LRFD Drilled Pier Axial Resistance Spreadsheet

User Manual

Created and Maintained by

North Carolina Department of Transportation

Geotechnical Engineering Unit

For Version W7EX2013_1.7

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Summary of Drilled Pier Spreadsheet Features that are interpreted or outside AASHTO

1. Required Factored Resistance
   This term is not defined by AASHTO. The required factored resistance is equal to the maximum factored load plus the factored weight of the column and pier minus the factored weight of the water and soil/rock removed. The required factored resistance should not be less than the maximum factored load provided by Structure Design.

2. Weathered Rock
   a. The nominal unit side resistance for weathered rock is set at 8 ksf.
   b. 0.6 is the side resistance factor for weathered rock. This is the side resistance factor AASHTO designates for IGM.
   c. These two interpretations result in a factored unit side resistance of 4.8 ksf for weathered rock.
   d. Tip resistance for weathered rock is calculated using the AASHTO equation 10.8.3.5.1c-1 which is the equation AASHTO designates for tip resistance in cohesive material.
   e. The undrained shear strength, (S_U), for weathered rock is calculated using an approach by Mayne and Harris that was developed for piedmont residual soils.
   f. 0.55 is the tip resistance factor for weathered rock. This is the tip resistance factor AASHTO designates for IGM.
   g. Load transfer in weathered rock is not defined by AASHTO. AASHTO Figures 10.8.2.2.2.1 and 2 are used in the spreadsheet and the curves AASHTO recommends for cohesive material.

3. Hard Rock
   a. Hard rock layers that have a GSI < 30 are modeled as weathered rock with an N_{60} value of 600 blows/ft.
   b. Drilled piers socketed in hard rock are designed based on side resistance only or tip resistance only. Future updates to the spreadsheet may include a displacement based analysis that allows a combination of both.
   c. Drilled piers are considered to have a rock socket if either the pier is embedded the greater of 3 feet or 1 pier diameter into hard rock or at least 50% of the total nominal side resistance is attributed to the hard rock layer(s).
   d. For a drilled pier tipped in hard rock with no rock socket, the side resistance from hard rock is ignored and nominal side resistance is based on the soil and weathered rock layers.
   e. For load transfer of a drilled pier tipped in hard rock with no rock socket, the total pier displacement is controlled by the rock layer below the base of the pier. The total pier displacement is calculated using FHWA GEC 10 Equation D-17 and assumes the entire load is carried by the tip. The AASHTO normalized load transfer curves along with the total factored side resistance are used to calculate the factored side resistance developed in the soil and weathered rock layers at this displacement.

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Section 1 – Program Inputs

1.1 – Elevations

***Bottom of Cap (BOC) Elevation* –** The bottom of cap elevation for the drilled pier.

***Top of Pier / Bottom of Column Elevation* –** The top of the drilled pier elevation, which is also the elevation of the bottom of the column. If there is no column (the drilled pier goes all the way to the BOC), the top of drilled pier elevation will equal the bottom of cap elevation.

***Natural Ground / Finished Grade Elevation* –** For stream crossings, this will be the natural ground elevation before scour. For grade separations, this will be the finished grade elevation.

***Groundwater Table (GWT) Elevation* –** The elevation of the ground water table or water surface.

***Design Scour (DSE) Elevation* –** The geotechnically adjusted scour elevation. If there is no scour, the design scour elevation will be equal to the natural ground or finished grade elevation.

***Amount of Contraction Scour (from BSR)* –** The amount of contraction scour that is reported on the BSR. If there is no contraction scour reported on the BSR or if the structure is for a grade separation, enter 0.

***Bottom of Permanent Casing Elevation* –** When permanent casing is or maybe required, this will be the elevation that the casing may not extend below. Side resistance will not be calculated for material above this elevation.

***Drilled Pier Tip Elevation* –** The elevation of the drilled pier tip.

1.2 – Drilled Pier Information

***Maximum Factored Axial Load (P_r)* –** The maximum factored axial load at the top of the column.

***Number of Drilled Piers per Bent* –** The total number of drilled piers at the bent location.

***Diameter of Column (d_{Column})* –** The diameter of the column. If the shaft is carried all the way to the bottom of cap, the column diameter will be zero.

***Diameter of Drilled Pier (d_{DP})* –** The diameter of the drilled pier.

***Unit Weight of Concrete (γ_c)* –** The unit weight of concrete. (Commonly accepted as 0.150 kcf)

***Compressive Strength of Concrete (f'_c)* –** The compressive strength of concrete. The minimum compressive strength for drilled pier concrete is 4,500 psi (4.5 ksi) per Section 1000 of the Standard Specifications.

1.3 – Subsurface Information and Soil/Rock Properties

***Subsurface Boring Name / ID No.* –** The name or ID number for the subsurface boring that is being used for the axial resistance calculations.

SPT Hammer Efficiency Rating (ER) – The hammer efficiency expressed as percent of theoretical free fall energy delivered by the hammer system actually used. This value should be listed on each subsurface bore log. If ER is not known, use 80% for automatic hammers and 60% for drop hammers.

Top of Boring (Collar) Elevation – The ground elevation for the subsurface boring. This elevation is used to calculate the overburden pressure for $N1_{60}$ values. This elevation is needed only when the user has selected the option to calculate $N1_{60}$ values internally.

Depth to Groundwater Table (for actual boring) - The depth of the groundwater table for the subsurface boring. This elevation is used to calculate the overburden pressure for $N1_{60}$ values. This elevation is needed only when the user has selected the option to calculate $N1_{60}$ values internally.

Layer No. – The number associated with the soil layer. The maximum number of soil layers that can be entered above the drilled pier tip is 8.

Material Description – The material that best describes the soil or rock layer.

Layer Elevations; Top – The top of the soil layer. The top of the first soil layer will correspond to the lowest elevation between design scour elevation, bottom of permanent casing elevation, natural ground elevation, or the bottom of column elevation.

Layer Elevations; Bottom – The bottom of the soil layer.

Total Unit Weight (γ) – The total unit weight of the soil or rock layer. The spreadsheet will automatically calculate effective unit weights based on the groundwater table.

N – The uncorrected SPT value for soil or weathered rock layers.

***N_{60}* –** The SPT value for soil or weathered rock layers corrected for hammer efficiency. This value is calculated internally by the spreadsheet.

***$N1_{60}$* -** The SPT value for soil or weathered rock layers corrected for hammer efficiency and overburden pressure. Depending on the option selected by the user, this value is either input manually or is calculated internally by the spreadsheet.

RQD – The Rock Quality Designation for hard rock layers.

GSI – The Global Strength Index for hard rock layers. Depending on the option selected by the user, this value can either be entered manually or can be calculated internally by the spreadsheet. The internal calculation uses a correlation with RQD developed by Truzman (2007) and is based on more than 1,000 surveys in different tunnel excavations.

$$GSI = 18.7e^{0.0152(RQD)}$$

***q_u* –** The Unconfined Compressive Strength for hard rock layers. q_u values should be based on AASHTO Table 10.4.6.4-1 (which uses Point Load Index Testing), actual values from Uniaxial Compressive Strength Testing, or values obtained from the NCDOT Rock Core Database.

***E_i* –** The Elastic Modulus for Intact Rock. Only applies to when the drilled pier tip is in hard rock. E_i values should be based on AASHTO Table C10.4.6.5-1 or the NCDOT Rock Core Database if lab test data is not available.

***ν* –** The Poisson's Ratio for Intact Rock. Only applies when the drilled pier tip is in hard rock. Poisson's Ratio values should be based on AASHTO Table C10.4.6.5-2 if lab test data is not available.

Section 2 – Side Resistance

Calculations for axial side resistance follow the methods listed in the AASHTO LRFD Bridge Design Specifications, 7th Edition, 2014, unless otherwise indicated. All equations and related variables are defined within the spreadsheet.

2.1 – Classification of Materials for Side Resistance Calculations

The rock and soil layers entered are separated for side resistance calculations using the following definitions.

***Cohesive Soil* –** cohesive material with an undrained shear strength (S_u) ≤ 5 ksf ($N1_{60} \leq 50$ blows/ft)

***Cohesionless Soil* –** cohesionless material with $N1_{60} \leq 100$ blows/ft

***Cohesive IGM* –** cohesive material with an undrained shear strength (S_u) between 5 and 10 ksf (50 blows/ft < $N1_{60} \leq 100$ blows/ft)

***Weathered Rock* –** material identified as weathered rock with an $N1_{60}$ value between 100 and 600 blows/ft (0.1 ft in 60 blows)

***Hard Rock* –** material identified as rock that reaches SPT refusal (0.1 ft / 60 blows)

2.2 - Side Resistance Calculations for Cohesive Soil

Side resistance calculations for cohesive soils are based on AASHTO (2014) 7th Edition, Section 10.8.3.5.1b with the following exception.

2.3 - Side Resistance Calculations for Cohesionless Soil

Side resistance calculations for cohesive soils are based on AASHTO (2014) 7th Edition, Section 10.8.3.5.2b.

2.4 - Side Resistance Calculations for Cohesive IGM

Side resistance calculations for cohesive IGM are not described in detail in AASHTO (2014) 7th Edition. AASHTO Section C10.8.2.2.3 references the FHWA Drilled Shaft Manual, FHWA GEC 010, Chapter 13 for details on IGM.

2.5 - Side Resistance Calculations for Weathered Rock

Weathered Rock is an NCDOT material description and is not defined in AASHTO. A unit side resistance of 8 ksf has been assigned to weathered rock for side resistance calculations. This value is based on available load test data.

2.6 - Side Resistance Calculations for Hard Rock

Side resistance calculations for hard rock are based on AASHTO (2014) 7th Edition, Section 10.8.3.5.4b.

Section 3 – Tip Resistance

3.1 – Classification of Materials for Tip Resistance Calculations

The rock and soil layers entered are separated for tip resistance calculations using the following definitions.

Cohesive Material **–** cohesive soil or cohesive IGM

Cohesionless Material **–** cohesionless soil

Weathered Rock **–** material identified as weathered rock where SPT-N does not reach 0.1 ft / 60 blows or hard rock that has a GSI < 30.

Hard Rock **–** material identified as rock that reaches SPT refusal (0.1 ft / 60 blows) and has a GSI ≥ 30.

3.2 - Tip Resistance Calculations for Cohesive Material

Tip resistance calculations for cohesive materials are based on AASHTO (2014) 7th Edition, Section 10.8.3.5.1c.

3.3 - Tip Resistance Calculations for Cohesionless Material

Tip resistance calculations for cohesionless materials are based on AASHTO (2014) 7th Edition, Section 10.8.3.5.2c.

3.4 - Tip Resistance Calculations for Weathered Rock

Tip resistance for drilled piers in weathered rock is based on AASHTO equation 10.8.3.5.1c-1 which is also used to calculate unit tip resistance for drilled piers in cohesive material. The equation is shown below.

$q_p = N_c(S_u)$, where $N_c = 9$ for weathered rock

The undrained shear strength, (S_u), for weathered rock is calculated using an approach by Mayne and Harris that was developed for piedmont residual soils. This method is shown below.

1. Calculate preconsolidation stress;

   $\sigma_p' = 0.47(N_{60})^m \rho_a$ *AASHTO Equation 10.8.3.5.2b-4*

2. Calculate vertical effective stress at the base of the drilled pier.

3. Calculate over-consolidation ratio;

   $OCR = \sigma_p'/\sigma_{vo}'$

4. Calculate normalized strength ratio corresponding to simple shear loading ;

   $(Su/\sigma_{vo}')_{DSS} = 0.23\ OCR^{0.8}$ *Jamiolkowski, et al., 1985*

5. Calculate S_u;

   $S_u = (0.23\ OCR^{0.8})\ (\sigma_{vo}')$

3.5 - Tip Resistance Calculations for Hard Rock

Tip resistance calculations for hard rock are based on AASHTO (2014) 7^{th} Edition, Section 10.8.3.5.4c. Hard rock layers that have a GSI < 30 will be modeled as weathered rock with an N value of 600 blows/ft (0.1 ft / 60 blows).

Section 4 – Total Factored Resistance

4.1 – Total Factored Side Resistance

The total factored side resistance is equal to the nominal side resistance for each material type multiplied by the resistance factor for that material. Resistance factors are taken from AASHTO Table 10.5.5.2.4-1.

When drilled piers are socketed in hard rock, the side resistance above the hard rock will be ignored.

For the purpose of this spreadsheet, a drilled pier will be considered socketed in hard rock if either of these conditions are met;

1. The pier is embedded at least 3 ft or 1 pier diameter into hard rock.
2. At least 50% of the total nominal side resistance is produced by the hard rock layer(s).

If the pier does not have a true rock socket, the side resistance from the hard rock will be ignored and side resistance will be based on the total side resistance in soil and weathered rock.

4.2 – Total Factored Tip Resistance

The total factored tip resistance is equal to the nominal tip resistance multiplied by the appropriate tip resistance factor. Tip Resistance factors are taken from AASHTO Table 10.5.5.2.4-1.

4.3 – Reduction of Resistance Factors due to lack of Redundancy

When only using one (1) drilled pier at a bent location, the resistance factors provided in Table 10.5.5.2.4-1 should be reduced by 20 percent. See ASSHTO Section 10.5.5.2.4 for more details.

Section 5 – Required Factored Resistance

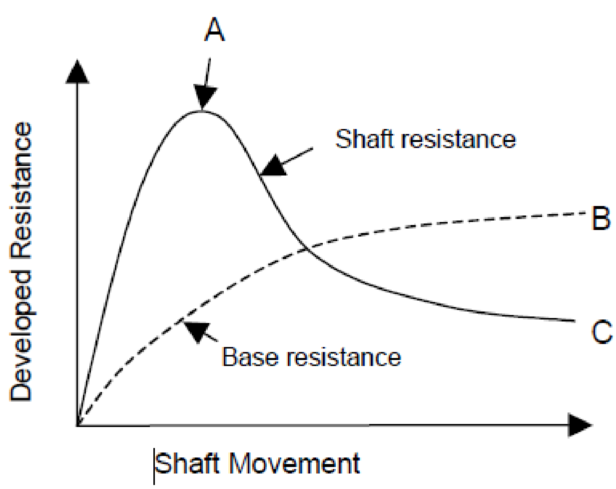
The required factored resistance as defined by the NCDOT Geotechnical engineering Unit using the following equation;

$$R_{req} = P_r + \gamma_{DC}(W_{Column} + W_{Pier}) - \gamma_{WA}W_{Water} - \gamma_{DC}W_{Soil/Rock} \geq P_r$$

Where: R_{req} = Required Factored Resistance
P_r = Maximum Factored Axial Load
γ_{DC} = Factor for Permanent Dead Loads
γ_{WA} = Factor for Water Loads
W_{Column} = Unfactored Weight of Column
W_{Pier} = Unfactored Weight of Drilled Pier
W_{WA} = Unfactored Weight of Water Displaced
$W_{Soil/Rock}$ = Unfactored Weight of Soil / Rock that will be Displaced

Section 6 – Load Transfer of Side and Tip Resistance

The maximum nominal side resistance and maximum nominal tip resistance do not occur at the same vertical displacement (settlement).



6.1 – Load Transfer for Soil

The normalized load-settlement curves shown in Figures 10.8.2.2.2-1 through 10.8.2.2.2-4 should be used to limit the nominal drilled pier axial resistance for drilled piers in soil.

The curves in Figures 10.8.2.2.2-1 and 10.8.2.2.2-3 show the settlements at which the side resistance is mobilized. The drilled pier skin friction R_s is typically fully mobilized at displacements of 0.2 percent to 0.8 percent of the drilled pier diameter for drilled piers in cohesive soils. For drilled piers in cohesionless soils, this value is 0.1 percent to 1.0 percent.

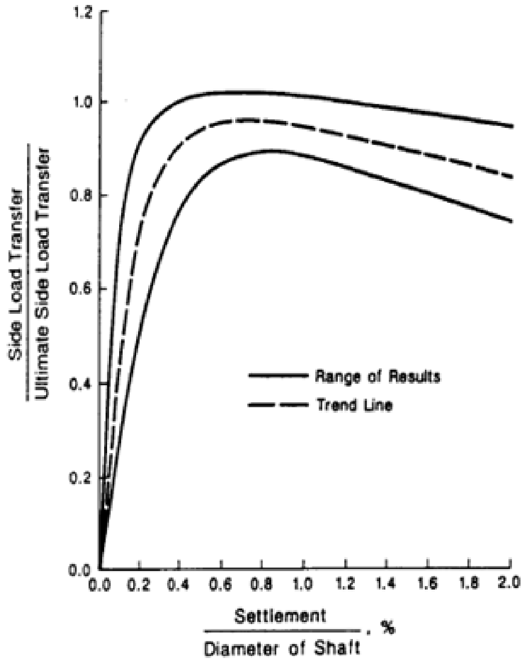


Figure 10.8.2.2.2-1 Normalized Load Transfer in Side Resistance versus Settlement in Cohesive Soils (from O'Neill and Reese, 1999)

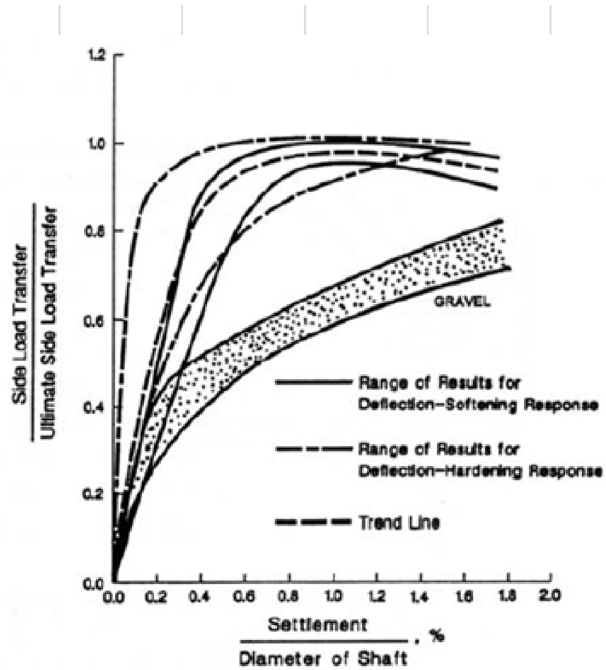


Figure 10.8.2.2.2-3—Normalized Load Transfer in Side Resistance versus Settlement in Cohesionless Soils (from O'Neill and Reese, 1999)

The drilled pier end bearing R_p is typically fully mobilized at displacements of two to five percent of the base diameter for drilled piers in cohesive soils. The resistance of drilled piers in cohesionless soils continues to increase as the settlement increases beyond five percent of the base diameter. The unit end bearing resistance for the strength limit state (see Article 10.8.3.3) is defined as the bearing pressure required to cause vertical deformation equal to five percent of the drilled pier diameter, even though this does not correspond to complete failure of the soil beneath the base of the drilled pier.

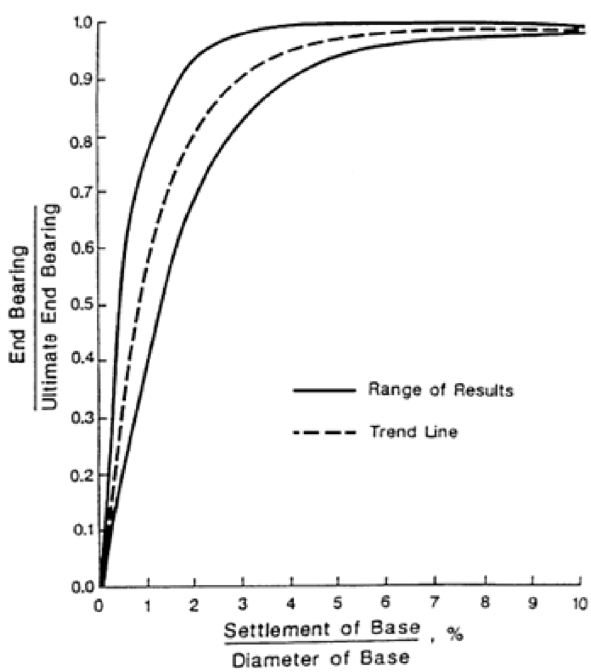


Figure 10.8.2.2.2-2—Normalized Load Transfer in End Bearing versus Settlement in Cohesive Soils (from O'Neill and Reese, 1999)

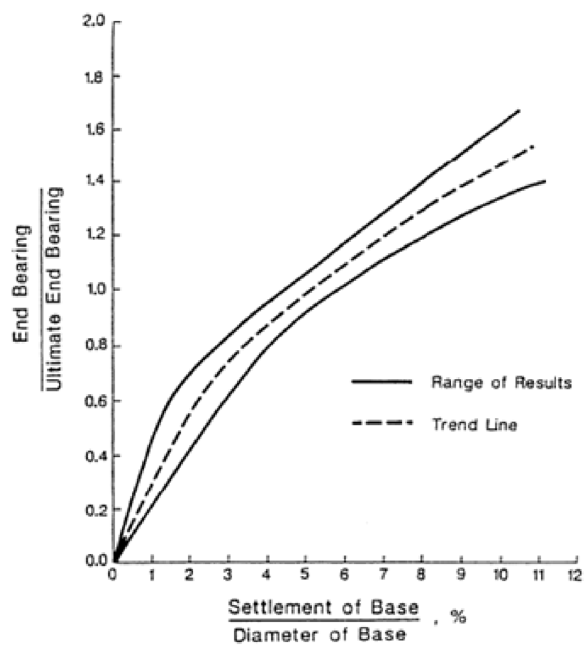


Figure 10.8.2.2.2-4—Normalized Load Transfer in End Bearing versus Settlement in Cohesionless Soils (from O'Neill and Reese, 1999)

6.2 – Load Transfer for IGM

AASHTO does not specify load transfer curves for cohesive IGM. Use the AASHTO Figures 10.8.2.2.2-1 through 4 to limit the nominal shaft axial resistance for drilled piers in IGM.

6.3 – Load Transfer for Weathered Rock

AASHTO does not specify load transfer curves for weathered rock.

When the majority of the shaft resistance is produced by weathered rock, treat it as a cohesive material and use AASHTO Figure 10.8.2.2.2-1.

When the drilled pier tip resistance is produced by weathered rock, treat it as a cohesive material and use AASHTO Figure 10.8.2.2.2-2.

6.4 – Load Transfer for Hard Rock without Rock Socket

When the drilled pier tip resistance is produced by hard rock but the side resistance is produced by soil and/or weathered rock, use AASHTO Figures 10.8.2.2.2-1 and 2.

6.5 – Load Transfer for Hard Rock with a Rock Socket

Typically, the axial compression load on a drilled pier socketed into rock is carried solely in side resistance until a total movement on the order of 0.4 inches occurs. Where combined side friction and end-bearing in rock is considered, the designer needs to evaluate whether a significant reduction in side resistance will occur after the peak side resistance is mobilized. When the rock is brittle in shear, much drilled pier resistance will be lost as vertical movement increases to the value required to develop the full value of q_p. If the rock is ductile in shear, then the side resistance and end-bearing resistance can be added together directly.

Section 7 – Developed Factored Resistance

Per NCDOT policy, the developed factored resistance, (R_{rd}), must be greater than or equal to the required factored resistance, (R_{req}).

7.1 – Drilled Piers Not Socketed in Hard Rock

For piers that are not socketed in hard rock, the total displacement of the pier will be controlled by the rock layer below the base of the pier. The total displacement, (w_c), will be calculated using FHWA GEC 10 Equation D-17 and assumes the entire load is carried by the tip. The normalized load transfer values along with the total factored side resistance will be used to calculate the factored side resistance developed in the soil and weathered rock layers at this displacement. The remaining factored resistance that will be carried by the drilled pier tip must be less than or equal to the total factored tip resistance.

7.2 – Drilled Piers Socketed in Hard Rock

For piers that are socketed in hard rock, the developed factored resistance will be based on one of the following conditions;

1. The factored side resistance of the rock socket
2. The factored tip resistance of the rock socket
3. A combination of factored side resistance and factored tip resistance.

Using a combination of side and tip resistance requires a displacement based analysis and falls outside the limitations of the current spreadsheet. If the engineer wishes to use a combination of side and tip resistance, use methods described in FHWA (2010) to compute the developed factored resistance.

Section 8 – Required Tip Resistance

The required tip resistance, (q_{req}), is the bearing pressure that must be verified in the field during construction.

Section 9 – References

AASHTO. 2014. *AASHTO LRFD Bridge Design Specifications, Customary U.S. Units, 7th Edition.* AASHTO, Washington, DC.

Brown, D.A., J.P. Turner, and R. J. Castelli, *2010 Drilled Shafts: Construction Procedures and LRFD Design Methods – Geotechnical Engineering Circular No. 10*, FHWA NHI-10-016. National Highway Institute, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C.

Mayne, P. W., 1993, "Axial-Load Displacement Behavior of Drilled Shaft Foundations in Piedmont Residuum," FHWA Reference No. 41-30-2125.