

LRFD DRIVEN PILE FOUNDATION DESIGN POLICY

North Carolina Department of Transportation
Geotechnical Engineering Unit

Policy Approval
or Update

4th Update

Revision Details

Commentary on Section C3.2.3 PDA and WEAP – Option 2 has been revised. This revision is based on a change in the required number of PDAs (AASHTO Table 10.5.5.2.3-1) in the current AASHTO LRFD Bridge Design Specification, 5th Edition, 2010. See Section for details.

This policy was originally developed by the Geotechnical Engineering Unit (GEU) in collaboration with the Structures Management Unit (SMU).

This policy is maintained by the Geotechnical Engineering Unit. Starting with the 4th update all future revisions will be approved and signed by the State Geotechnical Engineer only.

Approved by:



Njoroge W. Wainaina, P.E.
State Geotechnical Engineer

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History of Policy Approval and Update

Name and Title	Date	Approval or Update
<p>Njoroge W. Wainaina, P.E. State Geotechnical Engineer</p> <p>Greg R Perfetti, P.E. State Bridge Design Engineer</p>	April 17, 2009	Approval
<p>Njoroge W. Wainaina, P.E. State Geotechnical Engineer</p> <p>Greg R Perfetti, P.E. State Bridge Design Engineer</p>	November 23, 2009	1 st Update
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Revision Details

Revision Date	Sections Revised	Comments
11/23/2009	<ul style="list-style-type: none">• Section 5.1.3 Scour Resistance• Section C8.2.2 Required Driving Resistance	See the Sections for details
09/07/2010	<ul style="list-style-type: none">• New Section 7 “End Bent Batter Piles” inserted after Section 6• Sections C2.2.3 Timber Piles and 3.2.3 PDA and WEAP – Option 2	See the Sections for details
05/09/2011	<ul style="list-style-type: none">• New Section 6.3 “Top-Down Construction”	See the Section for details
12/20/2011	<ul style="list-style-type: none">• Section C3.2.3 PDA and WEAP – Option 2	See the Section for details

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Section 0 Definitions

AASHTO LRFD TERMINOLOGY

	DEFINITION
P_n	Nominal compressive resistance, i.e., pile axial structural resistance
P_r	Factored structural resistance based on driving conditions for steel piles and tension or compression-controlled section for concrete piles
R_n	Nominal resistance, i.e., geotechnical resistance
R_r	Factored geotechnical resistance based on drivability analysis

NCDOT TERMINOLOGY

	DEFINITION
Maximum Factored Resistance	R_r reduced for downdrag load, scour resistance and dead load of piles above the design scour elevation
Factored Resistance	Resistance equal to or larger than the maximum factored axial pile load
Required Driving Resistance	Factored resistance plus any additional resistance for downdrag and scour divided by a resistance factor
Point of Fixity	Elevation below which pile is considered fixed
Cored Slab Standard Bridge	Cored slab bridge designed per Structure standard bridge plans

Section 1 Factored Structural Resistance

POLICY

1.0 Factored Structural Resistance

1.1 Pile Axial Structural Resistance

Determine nominal compressive resistance based on AASHTO LRFD Specifications.

1.2 Prestressed Concrete Piles

- Resistance factor = 0.75 for compression-controlled sections
- Resistance factor = 1.00 for tension-controlled sections

1.3 Driving Conditions

Determine factored structural resistance based on driving conditions.

COMMENTARY

C1.0

See Section 0 Definitions for “Factored Structural Resistance”.

C1.1

For steel piles, see AASHTO LRFD 6.9.4.1 for details. For prestressed concrete piles, see AASHTO LRFD 5.7.4.4 and 4.5.3.2.2b for details.

The SMU developed charts to use for a preliminary estimate of pile axial structural resistance. Use the Nominal Compressive Resistance Chart for steel piles and the Interaction Diagrams for prestressed concrete piles. The charts account for buckling and are based on pile type, size and unbraced pile length.

Use Unbraced Length (L) as defined below.

- Pile bents not subject to scour:
 $L = (\text{BOC EL} - \text{GND EL}) + 5 \text{ ft}$
- All bents subject to scour:
 $L = \text{BOC/BOF EL} - \text{Design Scour EL}$

where,

BOC = Bottom of Cap

BOF = Bottom of Footing

GND = Ground

EL = Elevation

C1.2

See AASHTO LRFD 5.5.4.2.1 for details.

These resistance factors are included in SMU’s Interaction Diagrams.

C1.3

See AASHTO LRFD 10.7.3.2.3 for details.

Steel piles driven to rock might be considered a severe driving condition. Consider use of pile points to reduce potential damage during pile driving.

AASHTO LRFD does not specify resistance factors for prestressed concrete piles based on driving conditions.

1.3.1 Steel H Piles

- Resistance factor = 0.6 for good (normal) driving conditions
- Resistance factor = 0.5 for severe driving conditions

1.3.2 Steel Pipe Piles

- Resistance factor = 0.7 for good (normal) driving conditions
- Resistance factor = 0.6 for severe driving conditions

C1.3.1

See AASHTO LRFD 6.5.4.2 for details.

AASHTO LRFD C6.15.2 states that “Due to the nature of pile driving, additional factors must be considered in selection of resistance factors that are not normally accounted for in steel members.” See AASHTO LRFD for more details.

These resistance factors are not included in SMU’s Nominal Compressive Resistance Chart and should be applied to obtain factored structural resistance.

C1.3.2

See AASHTO LRFD 6.5.4.2 for details.

These resistance factors are not included in SMU’s Nominal Compressive Resistance Chart and should be applied to obtain factored structural resistance.

Section 2 Maximum Factored Resistance

POLICY

2.0 Maximum Factored Resistance

2.1 Drivability Analysis

Determine factored geotechnical resistance based on drivability analysis.

2.1.1 Minimum Blow Count (at bearing)

Minimum blow count is defined as 30 BPF.

2.1.2 Maximum Blow Count (at bearing)

Maximum blow count is defined as 180 BPF.

2.1.3 Refusal (during driving)

Refusal blow count is defined as 240 BPF.

2.1.4 Piles Driven to Rock

Piles driven to rock are defined as 5 blows per ¼ inch of movement.

2.2 Pile Driving Stress Limit

2.2.1 Steel Piles

Driving resistance, $\phi_{da} = 1.00$ (AASHTO LRFD 6.5.4.2 and Table 10.5.5.2.3-1)

- In compression and tension: AASHTO LRFD Eq. 10.7.8-1

$\sigma_{dr} = 0.9\phi_{da}f_y = 45$ ksi for 50 ksi steel.

COMMENTARY

C2.0

See Section 0 Definitions for “Maximum Factored Resistance”.

C2.1

Use readily available hammers for drivability analysis and consult with GEU Operations Engineer for available hammers.

See AASHTO LRFD 10.7.8 and Section 2.2 below for details.

C2.1.1

Minimum BPF < 30 indicates that the selected hammer may be too big.

C2.1.2

Maximum BPF > 180 indicates that the selected hammer may be too small.

C2.1.3

In general, with an appropriate (approved) hammer, if blow counts exceed 240 BPF, then pile tip may have reached a very competent layer.

C2.2.1

Steel yield stress, $f_y = 50$ ksi

Based on judgment, stress limit may be lowered to a minimum of $\sigma_{dr} = 0.8 \phi_{da} f_y = 40$ ksi.

2.2.2 Prestressed Concrete Piles

Driving resistance, $\phi_{da} = 0.75$ for compression controlled sections and 1.00 for tension controlled sections (AASHTO LRFD 5.5.4.2.1 and Table 10.5.5.2.3-1)

a) Normal Environments

- In compression: AASHTO LRFD Eq. 10.7.8-4

$$\sigma_{dr} = \phi_{da} (0.85 f'_c - f_{pe})$$

$\sigma_{dr} \leq 3.5$ ksi, recommended value

- In tension: AASHTO LRFD Eq. 10.7.8-5

$$\sigma_{dr} = \phi_{da} (0.095 \sqrt{f'_c} + f_{pe})$$

$\sigma_{dr} \leq 1.0$ ksi, recommended value

b) Severe Corrosive Environments

- In compression: Same as normal environments

- In tension: AASHTO LRFD Eq. 10.7.8-6

$$\sigma_{dr} = \phi_{da} f_{pe}$$

$\sigma_{dr} \leq 0.8$ ksi, recommended value

2.2.3 Timber Piles

Driving resistance, $\phi_{da} = 1.15$ (AASHTO LRFD 8.5.2.2)

- In compression and tension: AASHTO LRFD Eq. 10.7.8-7

$$\sigma_{dr} = \phi_{da} (F_{co})$$

$F_{co} = 0.9 \sim 1.25$ ksi

$\sigma_{dr} = 1.00 \sim 1.40$ ksi, recommended value

2.3 Scour Resistance and Downdrag Load

Determine maximum factored resistance by reducing the factored geotechnical resistance for downdrag load, scour resistance and dead load of piles above design scour elevation.

C2.2.2

In accordance with the SMU standard prestressed concrete pile details,

- $f'_c = 5$ ksi
- strand area = 0.153 in² (0.5 inch diameter)
- strand yield strength = 270 ksi
- applied prestress (before loss) = 270 x 0.75 = 202.5 ksi
- $f_{pe_strand} = 170$ ksi, effective prestressing stress per strand (after loss)
- $f_{pe} = (170 \text{ ksi} \times \text{strand area} \times \text{number of strand} \div \text{concrete area})$, where f_{pe} is effective prestressing stress in concrete

C2.2.3

AASHTO LRFD 2010 –

F_{co} : base resistance of wood in compression parallel to grain as specified in AASHTO LRFD 8.4.1.4

Reference Design Values for Piles (AASHTO LRFD Table 8.4.1.4-1)

Species	F_{co} (ksi)
Pacific Coast Douglas-Fir	1.25
Red Oak	1.10
Red Pine	0.90
Southern Pine	1.20

C2.3

See Section 5.1.1 and 5.1.2 for downdrag and dead load details.

For scour resistance, use static analysis to calculate skin resistance from ground line to design scour elevation. See Section 5.1 for static analysis methods.

Section 3 Resistance Factors

POLICY

COMMENTARY

3.0 Resistance Factors

3.1 Static Analysis

Use AASHTO LRFD Resistance Factors for all piles except steel H piles in the Coastal Plain.

C3.1

See AASHTO LRFD Table 10.5.5.2.3-1 for details.

3.1.1 Exception

Use NCDOT Resistance Factor of 0.7 for steel H piles in the Coastal Plain.

C3.1.1

NCDOT Resistance Factors are based on NCSU localized resistance factors calibration research. This factor applies to all soils and all static analysis methods for H piles in the Coastal Plain. This is an exception to AASHTO LRFD Specifications. See Section 9.0 Reference No. 4 for details.

See Subarticle 1018-2(B), (1) of the Standard Specifications for determining soils in the Coastal Plain. If in doubt, consult project geologic engineer.

3.2 Dynamic Monitoring

Use the same resistance factor for both drivability analysis and pile driving criteria.

C3.2

This is an exception to the AASHTO LRFD Specifications. These resistance factors are higher than the AASHTO LRFD Resistance Factors and were established based on NCDOT's pile driving experience.

3.2.1 WEAP without PDA

Use a resistance factor of 0.60 for hammer approval.

C3.2.1

PDA may be used without meeting AASHTO LRFD requirements in order to monitor stresses and resistance during pile driving.

3.2.2 PDA and WEAP – Option 1

Use a resistance factor of 0.6 for hammer approval with limited quantity of PDAs.

C3.2.2

Minimum number of PDA tests required is two piles per site condition, but no less than 2% of the production piles.

3.2.3 PDA and WEAP – Option 2

Use a resistance factor of 0.75 for hammer approval with required quantity of PDAs.

Section 4 Overburden Pressure and Hammer Efficiency Corrections

POLICY

COMMENTARY

4.0 Overburden Pressure and Hammer Efficiency Corrections

4.1 Overburden Pressure Correction

Correct SPT blow counts for overburden pressure.

C4.1

See AASHTO LRFD 10.4.6.2.4 for details.

Software “Driven” can automatically correct for overburden pressure.

4.2 Hammer Efficiency Correction

Correct SPT blow counts for hammer efficiency.

C4.2

See AASHTO LRFD 10.4.6.2.4 for details.

4.2.1 Hammer Efficiency Correction Exception

Hammer efficiency correction is not required for steel H piles in the Coastal Plain where NCDOT Resistance Factors apply.

C4.2.1

NCSU did not make hammer efficiency corrections for their research.

4.2.2 Default Hammer Efficiency Correction Values

Use hammer efficiency from test results if available; otherwise use 60% for manual hammers and 80% for automatic hammers.

Section 5 Static Analysis

POLICY

5.0 Static Analysis

5.1 Static Analysis

Use AASHTO LRFD methods for static analysis.

5.1.1 Downdrag Load

To account for downdrag, add factored downdrag load to maximum factored axial load for static analysis.

5.1.2 Dead Load

To account for dead load of concrete piles above the design scour elevation, add factored dead load to maximum factored axial load for static analysis.

5.1.3 Scour Resistance

To account for scour, subtract factored scour resistance from nominal resistance calculated for static analysis.

COMMENTARY

C5.1

See AASHTO LRFD 10.7.3.8.6 for details.

Use software program “Driven” with Nordlund/Timlinson method or hand calculations with other AASHTO LRFD methods. When using Driven, select predominant soil type to determine analysis method and appropriate resistance factor.

C5.1.1

See AASHTO LRFD Table 3.4.1-2 for Downdrag factors. See AASHTO LRFD 3.11.8 and 10.7.3.7 for downdrag analysis.

C5.1.2

See AASHTO LRFD Table 3.4.1-2 for Component and Attachments factors.

Typically, dead load for steel piles may be neglected. However, if weight of steel piles is significant, dead load of steel piles above the design scour elevation may be considered.

C5.1.3

For analysis purposes, lower ground line to the contraction scour elevation (CSE) to account for contraction scour reported in the bridge survey report.

- If the CSE is lower than or equal to the design scour elevation (DSE), consider all scour as contraction scour.
- If the CSE is higher than the DSE, consider the difference between the CSE and the DSE as local scour.

When calculating nominal resistance, correct blow counts for overburden pressure by lowering the ground line to the CSE.

5.2 Steel H Pile Resistance Configuration

5.2.1 AASHTO LRFD Resistance Factors

Use box shape for skin resistance and H shape for tip resistance when AASHTO LRFD Resistance Factors are used.

C5.2.1

Consider rectangular perimeter defined by the soil plugged cross-section. Also, see AASHTO LRFD 10.7.3.8.6b for details.

5.2.2 NCDOT Resistance Factors

Use H shape for both skin and tip resistance when NCDOT Resistance Factors are used. This applies to steel H piles used in the Coastal Plain.

C5.2.2

Consider the unplugged cross-section. Also, see Section 3.1.1.

Section 6 Pile Bents

POLICY

COMMENTARY

6.0 Pile Bents

6.1 Lateral Deflection & Pile Stresses

The SMU will check bent deflections and structural adequacy of piles.

6.2 Point of Fixity (POF)

This is a strength limit analysis. Use factored loads for POF analyses.

C6.2

Other methods such as cantilever beam may be used to supplement L-Pile in determining POF.

6.2.1 Preliminary POF

For preliminary POF analysis, use the maximum factored resistance and a shear load of 3 kips per pile (no moment). Also, use the following lateral deflection limits for a single pile with a free head condition for selecting pile type and size.

- Steel Piles 6"
- Prestressed Concrete Piles 3"

Point of fixity should be selected from between where the deflection curve first intercepts the "point of the first zero deflection" and the "maximum negative deflection point."

6.2.2 Iteration Limit for POF Analysis

Terminate POF analysis if either one of the following conditions are met.

- new POF is less than 3 ft higher than the previous POF, or
- new POF is less than 2 ft below the previous POF.

Otherwise, provide the SMU the new POF and continue the iteration process or change the pile design.

6.3 Point of Fixity (POF)

Refer to the Structure Design Manual – Sections 6.4.2 or 6.5.2 for span length limits for top-down construction. For projects where pile driving operations may establish the size of the crane used, develop a preliminary estimate of the pile driving hammer energy range required to construct the foundation. When the estimated energy range is greater than 40 ft.-kips or other factors that may influence the required crane size are present, coordinate with the Structure Design Unit to assess whether the proposed span lengths are attainable.

C6.3

Structure Design Manual – Section 6.1.2 does not recommend use of cored slab or box beams superstructures for bridges with more than 4 spans. The attainable span lengths may be reduced by the size of the crane required to construct the foundation. Factors that influence the size of the crane include pile type (e.g. prestressed concrete piles), design pile tonnages (maximum factored load) in excess of 130 tons, and pile driving equipment with high energy ranges (≥ 40 foot-kips).

Section 7 End Bent Batter Piles

POLICY

7.0 End Bent Batter Piles

7.1 General

Batter piles are required if vertical piles will not provide sufficient lateral earth pressure resistance or overturning resistance at end bents. This situation may occur when there is not sufficient pile embedment.

7.2 Batter Piles Design Guidelines

- Design a minimum of two battered piles for pile embedment depth equal or less than 15 feet for all bridges except Cored Slab Standard Bridges.
- No battered piles for Cored Slab Standard Bridges.

COMMENTARY

C7.1

Active lateral earth pressure developed from the bottom of the end bent cap to the finished grade (except for integral abutments) shall be resisted by piles to prevent the transfer of excessive lateral earth pressure applied to the bridge superstructures.

Section 8 Seismic Design

POLICY

8.0 Seismic Design

8.1 General

The SMU will use a map showing general seismic zones in NC to determine whether or not a bridge will be designed for seismic loads. This will be reflected in SMU's Request for Foundation Recommendations. For seismic design, the SMU may request bridge site classification per definition in AASHTO LRFD 3.10.3.

8.2 Site Effects

The SMU will characterize the seismic hazard in accordance with AASHTO LRFD 3.10.2.

COMMENTARY

C8.1

A map showing general seismic zones in NC is available in the SMU Design Manual.

C8.2

See AASHTO LRFD 3.10.3 for details.

GEU provided the SMU with the following general site classes (see below) for development of the North Carolina seismic zone map.

- Counties with Site Class C or better are: Stanley, Union, Anson, southern part of Montgomery, Mecklenburg, Cabarrus, Divisions 9 and 11-14.
- Counties with Site Class D are: Richmond, Scotland, Robeson, Columbus, Pender, Brunswick, New Hanover, southern parts of Moore & Hoke and western part of Bladen.

If a bridge will be designed for seismic loads, determine whether the assumed site class applies to the site based on subsurface information (borings). If assumed site class is not applicable, GEU will provide the SMU with site class for the site when requesting structure information.

Section 9 Foundation Recommendations

POLICY

COMMENTARY

9.0 Foundation Recommendations

9.1 Preliminary Foundation Recommendations

Determine if PDA will be used for the project. If PDA will be used, determine appropriate resistance factor based on the purpose of the PDA.

GEU will provide the SMU with the following:

- Proposed pile type, size and Maximum Factored Resistance.
- Preliminary POF for interior bents.

C9.1

See Section 3.2 for details.

See Section 0 Definitions for “Maximum Factored Resistance”. Use standard form to request structure information. The SMU will provide controlling factored loads, pile configurations (number of piles and spacing) and bottom of cap elevations for each bent.

9.2 Final Foundation Recommendations

9.2.1 Factored Resistance

Provide proposed pile type, size and Factored Resistance. Provide factored resistance equal to maximum factored axial load rounded up to the nearest 5 tons.

C9.2.1

See Section 0 Definitions for “Factored Resistance”.

9.2.2 Required Driving Resistance

Provide a standard foundation note on plans with Required Driving Resistance.

C9.2.2

Required Driving Resistance =
(Factored Resistance + Factored Downdrag Load + Factored Scour Resistance + Factored Dead Load) / Resistance Factor

Factored Dead Load is defined as factored pile dead load above ground line.

9.2.3 Estimated Pile Lengths

Estimate pile lengths based on static analysis and minimum pile penetration (tip no higher than elevation).

C9.2.3

See AASHTO LRFD 10.7.3.3 and 10.7.6 for details.

9.2.4 Point of Fixity

For pile bent, provide final POF elevation.

9.2.5 Hammer Energy

If it is determined that a Delmag D19-32 (or D19-42) or an equivalent hammer is not sufficient to drive piles to the Required Driving Resistance, include a standard foundation note on plans with the “Estimated Hammer Energy Range”.

9.2.6 Scour Critical Elevation (SCE)

1. Use 500 year hydraulics scour elevation, if available, as SCE.
2. Otherwise, use 2 ~ 3 ft below design scour elevation as SCE.
3. In all cases, at least 5 ft embedment is required below SCE.

Section 10 References

1. *AASHTO LRFD Bridge Design Specifications*, 5th (2010) Edition and Errata.
2. *Design and Construction of Driven Pile Foundations*, FHWA-NHI-05-042, April 2006.
3. *LRFD for Highway Bridge Substructures and Earth Retaining Structures*, FHWA-NHI-05-094, January 2006, January 2007 Revision.
4. *Load and Resistance Factor Design (LRFD) for Analysis/Design of Piles Axial Capacity*, Rahman, M.S., M.A. Gabr, R.Z. Sarica and M.S. Hossain, NCSU Research Report No. FHWA/NC/2005-8, July 2002
5. *Standard Specifications for Roads and Structures*, North Carolina Department of Transportation, July 2006.