Chapter 17

FOUNDATIONS

NDOT STRUCTURES MANUAL

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Chapter 17
FOUNDATIONS

A critical consideration for the satisfactory performance of any structure is the proper selection and design of a foundation that will provide adequate support and addresses constructibility considerations. This Chapter discusses NDOT-specific criteria that are supplementary to Section 10 of the *LRFD Specifications* for the design of spread footings, driven piles and drilled shafts. Section 11.7 presents NDOT criteria for the selection of an appropriate foundation type within the context of structure-type selection.

17.1 GENERAL

17.1.1 Chapter Scope

Chapter 17 has been prepared primarily for use by the bridge designer and as a reference for the geotechnical engineer and hydraulics engineer. The *NDOT Geotechnical Policies and Procedures Manual*, which is the responsibility of the Geotechnical Section, discusses the geotechnical considerations for the design of bridge foundations. The *NDOT Drainage Manual*, which is the responsibility of the Hydraulics Section, discusses the evaluation of hydraulic scour for bridge foundations.

17.1.2 Design Methodology

This Chapter is based upon the load and resistance factor design (LRFD) methodology. The following summarizes the concepts in the *LRFD Specifications* for the design of foundations.

Considering basic design principles for foundations, the *LRFD Bridge Design Specifications* implemented a major change when compared to the traditional principles of the *Standard Specifications for Highway Bridges*. The *LRFD Specifications* distinguishes between the strength of the in-situ materials (soils and rock strata) supporting the bridge and the strength of the structural components transmitting force effects to these materials. The distinction is emphasized by addressing in-situ materials in Section 10 “Foundations” and structural components in Section 11 “Abutments, Piers and Walls,” which is necessitated by the substantial difference in the reliability of in-situ materials and man-made structures. The foundation provisions of the *LRFD Specifications* are essentially strength design provisions with a primary objective to ensure equal, or close to equal, safety levels in all similar components against structural failure.

Sections 5 and 6 of the *LRFD Specifications* specify requirements for concrete and steel components. The appropriate provisions from these Sections are applied in the structural design of footings, steel and concrete piles and drilled shafts.

The target safety levels for each type of foundation are selected to achieve a level of safety comparable to that inherent in those foundations designed with the *Standard Specifications*. This approach differs from that for superstructures, where a common safety level has been selected for all superstructure types.

Historically, the primary cause of bridge collapse has been the scouring of in-situ materials. Accordingly, the *LRFD Specifications* introduced a variety of strict provisions for scour protection, which may result in deeper foundations.

17.1.3 Bridge Foundation Design Process

The selection of a foundation type involves an evaluation of the load/structural considerations for the superstructure and substructure, the geotechnical factors pertaining to the native soils, and site conditions. The following summarizes the NDOT procedure for selecting and designing a bridge foundation type:

1. Preliminary Structure Layout. The bridge designer obtains preliminary soils information from the Geotechnical Section to assist with the selection of support locations and span lengths. Preliminary foundation loads are calculated and provided to the Geotechnical Section.

2. Scour Potential. For bridges over waterways, the Hydraulics Section evaluates the proposed bridge site and preliminary structure layout to identify the predicted hydraulic scour based on material properties provided by the Geotechnical Section. This analysis is provided to both the Structures Division and the Geotechnical Section.

   As part of the specific subsurface site investigation, the Geotechnical Section will provide a geologic or historic elevation for scour. The Hydraulics Section will calculate an anticipated hydraulic scour depth. The bridge designer in conjunction with the Geotechnical Section and Hydraulics Section will determine a "design" scour for the design of the foundation.

3. Geotechnical Data. For all sites, the Geotechnical Section conducts a site-specific subsurface investigation and prepares a Geotechnical Report. The Geotechnical Section provides this Report to the Structures Division.

4. Foundation Type Selection. Based on information provided by the bridge designer (e.g., structure layout, vertical and lateral loads, settlement criteria), the Geotechnical Section provides the foundation-type recommendation to the Structures Division in the Geotechnical Report. In the absence of mitigating circumstances, including the evaluation of the estimated construction costs, the Structures Division typically accepts this foundation-type recommendation. Environmental considerations may not allow the use of driven piles.

5. Detailed Structural Design. The bridge designer performs the detailed structural design of the foundation based on Section 10 of the *LRFD Bridge Design Specifications* as modified by Chapter 17 of the *NDOT Structures Manual* in conjunction with the structural requirements of Sections 5 and 6 of the *LRFD Specifications.*

17.1.4 Bridge Design/Geotechnical Design Interaction

17.1.4.1 Overview

Prior to the design of the foundation, the bridge designer must have knowledge of the environmental, climatic and loading conditions expected during the life of the proposed unit. The primary function of the foundation is to spread concentrated loads over a sufficient zone, to provide adequate bearing resistance and limitation of movement and, when necessary, to transfer loads through unsuitable foundation strata to suitable strata. Therefore, knowledge of the subsurface soil conditions, ground water conditions and scour is necessary.

The Geotechnical Section is responsible for developing a subsurface exploration program and preparing preliminary geotechnical design recommendations and a Final Geotechnical Report. The Structures Division uses this information to design bridge foundations and other structures. The successful integration of the geotechnical design recommendations into the bridge design will require close coordination between the Geotechnical Section and the Structures Division.

17.1.4.2 Preliminary Geotechnical Design Recommendations

The preliminary geotechnical design recommendations provide general geotechnical recommendations based on existing soil information and any preliminary subsurface investigation that may have been conducted for the project. These general geotechnical recommendations are used to select the bridge foundation and initiate the preliminary structure design. The geotechnical recommendations are used in conjunction with the input of the Hydraulics Section (as applicable) to establish support locations. Prior to beginning work on preliminary bridge design, the bridge designer will review the preliminary geotechnical design recommendations to gain knowledge of the anticipated soil conditions at the bridge site and the recommended general foundation types. The preliminary geotechnical design recommendations provide a preliminary footing elevation and an expected allowable bearing pressure when spread footings are recommended. For deep foundations, the recommendations will include the use of a driven pile or drilled shafts. Driven piles will include pile capacity and type. This preliminary geotechnical information is used to estimate sizes of foundation members and prepare the preliminary bridge design.

17.1.4.3 Final Geotechnical Report

17.1.4.3.1 *Subsurface Exploration*

After a field review has been conducted, a detailed subsurface exploration is performed based on the bridge abutment and pier locations and anticipated foundation type as shown on the Preliminary Front Sheet. The Geotechnical Section determines the proposed boring locations. Typically, the structural modeling and analysis of the bridge proceed based on the preliminary geotechnical design recommendations while the geotechnical subsurface exploration is conducted. During this time, the Structures Division assumes a preliminary point-of-fixity or preliminary footing elevation to model the substructure. The Structures Division determines, verifies and provides foundation loads or calculated bearing pressures to the Geotechnical Section. The Structures Division provides the design loads (vertical and horizontal) at the bottom of substructure units. The Structures Division also provides the elevation at which the loads or bearing pressures are applied. When the geotechnical subsurface exploration has been completed, the Geotechnical Section will perform laboratory testing and geotechnical design. They will issue a Final Geotechnical Report based on the field exploration, laboratory testing, geotechnical design, the preliminary bridge design and the loads provided by the Structures Division.

17.1.4.3.2 *Foundation Design*

The Final Geotechnical Report is used to design foundations for bridges and bridge-related structures. For deep foundations, the Final Geotechnical Report provides tip elevations and p-y soil models of the subsurface that are used to perform foundation lateral soil-structure interaction analyses. The Structures Division then performs the lateral soil-structure interaction analysis with computer programs such as StrainWedge, LPile Plus or COM624P. The Structures Division uses this information to compute lateral displacements and to analyze the structural adequacy of the columns and foundations. The lateral soil-structure interaction analysis is also used to select the appropriate method (point-of-fixity, stiffness matrix, linear stiffness springs or p-y nonlinear springs) to model the bridge foundation in the structural design software. For spread footings, the Final Geotechnical Report provides the estimated footing elevation, allowable bearing pressure, and estimates on settlements and lateral displacements. The Structures Division uses this information to finalize the design of the footing and verify that members are not overstressed. The Final Geotechnical Report may also include notes and tables to be incorporated in the contract documents.

17.1.4.3.3 *Seismic Design*

For bridges on deep foundations requiring rigorous seismic analysis, the Structures Division performs lateral soil-structure interaction analyses using Extreme Event I loadings. If soil liquefaction is anticipated, the Geotechnical Section will provide the Structures Division with foundation downdrag loads due to liquefaction for use in developing the Extreme Event I load combination. The Geotechnical Section will also provide any lateral soil forces that act on the foundation as a result of seismically induced stability movements of earth retaining structures (e.g., embankments, retaining walls) or lateral soil movements attributable to lateral spread. These additional lateral loads should be included in the Extreme Event I load combinations when evaluating lateral soil-structure interaction. The Geotechnical Section will generate the p-y soil model of the subsurface that accounts for cyclic loadings and any liquefied soil conditions. The Structures Division then performs the lateral soil-structure interaction analysis with computer programs such as StrainWedge, LPILE Plus or COM624P. The Structures Division uses this information to calibrate the seismic model of the structure.

17.1.4.3.4 *Foundation Redesign*

If structural members are overstressed due to anticipated deformations or if the deformations exceed acceptable limits from any loading combination, then a redesign of the foundation is required. Redesign may include the adjustment of support member spacing or modification of member sizes. When a redesign of the foundation is required, the Structures Division must resubmit the redesign information (e.g., new foundation layout, sizes, foundation load combinations) to the Geotechnical Section. The Geotechnical Section will analyze the new foundation and resubmit any necessary information to the Structures Division.

17.1.5 Bridge Design/Hydraulic Design Interaction

Bridges and other structures exposed to stream flow may be subject to local and/or contraction scour. The bridge designer must work closely with the Hydraulics Section to determine the extent of scour. This may require an interactive design process. When a redesign of the foundation is required, the Structures Division must resubmit the redesign information (e.g., new foundation layout, sizes, foundation load combinations) to both the Hydraulics Section and the Geotechnical Section. The Geotechnical Section will analyze the new foundation and resubmit the necessary information to the Structures Division. The Hydraulics Section will analyze the new foundation and confirm that the new design adequately accommodates local and contraction scour.

17.2 SPREAD FOOTINGS AND PILE CAPS

Reference: LRFD Article 10.7

This discussion applies to both spread footings supported on soil and to pile caps. Pile caps distribute loads among two or more driven piles or drilled shafts that support a single column, group of columns or pier wall.

17.2.1 Usage

As noted in Section 11.7.2, spread footings are NDOT's preferred foundation type if soils and estimated settlements allow their use. Spread footings are thick, reinforced concrete members sized to meet the structural and geotechnical loading requirements for the proposed structural system. A factor affecting the size of the footing is the structural loading versus the ability of the soil to resist the applied loads. Spread footings are prohibited:

- at stream crossings where they may be susceptible to scour, and
- on MSE fills.

17.2.2 Dynamic Load Allowance (IM)

If a significant portion of the footing is above ground, dynamic load allowance (IM), traditionally termed impact, shall be applied to the proportioning of footings.

17.2.3 Thickness

Reference: LRFD Articles 5.13.3.6 and 5.13.3.7

The footing thickness may be governed by the development length of the column or wall reinforcement, or by shear requirements. Generally, shear reinforcement in footings should be avoided. If shear governs the thickness, it is usually more economical to use a thicker footing without shear reinforcement instead of a thinner footing with shear reinforcement.

Use a minimum footing thickness of 2 ft for bridge abutments and piers.

17.2.4 Depth

Reference: LRFD Articles 5.8.3, 5.13.3.6 and 5.13.3.8

The following will apply:

1. In Waterways. On soil, the top of spread footing must be located below the design scour depth. On rock, the bottom of the footing must be 1 ft below the surface of the scour-resistant rock.

2. Minimum Embedment and Bench Depth. Spread footings shall be embedded a sufficient depth to provide the greatest of the following:

- adequate bearing, scour and frost heave protection;
- 3 ft to the bottom of footing; or
- 2 ft of cover over the footing.

Pile caps may be located above the lowest anticipated scour level provided that the piles are designed for this condition. Footings shall be constructed so as to neither pose an obstacle to water traffic nor be exposed to view during low flow. Footings shall be constructed so as to pose minimum obstruction to water and debris flow if exposed during high flows.

Abutment footings shall be constructed so as to be stable if scour or meandering causes a loss of approach fill.

17.2.5 Bearing Resistance and Eccentricity

Reference: LRFD Article 10.6.3

The required nominal bearing and the geotechnical resistance factor shall be shown in the contract documents. See Chapter 5.

17.2.5.1 Soils Under Footings

Reference: LRFD Article 10.6.3.1.5

In contrast to the approach in the *Standard Specifications for Highway Bridges*, a reduced effective footing area based upon the calculated eccentricity is used to include the effects of bearing resistance and eccentricity. Uniform design bearing pressure is assumed over the effective area. Figure 17.2-B provides an example.

The location of the resultant of the center of pressure based upon factored loads should be within the middle ½ of the base.

17.2.5.2 Rock

Reference: LRFD Article 10.6.3.2.5

Following the traditional approach, a triangular or trapezoidal pressure distribution is assumed for footings on rock. This model acknowledges the linear-elastic response of rock.

The location of the resultant center of pressure based upon factored loads should be within the middle ¾ of the base.

17.2.6 Sliding Resistance

Reference: LRFD Article 10.6.3.3

Use the coefficients of friction in the *LRFD Specifications* for sliding resistance.

Keys in footings to develop passive pressure against sliding are not commonly used for bridges. When it becomes necessary to use a key, the bridge designer should consult with the Geotechnical Section.

17.2.7 Differential Settlement

Reference: LRFD Articles 3.12.6, 10.6.2.2 and 10.7.2.3

17.2.7.1 NDOT Practice

Differential settlement (SE) is considered a superstructure load in the *LRFD Specifications*. Differential settlement is defined as the difference between the settlements of two adjacent foundations. Generally, due to the methods used by NDOT to proportion foundations, settlements are within a tolerable range and, therefore, force effects due to differential settlement need not be investigated. The following presents general NDOT practices on the acceptable limits for settlement:

1. Estimated Differential Settlement. If the Geotechnical Section estimates that the differential settlement is ½ in or less, the bridge designer may usually ignore the effects of differential settlement in the structural design of the bridge.

2. Angular Distortion. Angular distortion is the differential settlement divided by the distance between the adjacent foundations. LRFD Article C10.5.2.2 states that angular distortions between adjacent foundations greater than 0.008 radians in simple spans and 0.004 radians in continuous spans should not be ordinarily permitted, and the Article suggests that other considerations may govern. NDOT does not use the LRFD limits for design, which are related to structural distress, because these angular distortions yield unacceptable impacts on rideability and aesthetics. Typically, meeting the requirements of Comment No. 1 on differential settlement should preclude exceeding the angular distortions allowed by the *LRFD Specifications*.

3. Piers. Continuous footings or deep foundations should be considered where differential settlement is a concern between columns within a pier.

17.2.7.2 Effects of Foundation Settlement

If varying conditions exist, settlement will be addressed in the Final Geotechnical Report, and the following effects should be considered:

1. Structural. The differential settlement of substructures causes the development of force effects in continuous superstructures. These force effects are directly proportional to structural depth and inversely proportional to span length, indicating a preference for shallow, long-span structures. They are normally smaller than expected and tend to be reduced in the inelastic phase. Nevertheless, they may be considered in design if deemed significant, especially those negative movements that may either cause or enlarge existing cracking in concrete deck slabs.

2. Joint Movements. A change in bridge geometry due to settlement causes movement in deck joints that should be considered in their detailing, especially for deep superstructures.

3. Profile Distortion. Excessive differential settlement may cause a distortion of the roadway profile that may be undesirable for vehicles traveling at high speed.

4. Appearance. Viewing excessive differential settlement may create a feeling of lack of safety.

5. Mitigation. Ground modification techniques may be used to improve the soil to address differential settlement concerns. These techniques include but are not limited to:

   - chemical grouting,
   - over-excavation and replacement,
   - surcharging,
   - the construction of stone columns, and
   - compaction grouting.

17.2.8 Reinforcement

Reference: LRFD Articles 5.10.8 and 5.13.3

Section 14.3 discusses NDOT practices for the reinforcement of structural concrete. The design of spread footings shall meet all applicable requirements in Section 14.3. Unless other design considerations govern, the reinforcement in footings should be as follows:

1. Steel in Top of Footing. For pile caps, the anchorage of piles or drilled shafts into footings requires tension reinforcement in the top of the footing to resist the potential negative bending under seismic action. The minimum reinforcement in the top of pile caps and spread footings shall be as required by design but, in no case, less than #6 bars at 12-in spacing.

2. Embedment Length. Vertical steel extending out of the footing shall extend down to the bottom pile cap or spread footing steel and shall be hooked on the bottom end regardless of the footing thickness.

3. Spacing. The minimum spacing of reinforcing steel in either direction is 6 in on center; the maximum spacing is 12 in on center.

4. Vertical Footing Reinforcement. In addition to the provisions of LRFD Article 5.8.3, the following shall apply: The minimum vertical reinforcement for spread footings and pile caps shall be #5 bars at 36-in spacing in each direction. Additionally, the minimum vertical reinforcement for column spread footings and pile caps shall be #5 bars at 12-in spacing in each direction in a band between "d" of the footing from the column face and beginning 6 in maximum from the column reinforcement. Vertical bars shall be hooked around the top and bottom flexure reinforcement in the footing or cap using alternating 90° and 135° hooks. See the *NDOT Bridge Drafting Guidelines* for typical detailing. These vertical bars enhance seismic performance and are not necessarily for shear resistance.

5. Tremie Seal. Where a tremie seal is used and there are no piles, the bottom footing reinforcement shall be 6 in above the bottom of footing. Where a tremie seal is used and there are piles extending through the tremie, the reinforcement shall be placed above the top of piling.

6. Other Reinforcement Considerations. LRFD Article 5.13.3 specifically addresses concrete footings. For items not included, the other relevant provisions of Section 5 should govern. For narrow footings, to which the load is transmitted by walls or wall-like bents, the critical moment section shall be taken at the face of the wall or bent stem; the critical shear section is a distance equal to the larger of "d_v" (d_v is the effective shear depth of the footing) or "$0.5d_v \cot \theta$" (θ is the angle of inclination of diagonal compressive stresses as defined in LRFD Article 5.8.3.4) from the face of the wall or bent stem where

the load introduces compression in the top of the footing section. For other cases, either LRFD Article 5.13.3 is followed, or a two-dimensional analysis may be used for greater economy of the footing.

17.2.9 Miscellaneous

17.2.9.1 Joints

Footings do not generally require construction joints. Where used, footing construction joints should be offset 2 ft from expansion joints or construction joints in walls and should be constructed with 3-in deep keyways.

17.2.9.2 Stepped Footings

Stepped footings may be used occasionally. Where used, the difference in elevation of adjacent stepped footings should not be less than 2 ft. The lower footing should extend at least 2 ft under the adjacent higher footing.

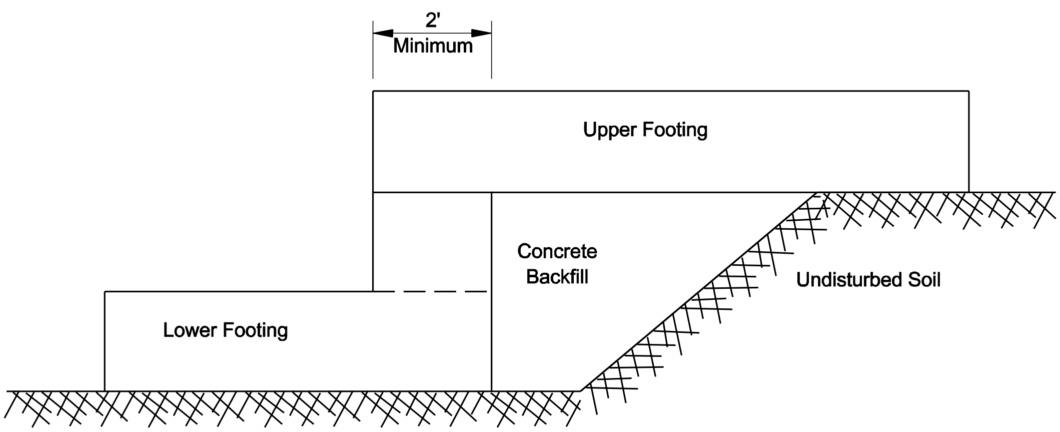
If high bearing pressures under a spread footing are present, use concrete backfill instead of granular backfill for support under the upper step. See Figure 17.2-A.

17.2.10 Example Analysis of a Spread Footing on Competent Soil

Figure 17.2-B presents a schematic example of a spread footing on soil.

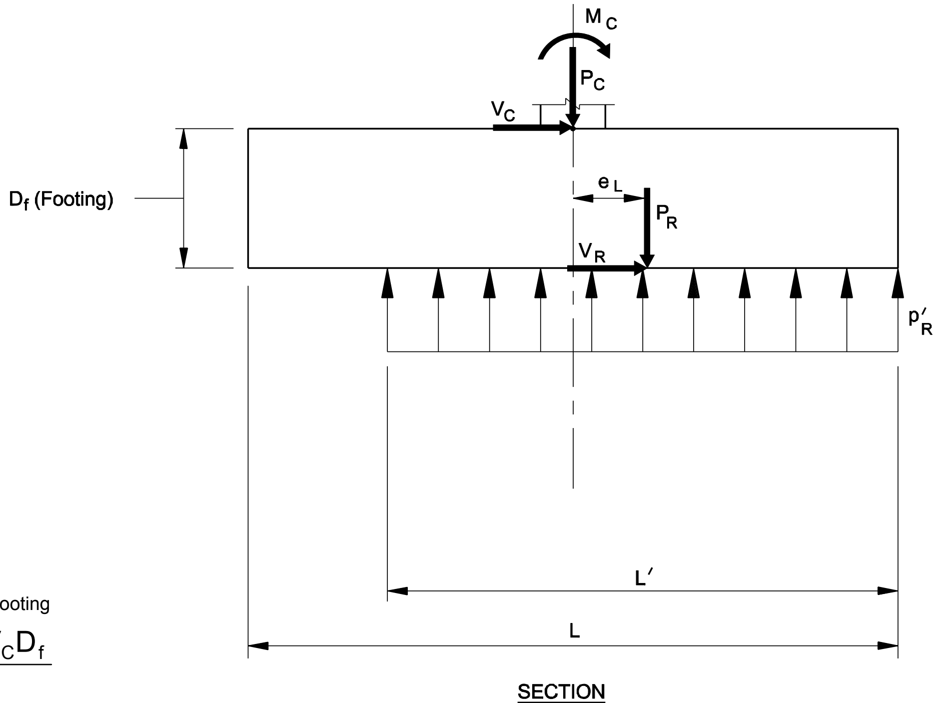
17.2.11 Example Analysis of Pile Caps

Figure 17.2-C presents a schematic example of the analysis of a pile cap to support a pier .



CONCRETE BACKFILL UNDER STEPPED FOOTING WITH HIGH BEARING PRESSURES

Figure 17.2-A



$$P_R = P_C + P_{Footing}$$

$$e_L = \frac{M_C + V_C D_f}{P_R}$$

$$V_R = V_C$$

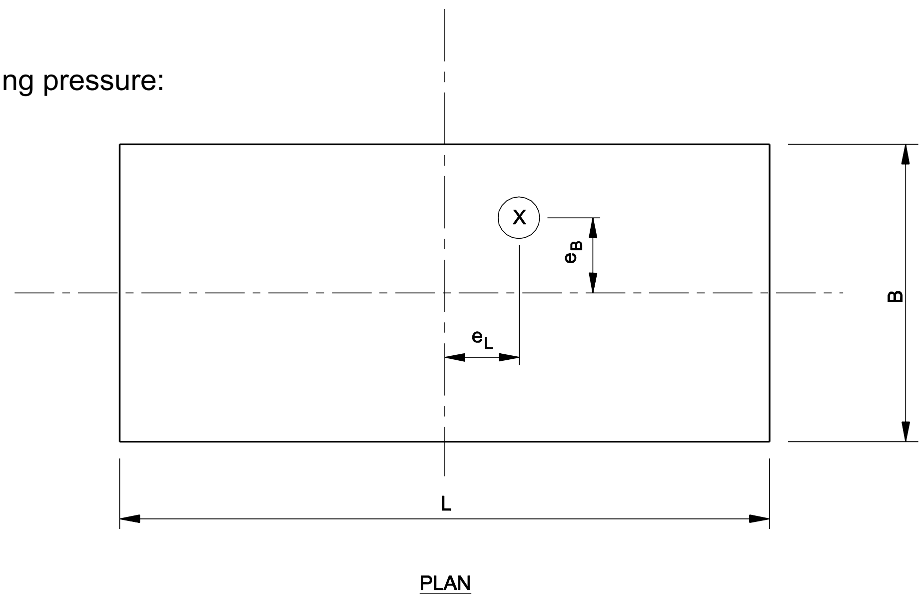
$$L' = L - 2e_L$$

In two dimensions, bearing pressure:

$$p'_R = \frac{P_R}{(L')(B')}$$

Where:

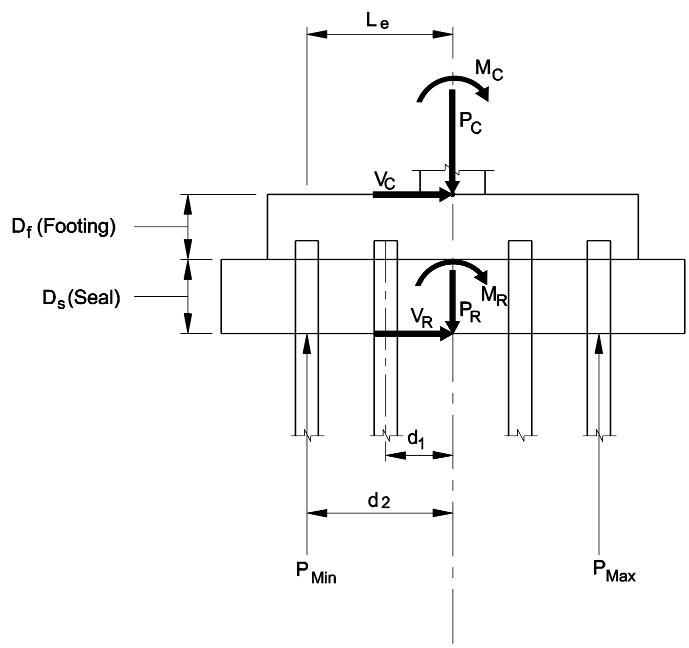
$$L' = L - 2e_L$$
$$B' = B - 2e_B$$



Note: See LRFD Article 10.6.3.1.5.

EXAMPLE ANALYSIS OF SPREAD FOOTING ON COMPETENT SOIL

Figure 17.2-B



P_R = $P_c + P_{footing} + P_{seal}$ – Buoyancy

Assumptions: Pile footing is rigid (footing is considered rigid if $L_e/D_f \leq 2.2$). Pile connections are pinned, or shear force in pile is small.

V_R = $V_c - V_{\text{passive soil pressure on footing and seal}}$ *Note: Passive soil pressure is typically ignored.*

M_R = $M_c + V_c (D_f + D_s)$

Pile Loads:

$$P_{max} = \frac{P_R}{\#\text{ of piles}} + \frac{M_R\ d_2}{\Sigma d_i^2}$$

$$P_{min} = \frac{P_R}{\#\text{ of piles}} - \frac{M_R\ d_2}{\Sigma d_i^2}$$

EXAMPLE ANALYSIS OF A PILE CAP

Figure 17.2-C

17.3 DRIVEN PILES

Piles serve to transfer loads to deeper suitable strata. Piles may function through skin friction and/or through end bearing.

17.3.1 Pile Types/Selection

See Section 11.7.2 for NDOT practices for selecting driven piles as the foundation type. To limit the number of pile types and sizes used throughout a project, use only one pile type and size, if practical.

17.3.1.1 Steel Pipe Piles

Reference: LRFD Articles 6.9.5 and 6.12.2.3

Steel pipe piles are the most common type of driven pile used by NDOT. A typical use of steel pipe piles is in waterways where the predicted scour is deep and driving conditions are favorable. The following applies:

1. Diameter. NDOT uses pipe pile diameters of 12 in to 24 in. The wall thickness typically varies between ⅜ in to ⅝ in, depending on the pile size and driving conditions.

2. Interior Filler. Steel pipe piles are typically filled with concrete and reinforced with 1% of the concrete area or as required by design to develop the pile loads.

17.3.1.2 Steel H-Piles

NDOT occasionally uses steel H-piles where deep scour is not anticipated and a bearing condition is anticipated. The steel H-piles typically used by NDOT are:

- HP10
- HP12

On large projects, where a significant savings may be realized by using non-typical sizes or where the design dictates, other standard AISC sizes may be used.

17.3.1.3 Prestressed Concrete Piles

NDOT rarely uses prestressed concrete piles. Where prestressed concrete piles are used, typical sizes are 12 in to 18 in square or octagonal sections. Spiral reinforcement is permitted in prestressed concrete piles.

17.3.1.4 Pile Selection

The Geotechnical Section ultimately determines the selected type of pile. Figure 17.3-A provides guidance in selecting pile types based on their typical usage by NDOT.

Pile Type	Soil Conditions and Structural Requirements
Steel pipe pile (closed or open end)	Loose to medium dense soils or clays where skin friction is the primary resistance and lateral stiffness in both directions is desirable, especially in rivers where deep scour is anticipated and high lateral stiffness is needed. Primarily used as a friction pile.
Steel H-pile	Rock or dense soil where end bearing is desirable and lateral flexibility in one direction is not critical. Primarily used for end bearing.
Prestressed concrete pile	Loose to medium dense soils or clays where skin friction is the primary resistance.

DRIVEN PILE SELECTION GUIDE

Figure 17.3-A

17.3.2 <u>Design Details</u>

Reference: LRFD Article 10.7.1

17.3.2.1 Pile Length

Reference: LRFD Articles 10.7.1.10, 10.7.1.11 and 10.7.1.12

Pile length will be determined on a project-by-project basis. All piles for a specific pier or abutment should be the same length where practical. Pile lengths should be shown in whole foot increments.

The design and minimum pile tip elevations shall be shown on the drawing of the structural element in the contract documents. Design pile tip elevations shall reflect the elevation where the required ultimate pile capacity is anticipated to be obtained. Minimum pile tip elevations shall reflect the penetration required, considering scour and liquefaction, to support both axial and lateral loads.

Piles placed at abutment embankments that are more than 5 ft in depth require pre-drilling. The size of the pre-drilled hole shall be 2 in larger than the diameter or largest dimension of the pile.

The Final Geotechnical Report will provide project-specific recommendations for the pile embedment, socketing and special construction requirements.

17.3.2.2 Reinforced Pile Tips

Where hard layers are anticipated, use reinforced pile tips to minimize damage for all steel piles. Where rock is anticipated, the pile tips shall be equipped with teeth designed to penetrate into the rock.

The Geotechnical Section recommends the type of pile tip to be used. The bridge designer must show this in the contract documents.

17.3.2.3 Battered Piles

Vertical piles are preferred. Battered piles, typically 1H:3V, may be considered where there is inadequate horizontal resistance. If battered piles are used, a refined analysis is recommended; a two-dimensional analysis is a minimum.

17.3.2.4 Spacing

Spacing of piles is specified in LRFD Article 10.7.1.2. Center-to-center spacing should not be less than the greater of 30 in or 2½ times the pile diameter/width of pile. The distance from the side of any pile to the nearest edge of footing shall not be less than 9 in.

Pile spacing should not normally exceed 10 ft.

17.3.2.5 Orientation

The orientation of steel H-piles (strong versus weak axis) is a design consideration, and it is preferable that all piles be oriented the same. For diaphragm-with-pile integral abutments, typically use a single row of steel H-piles or steel pipe piles, driven vertically, with the strong axis parallel to the diaphragm centerline.

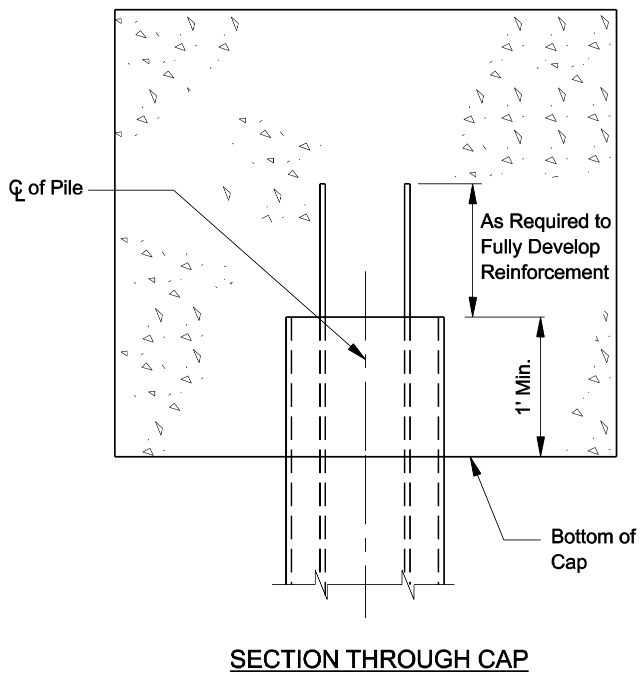
17.3.2.6 Pile Connection Details

The following applies to the connection of piles to pile caps or to bent caps unless seismic analysis dictates otherwise:

1. Steel Pipe Piles. The reinforcing steel must be extended into the pile cap and fully developed through adequate development length or standard hooks. The reinforcing steel extends to the minimum tip elevation of the pile. See Figure 17.3-B.

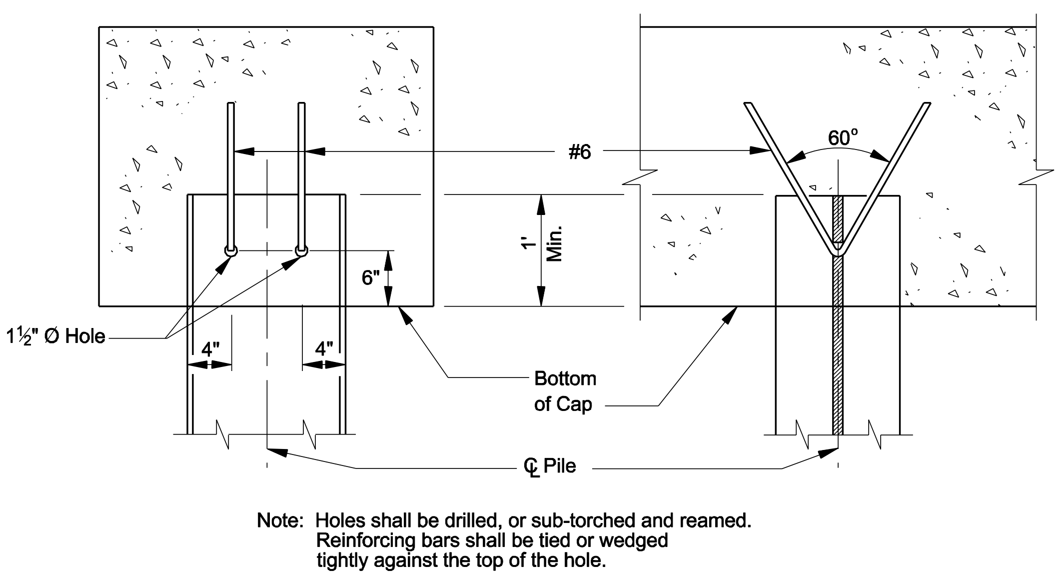
2. Steel H-Piles. Two V-shaped #6 reinforcing bars should be used to anchor steel piles to pile-supported footings or caps. The diameter of the hole should be 1½ in. The reinforcing bars shall be tied or wedged tightly against the top of the hole to reduce the possibility of slip between the reinforcing bar anchor and the pile. The reinforcing bars should extend into the cap or footing a minimum of 1′-8″ beyond the bottom mat of reinforcement. See Figure 17.3-C.

3. Prestressed Concrete Piles. The piles may be connected to the caps or footings by simply being embedded the larger of 1 ft or an equivalent of one pile width. No roughening of the pile is required. However, the pile surface to be embedded shall be clean and free of any laitance prior to placement of the cap or footing concrete.



STEEL PIPE PILE CONNECTION

Figure 17.3-B



STEEL H-PILE CONNECTION

Figure 17.3-C

17.3.3 Force Effects

17.3.3.1 Downdrag (DD) Loads

When a pile penetrates a soft layer subject to settlement, the designer must evaluate the force effects of downdrag or negative loading on the foundations. Downdrag acts as an additional permanent axial load on the pile and may cause additional settlement. If the force is of sufficient magnitude, structural failure of the pile or a bearing failure at the tip is possible. For piles that derive their resistance mostly from end bearing, the structural resistance of the pile must be adequate to resist the factored loads including downdrag.

Downdrag forces can be mitigated by the following methods:

- provide friction-reducing material around the piles;
- construct embankments a sufficient amount of time in advance of the pile driving for the fill to settle; or
- prebore and backfill the space around the installed pile with pea gravel (may be less effective if the adjacent soil continues to settle).

17.3.3.2 Uplift Forces

Uplift forces can be caused by lateral loads, buoyancy or expansive soils. Piles intended to resist uplift forces should be checked for resistance to pullout and structural resistance to tensile loads. The connection of the pile to the cap or footing must also be checked.

17.3.3.3 Laterally Loaded Piles

The resistance of laterally loaded piles must be estimated according to approved methods. Several methods exist for including the effects of piles and surrounding soil into the structural model for lateral loadings including seismic loads. NDOT's preferred method is discussed in Section 17.5.

17.3.3.4 Group Effect

Minimum spacing requirements are not related to group effect. Group effects are specified in LRFD Articles 10.7.3.7.3 and 10.7.3.10.

17.3.4 Pile Loads

17.3.4.1 Contract Documents

Applicable pile loads shall be shown in the contract documents. See Chapter 5. This information will help ensure that pile driving efforts during construction will result in a foundation adequate to support the design loads.

17.3.4.2 Static Load Tests

Reference: LRFD Article 10.7.3.8.2

NDOT occasionally performs static load tests on driven piles. The Geotechnical Section will determine the number and location of the static load tests. Test locations and sizes should be shown in the contract documents.

17.3.4.3 Dynamic Pile Monitoring

Reference: LRFD Article 10.7.3.8.3

During the installation of production piles, dynamic pile monitoring ensures that driving occurs in accordance with the established criterion. It provides information on soil resistance at the time of monitoring and on driving performance. Dynamic pile monitoring also reveals driving stresses, which helps prevent pile damage. If damage is imminent, the monitoring provides an alert early enough to save the pile from complete destruction.

Data obtained during pile-driving monitoring is used to verify pile resistance with CAPWAP.

17.4 DRILLED SHAFTS

Reference: LRFD Article 10.8

17.4.1 Usage

Section 11.7.2 presents NDOT practices for selecting drilled shafts as the foundation type. Drilled shafts should also be considered to resist large lateral or uplift loads where deformation tolerances are relatively small.

Drilled shafts derive load resistance either as end-bearing shafts transferring load by tip resistance or as friction shafts transferring load by side resistance or a combination of both. Friction-only shafts are the most desirable but may not be the most economical. Drilled shafts are typically good for seismic applications.

17.4.2 Drilled Shaft Axial Compressive Resistance at the Strength Limit State

The *LRFD Specifications* provides procedures to estimate the axial resistance of drilled shafts in cohesive soils and cohesionless soils in LRFD Articles 10.8.3.5.1 and 10.8.3.5.2. In both cases, the resistance is the sum of the shaft and tip resistances. LRFD Article 10.8.3.5.4 discusses the determination of axial resistance of drilled shafts in rock.

17.4.3 Structural Design

The following will apply to the design of drilled shafts:

1. Column Design. Because even soft soils provide sufficient support to prevent lateral buckling of the shaft, drilled shafts surrounded by soil may be designed according to the criteria for short columns in LRFD Article 5.7.4.4 when soil liquefaction is not anticipated. If the drilled shaft is extended above ground to form a pier, it should be analyzed and designed as a column. Similarly, the effects of scour around the shafts must be considered in the analysis.

2. Casing**.** A casing may be used to maintain the excavation, especially when placing a shaft within the water table. This casing, if left in place after construction, shall not be considered in the determination of the structural resistance of the shaft. However, it should be considered when evaluating the seismic response of the foundation because the casing will provide additional resistance.

3. Lateral Loading. Section 17.5 discusses the analysis of drilled shafts for lateral loading and resistance.

17.4.4 Design Details

The following details apply to the design of drilled shafts:

1. Location of Top of Shaft. Drilled shafts are normally terminated 1 ft to 2 ft below finished grade.

2. Reinforcement. Section 14.3 discusses NDOT practices for the reinforcement of structural concrete. The design of drilled shafts shall meet all applicable requirements in Section 14.3. Additional reinforcement criteria include:

- The shaft will have a minimum reinforcement of 1% of the gross concrete area and the reinforcement will extend from the bottom of the shaft into the footing.

- For confinement reinforcement, use spirals (up to #7) or butt-welded hoops.

- The design and detailing of drilled shafts must conform to the clearances for reinforced steel cages as specified in the *NDOT Standard Specifications*:

  + 4 in for drilled shafts having a diameter of less than 5 ft, or
  + 6 in for drilled shafts having a diameter of 5 ft or more.

  Non-corrosive rollers will ensure that the annular space around the cage is maintained.

- Detail drilled shafts and columns to accommodate concrete placement considering the multiple layers of reinforcing steel including lap splices. Maximize lateral reinforcement spacing. Consider recommendations from the Association of Drilled Shaft Contractors.

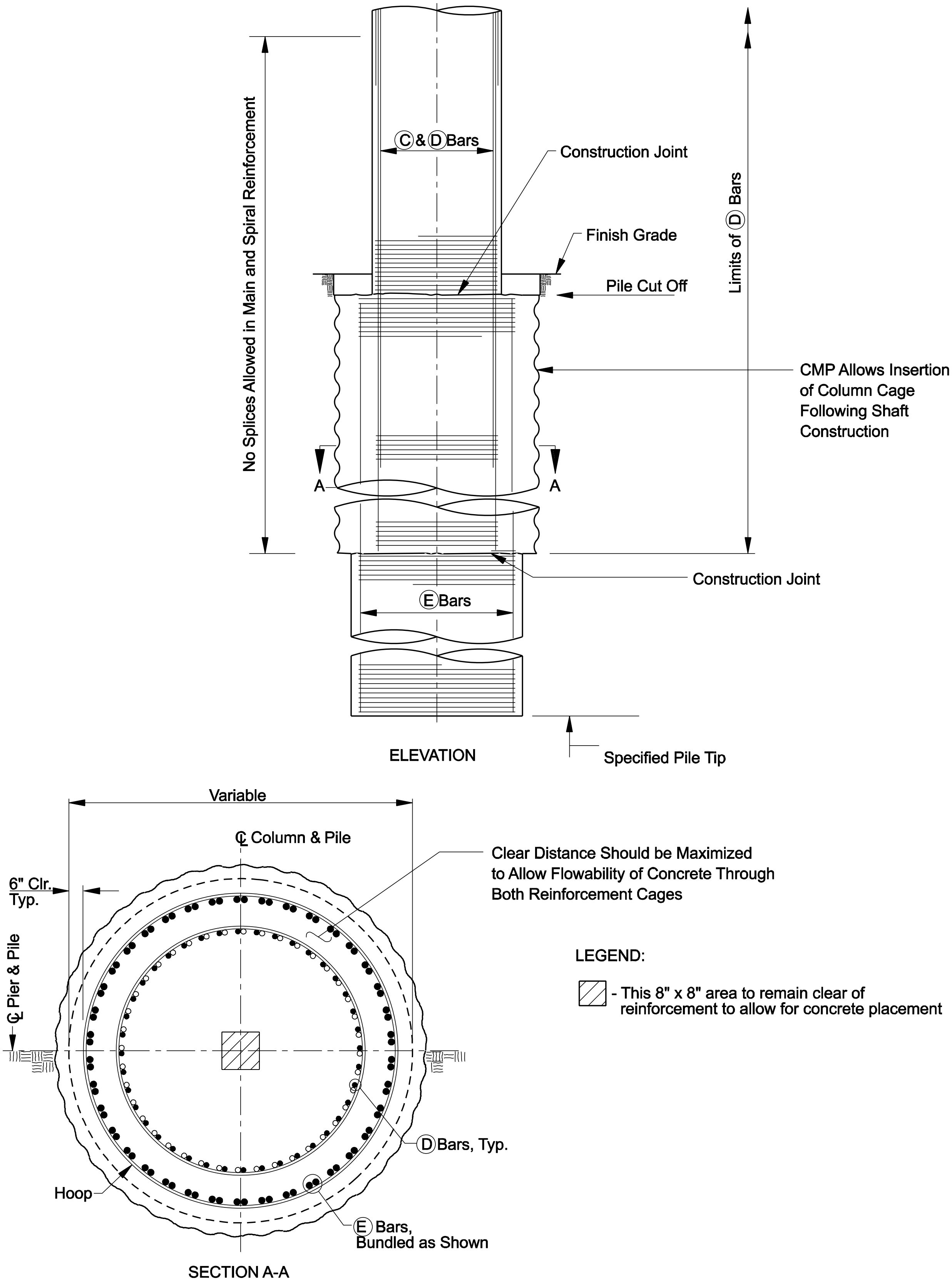
Figure 17.4-A illustrates the typical drilled shaft and column longitudinal and transverse reinforcement.

3. Construction Joints. Do not use keys in the design of construction joints for drilled shafts.

4. Diameter. The diameter of a drilled shaft supporting a single column shall be at least 1½ ft greater than the greatest dimension of the column cross section.

5. Constructibility. Detail drilled shafts and columns to accommodate concrete placement through the layers of reinforcing steel. Limit lap splices in the drilled shaft locations and provide adequate openings.

6. Casing. A permanent casing (typically CMP) is often used to facilitate insertion of the column cage into the upper portion of the shaft after the shaft concrete has been placed up to the first construction joint. See Figure 17.4-A.



DRILLED SHAFT DETAIL

Figure 17.4-A

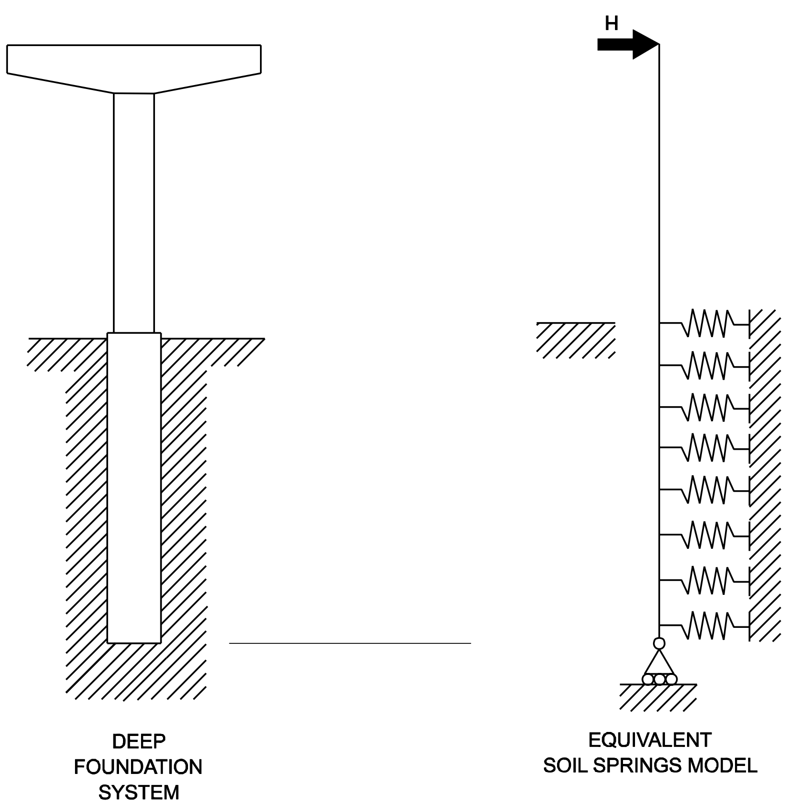
17.5 MODELING FOR LATERAL LOADING

In the initial stages of design, when using driven piles or drilled shafts, estimate the preliminary point-of-fixity at the top of the pile (bottom of the column).

For final design, a structural model with site-specific p-y curves is used to represent the soil and determine the lateral resistance of piles or shafts. The soil surrounding the pile is modeled as a set of equivalent non-linear soil "springs," as represented in Figure 17.5-A. Figure 17.5-B shows a set of typical p-y curves. The soil resistance "p" is a non-linear function of the corresponding horizontal pile deflection "y." The solution's accuracy is a function of the spacing between nodes used to attach the soil springs to the pile (the closer the spacing, the better the accuracy), and the pile itself. Simple girder column elements are usually adequate for modeling pile behavior.

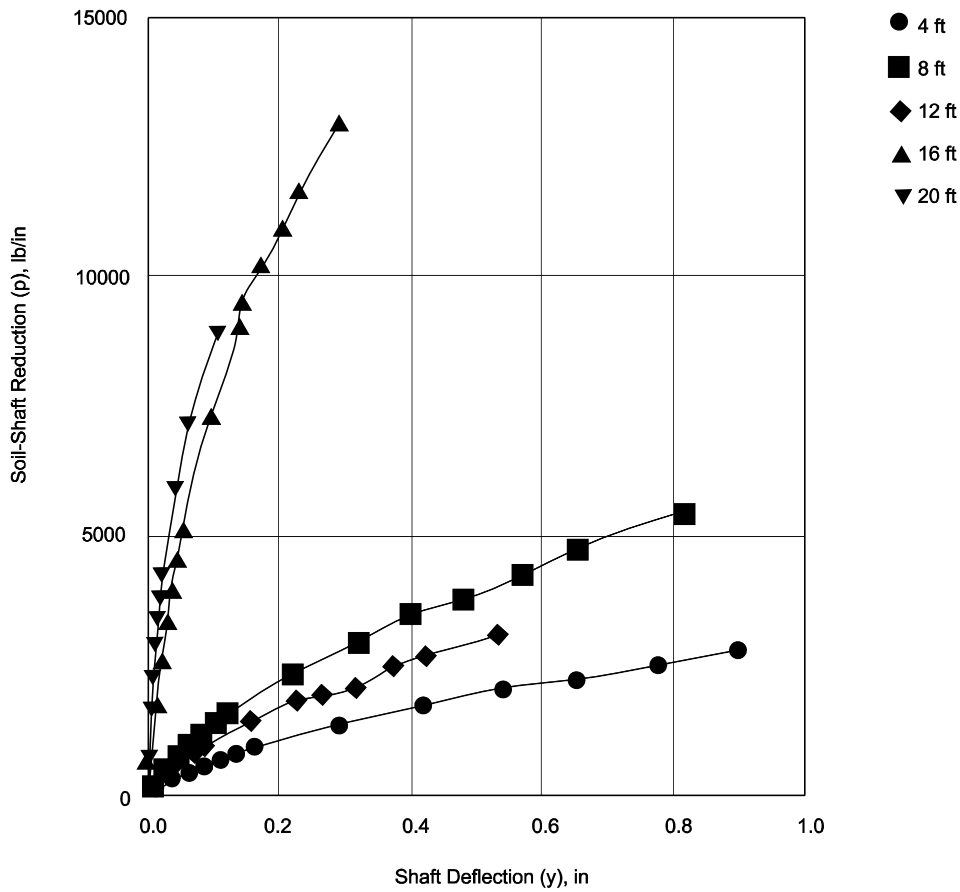
The node placement for springs should model the soil layers. Generally, the upper ⅓ of the pile in stiff soils has the most significant contribution to the lateral soil reaction. Springs in this region should be spaced at no more than 3 ft apart. Springs for the lower ⅔ of the pile may transition to a much larger spacing. Stiff foundations in weak soils will transfer loads much deeper in the soil, and the use of more springs is advised.

NDOT uses computer software (e.g., StrainWedge, LPILE Plus, COM624P) to model soil-structure interaction. The interaction between the Structures Division and the Geotechnical Section is discussed in Sections 17.1.4.3.2 and 17.1.4.3.3.



METHOD OF MODELING DEEP FOUNDATION STIFFNESS

Figure 17.5-A



EXAMPLE p-y CURVE

Figure 17.5-B