is going to be adopted
- There is a difference between adopting AASHTO (2007) and adopting LRFD principles

Assemble a Team

1

- Geotechnical and Bridge Group
  - Initiative from the geotechnical group
- Local peer reviewer(s)
- External peer reviewer(s)
- Beware of self-proclaimed LRFD experts

Structural Specialist

Geotechnical Specialist

Identify End-Product

1 2

- Several forms of end-product
  - Examples: Design guidelines, policy memos
- Identify topics
  - Shallow foundations
  - Deep foundations
    - Drilled shafts, Driven piles
  - Retaining walls
  - Others

Perform Parametric Studies

1 2 3

- Break down problem at the most basic level to identify potential conflicts/issues

$$q_s = \beta \, \sigma_v$$

- Perform sensitivity analysis
- Do not perform "single-point" analysis
- Plot graphs and evaluate trends
- Be careful with spreadsheets/programs
  - Perform verification hand calculations

Identify Effects on Local Practice

1 2 3 4

- Evaluate results of parametric studies with respect to local successful past practice
  - Compare local practice with newer LRFD framework
  - Evaluate effect on costs
- ***ADOT Examples***
  - Modify shallow foundation settlement analysis
  - Modify definition of IGM for drilled shafts
  - Modify load-transfer curves for gravelly soils

Consult Local Peer Reviewers

1 2 3 4 5

- Confirm the proposed modifications
- Document decisions
  - Find supporting data
- ***ADOT Examples***
  - Past successful practice for spread footings
  - Utah DOT database on gravelly soils
  - Past successful practice for shafts

Perform Calibrations

1 2 3 4 5 6

- Always use judgment and experience to evaluate calibration results
- Use reliability theory if appropriate statistical data is available
- ***ADOT Examples***
  - Determine resistance factors for side resistance of drilled shafts in gravelly soils
  - Use resistance factors for sands in AASHTO as interim (conservative) guidance

Initiate Training Programs

1 2 3 4 5 6 7

- Get the word out to practicing engineers
- Start training and outreach programs
- ***ADOT Examples***
  - Four 3-day NHI classes
  - Two ASCE AZ section presentations
  - 2007 “Roads and Streets” Conference
  - ***Train DOT and consultant engineers***

Prepare Policy Memoranda

1 2 3 4 5 6 7 8

- Guidance style ***NOT*** cryptic code style
- Clearly identify deviations from AASHTO
- Provide examples using representative soil conditions, bridge configuration/loads
- Consider other effects, e.g., scour
- ***ADOT Examples*** -- Prepared 3 memos

Structural Specialist

Geotechnical Specialist

External and Local Peer Reviews

1 2 3 4 5 6 7 8 9

- Request a credible external peer review for the policy memoranda
- Don't wait till the end to get an external review – do it along the way
- Reconvene local peer reviewers
- ***ADOT Example***
  - External Reviewer – Jerry DiMaggio/FHWA

Release / Update Memos

1 — 2 — 3 — 4 — 5 — 6 — 7 — 8 — 9 — 10

- Final discussion between State Bridge Engineer and Geotechnical Engineer
- Release memos
- Update memos as necessary
  - New AASHTO Editions, Comments, Errors, Clarifications, Additional Data, etc.
- Recommended best practice regardless of LRFD or ASD

Example Policy Memorandum

Development of Factored Bearing Resistance Chart by a Geotechnical Engineer for Use by a Bridge Engineer to Size Spread Footings on Soils Based on Service and Strength Limit States.[1]

To: The Materials Group
Arizona Department of Transportation

Date: December 20, 2007

Re: Development of Factored Bearing Resistance Chart by a Geotechnical Engineer for Use by a Bridge Engineer to Size Spread Footings on Soils Based on Service and Strength Limit States.[1]

Section 10.6.2.4.2 of AASHTO (2007) presents two methods for computing immediate settlement of footings. One method is based on elastic theory and the other method is based on an empirical method by Hough. Section C.10.6.2.4.2 of AASHTO (2007) indicates that use of these methods will lead to "generally conservative settlement estimates." With respect to the Hough method, FHWA (2006)[2] noted that it over-predicts the settlement by a factor of 2 or more. The AASHTO method based on elastic theory gives similar results due to the unlimited depth of stress (or strain) influence below the footing. Such conservatism may lead to unnecessary use of costlier deep foundations or costly ground improvement measures for cases where spread footings may be viable. Therefore, ADOT will allow the use of the method presented in FHWA (2006) for computation of immediate settlement of a spread footing.

While this memorandum concentrates on immediate settlements, additional long-term (time-dependent) consolidation type settlements should also be evaluated by the geotechnical engineer, as appropriate, and reported to the bridge engineer, who can then evaluate whether total (immediate + long-term) settlements can be tolerated. The procedures in AASHTO (2007) shall be used for determination of long-term settlements.

Reason for memo, which section of AASHTO is being modified, etc.

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[1] This memorandum is based on AASHTO (2007). The designer should contact ADOT Materials Group for an updated version of this memorandum in the event any interim revisions to AASHTO (2007) are issued or a new edition of AASHTO is issued.

[2] The full citation for FHWA (2006) is included in the References section and a free PDF copy is available from ADOT's Materials Group.

Example Policy Memorandum

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I. FHWA (2006) method

The method recommended in FHWA (2006) for computation of immediate settlements under spread footings is the method ... mmertmann, *et al.* (1978) modified to be consistent with the elastic constants of various soils ... sted in Table C.10.4.6.3-1 of AASHTO (2007). This

FHWA (2006) method

II. **Factored Bearing Resistance Charts**

Recommendations regarding bearing resistance and settlements shall be provided in a chart termed "Factored Bearing Resistance Chart" wherein factored ***net*** bearing resistance is plotted on the ordinate versus ***effective*** footing width on the abscissa for a range of immediate settlements.

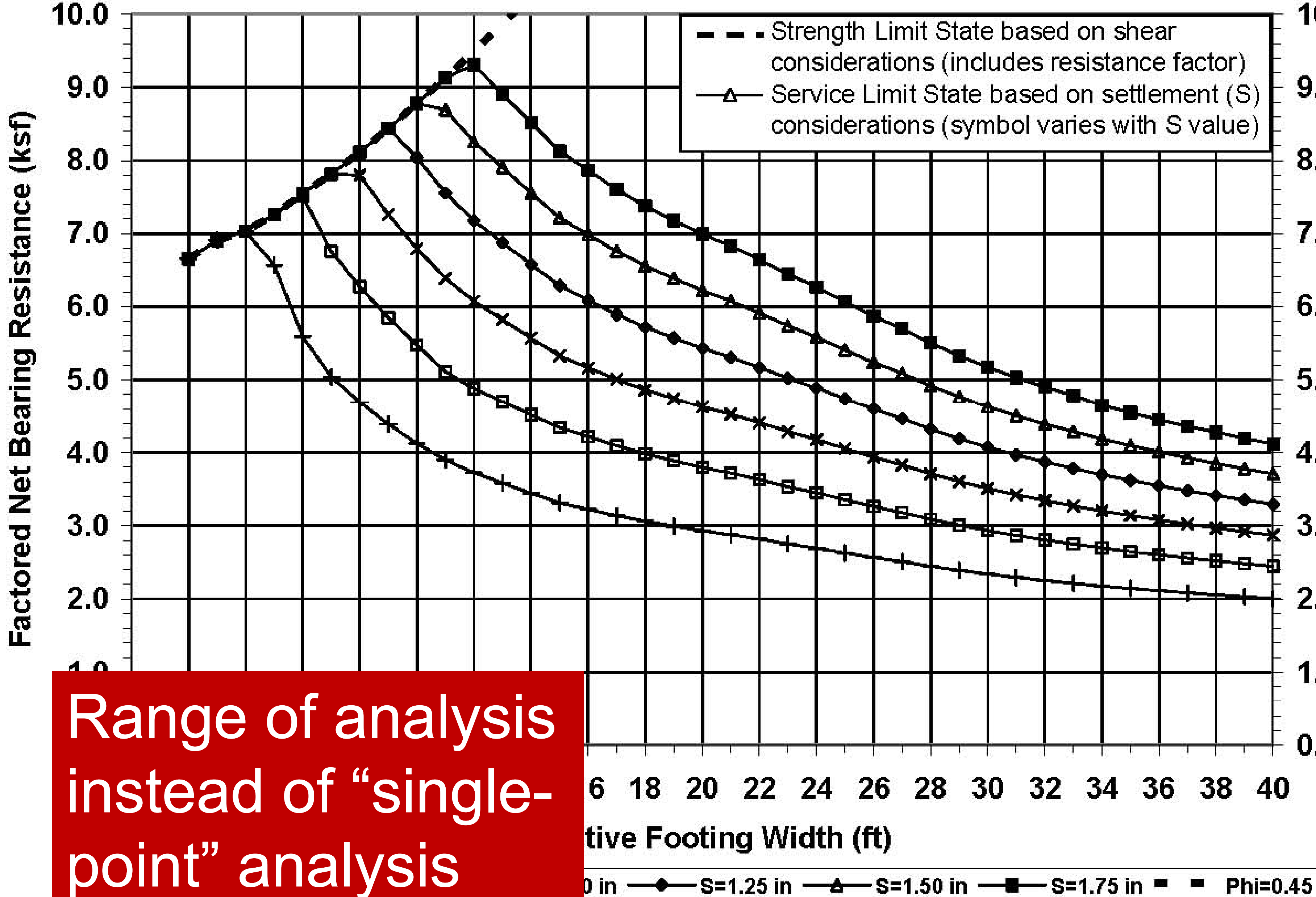
Factored Bearing Resistance Charts

service limit states. Thus, the factored bearing resistance chart permits an evaluation of strength as well as service limit states.

The following should be noted with respect to Figure 1:

- The nominal ***net*** bearing resistance, q_{nn}, is evaluated for the final footing configuration by deducting from nominal bearing resistance, q_n, the overburden stress at the footing base elevation based on the final ground surface elevation above the footing. The nominal bearing resistance, q_n, can be determined by using appropriate equations in Section 10.6.3 of AASHTO (2007). The factored ***net*** bearing resistance, q_{Rn}, is obtained by multiplying the nominal net bearing resistance, q_{nn}, with an appropriate resistance factor, ϕ_b, from Table 10.5.5.2.2-1 of AASHTO (2007). Thus, $q_{Rn} = \phi_b\, q_{nn}$. The steeply rising dashed curve in Figure 1 shows the relationship between the factored net bearing resistance, q_{Rn}, and the effective footing width, B' and is used to evaluate the strength limit state. The effective footing width, B', accounts for load eccentricity as discussed later.

[3] The resistance factor for the service limit state in AASHTO (2007) is 1.0. Therefore, the nominal net bearing resistance at a given settlement value can also be thought of as a factored net bearing resistance at that value of settlement.



Range of analysis instead of "single-point" analysis

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bearing resistance is equal to the nominal bearing resistance and the family of settlement-related curves can be plotted on the same chart as the factored net bearing resistance derived for the strength limit state based on shear considerations. This family of settlement-based curves is used to evaluate the service limit state.

Table 1
Hypothetical Soil Profile and Associated Soil Properties for Project-Specific Conditions

Depth (ft)	Soil Type	Total unit weight, γ_s, (pcf)	N_{60} (-)	Elastic Modulus, E_s, (tsf)
0 – 25	Fine to coarse Sands	120	25	$10N1_{60}$
25 – 75	Gravelly Sands	125	42	$12N1_{60}$
75 – 90	Fine to coarse Sands	120	18	$10N1_{60}$
90 – 130	Gravels	125	49	$12N1_{60}$

Notes:

1. Assume depth 0 to correspond to Elevation 1,000 ft.
2. N_{60} is energy-corrected Standard Penetration Test (SPT) N-value based on Eq. 10.4.6.2.4-2 of AASHTO (2007)

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- In Figure 1, the family of settlement-based curves was generated by using the FHWA (2006) method. For a proper representation of the overburden effects, the subsurface profile in Table 1 was divided into 5-ft layers. In actual designs, one can conceivably use an actual N_{60}-value at each SPT depth with the sampling interval, typically 5 feet, being equal to a layer of soil for analytical purposes. However, in this approach one has to be careful about critically reviewing anomalous SPT "refusal" values due to the effects of larger particle sizes such as gravel and boulders.

- For the factored net bearing resistance, q_{Rn}, on the Y-axis of a bearing resistance chart the equivalent ***net*** uniform (Meyerhof) vertical bearing stress, q_{nveu}, at the base of the footing should be used for the applicable limit state under consideration, e.g., strength limit state, service limit state, etc. The equivalent net uniform vertical bearing stress, q_{nveu}, is computed as follows

  Step 1: Compute the total (factored) equivalent uniform vertical bearing stress, q_{tveu}, as follows:

$$q_{nveu} = q_{tveu} - \gamma_p (\gamma_s D_f)$$

footing, A', is determined as follows:

$A' = B'L' = (B-2e_B)(L-2e_L)$ Eq. (2)

where e_B and e_L are the eccentricities in the B and L directions, respectively, see Section 10.6.1.3 of AASHTO (2007). Eccentricities shall be calculated based on total (factored) vertical loads and total (factored) moments at the base of the footing, i.e., including the effect of the weight of soil and footing above the footing base. As an approximation, the difference in unit weights of reinforced concrete and soil can be neglected within the thickness of the footing slab.

Step 2: Compute the net equivalent uniform vertical bearing stress, q_{nveu}, as follows:

$q_{nveu} = q_{tveu} - \gamma_p (\gamma_s D_f)$ Eq. (3)

where D_f is embedment depth of footing, γ_s is the unit weight of the soil within D_f, and γ_p is the load factor for permanent vertical earth pressure load (designated by the symbol "EV" in AASHTO (2007)) consistent with the limit state used to determine V, e_B and e_L. The load factor for "EV" load can be obtained from Tables 3.4.1-1 and 3.4.1-2 of AASHTO (2007).

Don't be cryptic
Provide discussions
Explain reasons
Include equations as necessary

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- The effective footing width on the X-axis of a bearing resistance chart represents the least lateral ***effective*** dimension of the footing. Thus, once B' and L' are computed as part of Equation (2), the smaller of the two effective dimensions is the effective footing width.

- The FHWA (2006) method defines a footing as continuous (or strip) when L/B (or L'/B') ≥ 10. Footings with 1 < L/B (or L'/B') <10 are categorized as rectangular and those with L/B (or L'/B') = 1 are categorized as square or circular. In order for the factored bearing resistance chart to be based on consistent definitions, the definition of the shape of the footing for the determination of the bearing resistance based on shear considerations for the strength limit state should be the same as that for the settlement method, i.e., the FHWA (2006) method.

- The footing size determined from the chart is a function of the depth of embedment of the footing, D_f and the effective length of the footing, L′. The depth of embedment, D_f is the

Use of Bearing Resistance Charts by Bridge Engineers

actual dimensions of D_f and/or L′ vary by more than ±20% from those noted on the charts then a new chart should be de[...]oped for the actual values of D_f and L′.

- Each factored bearing resistance chart should be specific to a given foundation element and should be developed based on location-specific geotechnical data. Consequently the charts should not be used for foundations at locations other than those at which they are applicable.

III Use of Bearing Resistance Charts by Bridge Engineers

The bearing resistance chart presented in Figure 1 provides the bridge engineer with a powerful tool for studying the interrelationships among effective footing widths, uniform bearing pressures (or resistances) and settlements. A common step-by-step procedure to evaluate the spread footing design is described in Section III.1. For the sake of discussion, assume the terminology listed in Table 2. Table 3 provides values of the various parameters that will be used to illustrate the step-by-step procedure.

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Table 2
Terminology for Parameters Used in Sizing a Spread Footing

Parameter	Limit State*	
	Service I Limit State	Strength I (maximum)
Vertical component of the resultant load	V_{SER}	V_{STR}
Moment	M_{SER}	M_{STR}
Eccentricity	$e_{B\text{-}SER}$ (=M_{SER} / V_{SER})	$e_{B\text{-}STR}$(=M_{STR} / V_{STR})
Equivalent total uniform bearing stress (based on Equation 1)	$q_{tveu\text{-}SER}$	$q_{tveu\text{-}STR}$

Table 3
Example Parameters for an Abutment Footing (L=150-ft)

Parameter	Limit State*	
	Service I Limit State	Strength I (maximum)
Vertical component of the resultant load	V_{SER} = 9,080 kips	V_{STR} = 12,028 kips
Moment	M_{SER} = 22,720 k-ft	M_{STR} = 35,290 k-ft
Eccentricity in the B-direction**	$e_{B\text{-}SER}$ = 2.50-ft	$e_{B\text{-}STR}$ = 2.93-ft

* Only one strength limit state is used herein for illustration purposes. In actual design all applicable strength limit states must be considered.

** The B-direction is the direction of the least lateral dimension of the footing. The eccentricity in the length (L) direction for an abutment footing is commonly negligible and is assumed to be zero for this example case, i.e., L′ = L. For cases where the footing has eccentricity in both directions, the eccentricity in the length (L) direction should also be evaluated. In the case of the eccentricity in both directions, the least lateral dimension is the smaller dimension of the footing after adjustment for the eccentricities.

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III.1 Step-by-Step Procedure for Sizing a Spread Footing at Service and Strength Limit States

1. Assume a total footing width, B_{SER}. Calculate effective footing width $B'_{SER} = B_{SER} - 2e_{B\text{-}SER}$. Calculate $q_{nveu\text{-}SER}$. Enter the cha[rt] with $q_{nveu\text{-}SER}$ and effective footing width, B'_{SER} and determine the settlement, δ_s. Comp[a]re δ_s with for a target tolerable total settlement value, δ_{st}. If necessary iterate the footing widt[h] until $\delta_s \approx \delta_{st}$.

   Example: Assume $\delta_{st} = 0.75$-in[6] ... [Assu]me $B_{SER} = 15$-ft
   Since $e_{B\text{-}SER} = 2.50$-ft, $B'_{SER} = B_{SER} - 2e_{B\text{-}SER} = 15\text{-ft} - 2(2.5\text{-ft}) = 10\text{-ft}$

Step-by-Step Procedure for Sizing a Spread Footing at Service and Strength Limit States

$q_{nveu\text{-}SER} = q_{tveu\text{-}SER} - \gamma_p(\gamma_s D_f) = 6.05\text{ ksf} - 0.72\text{ ksf} = 5.33\text{ ksf}$

Enter Figure 1 with $B'_{SER} = 10$-ft from X-axis and $q_{veu\text{-}SER} = 5.33$ ksf from the Y-axis and find the point of intersection on the chart which represents the estimated settlement for this particular set of B'_{SER} and $q_{veu\text{-}SER}$ values. From Figure 1, the estimated settlement, δ_s. is slightly less than 0.75-in. Since $\delta_s \approx \delta_{st}$ the assumed footing width is correct. Otherwise, repeat the process with another assumed footing width till $\delta_s \approx \delta_{st}$ is achieved.

2. Check if $e_{B\text{-}STR} < B_{SER}/4$. If yes, then denote the total footing width after this step as B_{STR} since it is based on comparison with strength limit state criterion for eccentricity.

   Example: For $B_{SER} = 15$-ft, $B_{SER}/4 = 3.75$-ft
   From Table 3, $e_{B\text{-}STR} = 2.93$-ft.
   Since $e_{B\text{-}STR} < B_{SER}/4$, a footing width of 15-ft is acceptable based on eccentricity consideration.
   Denote the footing width for strength limit state design as $B_{STR} = 15$-ft. This is the footing width that is also used for structural design and detailing.

3. For strength limit state, determine the effective width of the footing $B'_{STR} = B_{STR} - 2e_{B\text{-}STR}$ and $q_{nveu\text{-}STR}$

   Example: For $B_{STR} = 15$-ft and $e_{B\text{-}STR} = 2.93$-ft.
   $B'_{STR} = B_{STR} - 2e_{B\text{-}STR} = 15\text{-ft} - 2(2.93\text{-ft}) = 9.14\text{-ft}$.
   For $L' = 150$-ft and $B'_{STR} = 9.14$-ft, $A'_{STR} = (150\text{-ft})(9.14\text{-ft}) = 1{,}371\text{ ft}^2$

[6] The value of 0.75-in is used for illustration purposes and does not represent a standard or fixed value. In actual design, the value shall be based on the tolerable total settlement determined by the bridge engineer.

Provide information for an actual design

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distribution as per Section 10.6.1.4 of AASHTO (2007) - uniform if no eccentricity, trapezoidal or triangular if there is eccentricity.

III.2 Evaluation of Extreme Event Limit State

Extreme Event Limit State defines criteria for extreme events such as earthquakes, and hurricanes. An extreme event limit state is evaluated at a nominal resistance based on shear considerations. From the factored bearing resistance chart, the nominal resistance values may be derived by dividing the factored bearing resistance values of the steeply rising dashed curve by the value of the resistance factor, ϕ_b, listed in the figure caption. Extreme event limit states often involve other considerations that may affect the selection of spread footings. Such conditions are external to the use of the bearing resistance chart and must be carefully evaluated separately.

IV. Reliability of Settlement Estimates and Estimating Differential Settlements

All analytical methods used for estimating settlements are based on certain assumptions. Therefore, there is an inherent uncertainty associated with the estimated values of settlements regardless of the method used to make the estimate. The uncertainty of the estimated differential settlement between two support elements is larger than the uncertainty of the estimated absolute settlements at the two support elements used to calculate the differential settlement, e.g., between

Reliability of Settlement Estimates and Estimating Differential Settlements

following approach is recommended for the evaluation of differential settlements between adjacent support elements:

- The actual settlement at any support element could be as large as the calculated value of the settlement.
- At the same time, the actual settlement of the adjacent support element could be zero.

Use of the above approach would result in an estimated maximum possible differential settlement equal to the larger of the two total settlements calculated at either end of any span. The angular distortions generated by differential settlements can be evaluated by using the guidance in Section C.10.5.2.2 of AASHTO (2007).

Example Policy Memorandum

Provide guidance for evaluation of deformations

Formula for Success

LRFD

Must Perform Deformation Analysis

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Practical Suggestions for Implementation of LRFD Specifications for Geotechnical Features

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President, NCS Consultants, LLC

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