Chapter 19

FOUNDATIONS

SCDOT BRIDGE DESIGN MANUAL

April 2006

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CHAPTER 19

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 aesthetic compatibility. Tolerable lateral and vertical movements shall be included for this support. This Chapter discusses SCDOT-specific criteria that are supplementary to Section 10 of the *LRFD Specifications* for the design of piles, drilled shafts, and spread footings. Section 12.5 presents Department criteria for the selection of foundation type within the context of structure-type selection. This Chapter does not discuss the geotechnical design for foundations (e.g., shear strength of surrounding soil, settlement calculations), which are discussed in the *SCDOT Geotechnical Design Manual*. Seismic design requirements for foundations are presented in the *SCDOT Seismic Design Specifications for Highway Bridges*.

19.1 GENERAL

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

19.1.1 Design Methodology

Considering basic design principles for foundations, the *LRFD Bridge Design Specifications* implemented a major change compared to those principles in the AASHTO *Standard Specifications for Highway Bridges*. The *LRFD Specifications* makes a clear distinction between the strength of the in-situ materials (soils and rocks) 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.” It 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.

The target safety levels for each type of foundation are selected to achieve a level of safety comparable with that inherent in those foundations designed with the AASHTO *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 in scour protection, which may result in deeper foundations.

Section 13.1 discusses the application of load factors to both superstructure and substructure design in the LRFD Equation.

19.1.2 Design Team/Geotechnical Coordination (For In-House-Designed Projects)

19.1.2.1 General

Prior to designing the foundation, the bridge designer must have a knowledge of the environmental, thermal, and loading conditions expected during the life of the proposed bridge. The primary function of the foundation is to spread concentrated loads over a sufficient area to provide adequate bearing capacity and limitation of movement. Quite often, it is necessary to transfer loads through unsuitable foundation strata to suitable strata. Therefore, a knowledge of the subsurface soil conditions, ground water conditions, and scour is necessary.

The Geotechnical Design Section (GDS) is responsible for developing a soil exploration program and preparing a Preliminary Geotechnical Report (PGR) and a Bridge Geotechnical Report (BGR). The Design Team uses these reports to design bridges and bridge-related structures. The successful integration of the geotechnical design recommendations into the bridge design will require a close coordination between the GDS and the Design Team.

19.1.2.2 Preliminary Geotechnical Report (PGR)

The PGR provides general geotechnical recommendations based on existing soil information and any preliminary subsurface investigation that may have been conducted for the project. The general geotechnical recommendations contained in the PGR are used to select the bridge foundation and perform preliminary seismic analyses/evaluations. The geotechnical recommendations contained in this Report are used in conjunction with the input of the Hydraulic Engineer and Design Team to establish the bridge length. Prior to beginning work on preliminary bridge plans, the Design Team Leader will review the PGR to gain knowledge of the anticipated soil conditions at the bridge site and possible foundation types. When drilled shafts or trestle-type pile bents are anticipated, the PGR provides estimates of preliminary point-of-fixity based on anticipated soil conditions. When drilled shaft/pile-supported footings are used, the preliminary point-of-fixity may be estimated at the top of the footing (bottom of the column). When spread footings are anticipated, the PGR provides a preliminary footing elevation and an expected allowable bearing pressure. This preliminary geotechnical information is used to estimate the sizes of foundation members and prepare preliminary bridge plans.

19.1.2.3 Bridge Geotechnical Report (BGR)

19.1.2.3.1 Subsurface Exploration

After the Design Field Review has been conducted, a detailed subsurface soil exploration is performed based on the bridge bent locations and anticipated foundation type. The GDS determines the proposed boring locations and provides the locations to the Design Team. The Design Team plots the locations on the bridge plan and profile sheets and provides copies to the GDS to be used for requesting the subsurface soil exploration. Typically, the structural design of the bridge proceeds based on the recommendations of the PGR while the geotechnical subsurface exploration is being conducted. During this time, the Design Team uses the preliminary point of fixity or preliminary footing elevation to model the substructure. The Design Team determines, verifies, and provides foundation loads or calculated bearing pressures to the GDS. For piles and drilled shafts, the Design Team provides the loads at the centerline of the bent cap or the bottom of the footing. For spread footings, the Design Team provides the calculated bearing pressure at the bottom of the footing. The Design Team also provides the elevation at which the loads or bearing pressures are applied. When the geotechnical subsurface exploration is complete, the GDS will issue a BGR based on the geotechnical data, the preliminary bridge plans, and the loads computed by the Design Team.

19.1.2.3.2 Foundation Design

The BGR is used to design foundations for bridges and bridge-related structures. For drilled shaft/pile bents and drilled shaft/pile-supported footings, the BGR provides estimated pile/shaft tip elevations, the minimum pile/shaft tip elevations required to maintain lateral stability (critical depth), and the necessary soil parameters to develop a p-y soil model of the subsurface that is used to perform foundation lateral soil-structure interaction analyses. The Design Team then performs the lateral soil-structure interaction analysis with computer programs such as LPILE or FB-Pier. The Design Team 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 BGR provides the estimated footing elevation, ultimate bearing factor, geotechnical resistance factor, and estimates on footing settlements and lateral displacements. The Design Team uses this information to finalize the design of the footing and verify that members are not overstressed. The BGR also includes notes and tables to be placed in the bridge plans.

19.1.2.3.3 Seismic Analysis

For drilled shaft/pile-supported bridges that require a rigorous seismic analysis, the Design Team performs lateral soil-structure interaction analyses using Extreme Event I loadings. If soil liquefaction is anticipated, the GDS will provide the Design Team with foundation downdrag loads due to liquefaction for use in developing the Extreme Event I load combination. The GDS 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 performing lateral soil-structure interaction. The GDS will provide the soil parameters necessary to generate a p-y soil model of the subsurface that accounts for cyclic loadings and any liquefied soil conditions. The Design Team then performs the lateral soil-structure interaction analysis with computer programs such as LPILE or FB-Pier. The Design Team uses this information to calibrate the seismic model. The Design Team performs the seismic analysis in accordance with the *SCDOT Seismic Design Specifications for Highway Bridges*.

19.1.2.3.4 Foundation Redesign

If structural members are overstressed or if deflections 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 Design Team must resubmit the redesign information (new foundation layout, sizes, foundation load combinations, etc.) to the GDS. The GDS will analyze the new foundation and resubmit the necessary information to the Design Team.

19.2 PILES

Reference: LRFD Article 10.7

19.2.1 General

Piles serve to transfer loads to deeper suitable strata. Piles may function through skin friction and/or through end bearing. SCDOT uses steel H-piles, steel pipe piles, and prestressed concrete piles, or combination piles-prestressed concrete piles with steel pile extensions.

19.2.2 Pile Selection

Figure 19.2-1 provides guidance in selecting pile types based on their typical usage by SCDOT.

Pile Type	Soil Conditions and Structural Requirements
Steel H-pile	Rock or dense soil where lateral flexibility in one direction is desirable
Steel pipe pile	Dense soil where lateral stiffness in both directions is desirable
Prestressed concrete pile	Loose to medium dense soils
Combination pile-prestressed concrete pile with steel pile extension	Non-uniform soils (such as a soft upper layer overlying a dense lower layer)

PILE SELECTION GUIDE

Figure 19.2-1

19.2.3 Pile Types

Generally, only one pile type and size should be used throughout a project. However, it is common practice to use steel piles at end bents when prestressed concrete piles are used at interior bents.

19.2.3.1 Steel H-Piles

The steel H-piles typically used by SCDOT are as follows:

- HP12 x 53
- HP14 x 73
- HP14 x 89
- HP14 x 117 (used where penetration is minimal and driven to very large bearings)

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.

19.2.3.2 Steel Pipe Piles

Reference: LRFD Articles 6.9.5 and 6.12.2.3

The following applies to the typical use of steel pipe piles on SCDOT projects:

1. Diameter. SCDOT uses pipe pile diameters of 16 in, 18 in, 20 in, or 24 in. The wall thickness is ½ in for all pipe pile sizes.
2. Interior Filler. Steel pipe piles are typically not filled with concrete.

19.2.3.3 Prestressed Concrete Piles

Typical sizes used by SCDOT for prestressed concrete piles are 18 in, 20 in, or 24 in square piles. Spiral reinforcement is permitted in prestressed concrete piles.

19.2.3.4 Combination Pile-Prestressed Concrete Pile with Steel Pile Extension

Pile extensions are used when driving into non-uniform soils. The steel pile extension is used to penetrate into a dense soil layer beneath a soft soil layer. The steel pile extensions typically used by SCDOT are as follows:

- W8 x 58
- HP10 x 57
- HP12 x 53

19.2.4 Pile Length

Reference: LRFD Articles 10.7.1.10, 10.7.1.11, and 10.7.1.12

All piles within a particular bent should be detailed to be the same length where practical. Pile lengths should be shown in whole foot increments.

Piles shall be a minimum of 10 ft in length. At end bents, if the depth to suitable rock strata is less than 10 ft, typical practice is to drive the piles in holes cored in the rock and backfill with Class 4000 DS Concrete. A minimum core depth of 5 ft into scour-resistant rock is recommended. The minimum tip elevation shall reflect the elevation where the required ultimate pile capacity can be obtained, the penetration required to resist lateral pile loads, and the penetration of any overlaying unsuitable soil strata, as specified in LRFD Article 10.7.1.11.

19.2.5 Tip Elevations

The estimated and minimum pile tip elevations shall be shown on the drawing of the structural element. Estimated 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 lateral loads.

19.2.6 Design Details

Reference: LRFD Article 10.7.1

19.2.6.1 Battered Piles

Vertical piles are preferred. If battered piles are used, a refined analysis is required.

19.2.6.2 Spacing

Spacing of piles is specified in LRFD Article 10.7.1.5. Center-to-center spacing should not be less than the greater of 30 in or 2½ times the pile diameter or width of pile. The distance from the side of any pile to the nearest edge of footing shall be greater than 9 in.

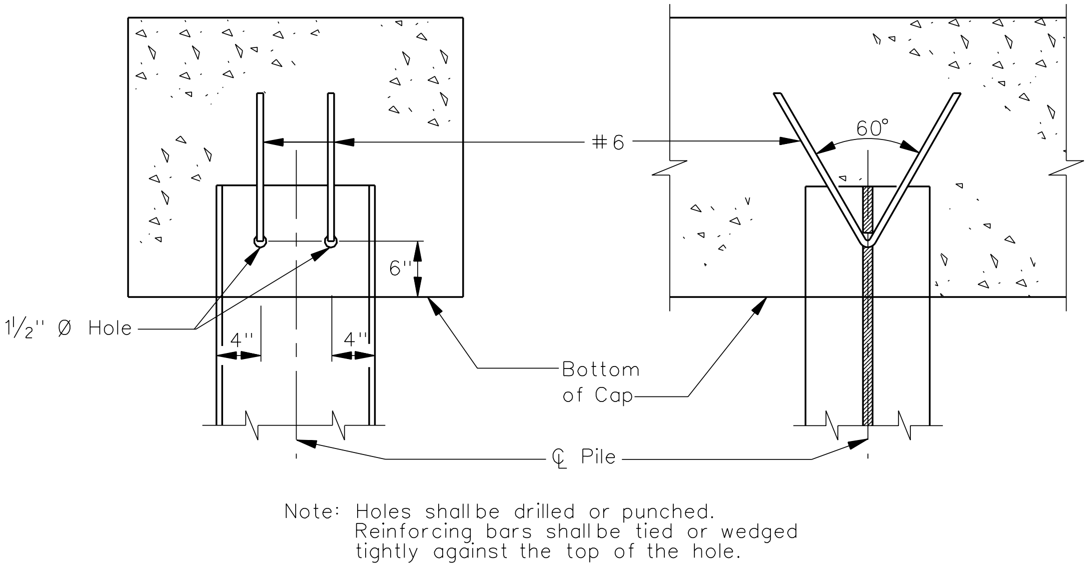
19.2.6.3 Pile Connection Details

The following applies to the connection of piles to pile-supported footings and to bent caps unless seismic analysis dictates otherwise:

1. Steel H-Piles. Two V-shaped #6 reinforcing bars should be used to anchor steel piles to pile-supported footings or bent caps. The diameter of the hole should be limited to 2 times the bar diameter (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 19.2-2.

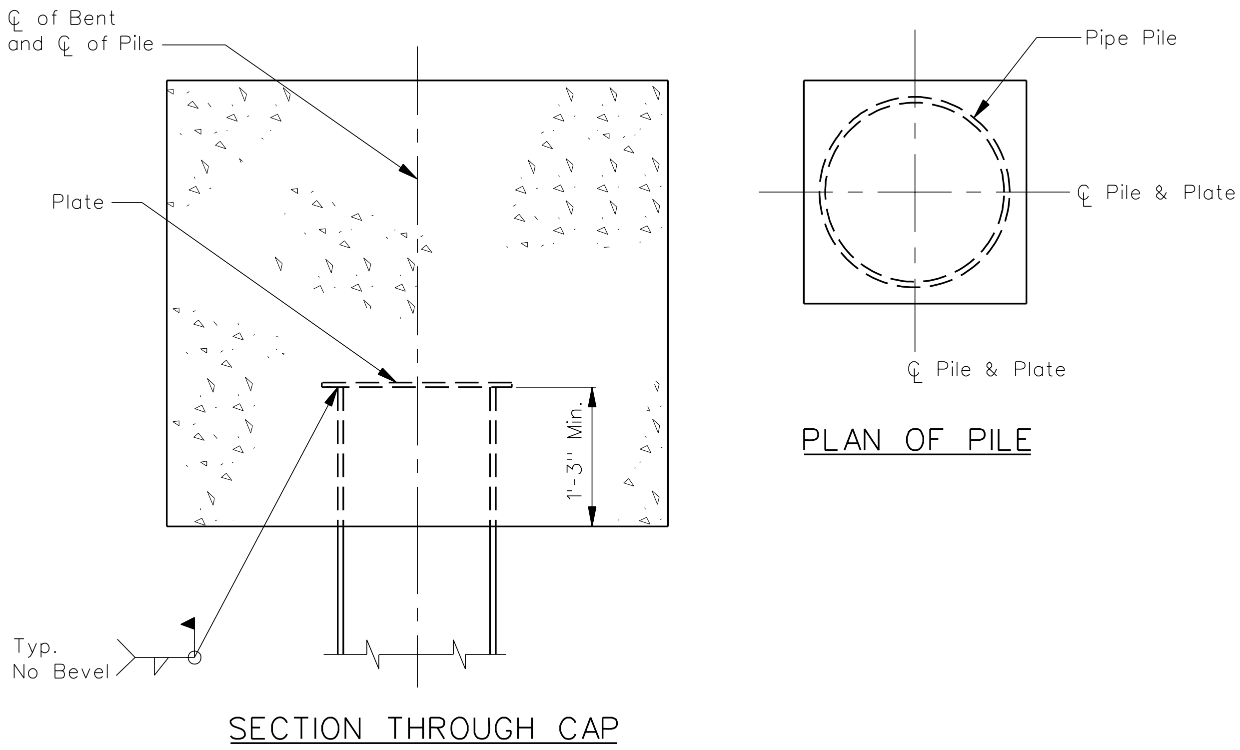
2. Steel Pipe Piles. A fillet-welded square steel end plate, as shown in Figure 19.2-3 should be used to anchor steel pipe piles to pile-supported footings or bent caps. The end plate and fillet weld is sized according to the specific requirements of the foundation. The pipe pile shall be embedded a minimum of 1′-3″.

3. Prestressed Concrete Piles. The piles may be connected to the caps or footings by simply being embedded 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 H-PILE CONNECTION

Figure 19.2-2



STEEL PIPE PILE CONNECTION

Figure 19.2-3

To allow for constructibility, the pile embedment shall have a tolerance of ±6 in. Unless approved otherwise by the State Bridge Design Engineer, the pile embedment into the cap shall not be less than 12 in.

19.2.6.4 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. At small magnitudes, the downdrag 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, such as bitumen coating or sleeves 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.

19.2.6.5 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.

19.2.6.6 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. These methods are discussed in Section 19.4.

19.2.6.7 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.

19.2.6.8 Pile Loads

Applicable pile loads shall be shown in the Plans. See Section 6.3. This information will help ensure that pile driving efforts during the construction process will result in a foundation adequate to support the design loads

19.2.6.9 Reinforced Pile Tips

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

19.2.6.10 Pile Load Tests

Reference: LRFD Article 10.7.1.13

Where pile design loads are high or where the pile quantity is large, pile load tests may be justified for economy. The designer should consult with the Geotechnical Design Section if considering pile load testing. Test locations and sizes should be shown in the Plans or described in the Special Provisions.

19.2.6.11 Wave Equation Analysis

Reference: LRFD Article 10.7.1.14

The geotechnical designer performs a Wave Equation analysis for all pile foundations. A Wave Equation analysis is required in the design phase to verify the results of the static analysis and to ensure driveability without damage to the pile or the driving equipment. Another Wave Equation analysis shall be made in the construction phase for approval of the specific driving equipment and methods proposed by the Contractor.

19.3 DRILLED SHAFTS

Reference: LRFD Article 10.8

19.3.1 Usage

Drilled shafts may be an economical alternative to piles. Drilled shafts should also be considered to resist large lateral or uplift loads where deformation tolerances are relatively small. Also use drilled shafts where significant scour is expected, where there are limitations at water crossing work, or where piles are not economically viable due to high loads or obstructions to driving. Limitations on pile driving vibration and/or noise may also dictate the use of drilled shafts.

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. Drilled shafts are typically good for seismic applications, and they are generally applicable to span lengths greater than 50 ft.

19.3.2 Drilled Shaft Axial 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 10.8.3.3 and 10.8.3.4, respectively. In both cases, the resistance is the sum of the shaft and tip resistances. LRFD Article 10.8.3.5 discusses the determination of axial resistance of drilled shafts in rock.

19.3.3 Design

The following will apply to the design of drilled shafts:

1. Location of Top of Shaft. Drilled shafts typically extend to the ground line or to at least 12 in above the water elevation expected during construction. If the distance from the top of a shaft to the bottom of a bent cap is less than 5 ft, extend the shaft to the bottom of the bent cap.

2. Rock-Socketed Shafts. Where casing through overburden soils is required, design the shaft as one size and step down when going into a rock socket.

3. Column Design. Because even soft soils provide sufficient support to prevent lateral buckling of the shaft, it 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 an interior bent or part of a bent, it should be analyzed and designed as a column. The effects of scour around the shafts must be considered in the analysis.

4. Reinforcement. 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.

5. 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.

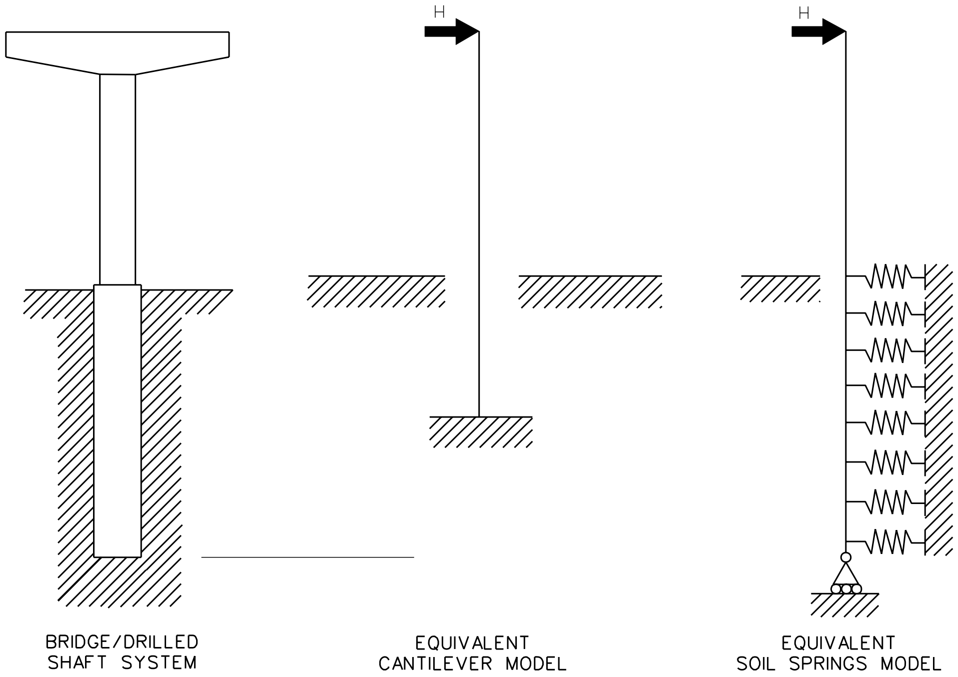
19.4 MODELING FOR LATERAL LOADING

Several possibilities exist for including the effects of piles and surrounding soil into the structural model for lateral loadings including seismic loads. Two of these methods are summarized in Figure 19.4-1 and include:

- equivalent cantilever model, and
- equivalent soil springs model.

The simplest approach is to assume that an equivalent cantilever column can be used to model the pile. The sectional properties of the cantilever are the same as that of the pile, but its length (depth to "fixity") is adjusted to provide either the same stiffness at ground level or the same maximum bending moment as in the actual soil-pile system.

The second technique noted above involves the use of p-y curves to represent the soil. The soil surrounding the pile is modeled as a set of equivalent soil "springs" indicating that the soil resistance "p" is a nonlinear function of the pile deflection "y." A disadvantage of this approach is the substantial increase in the size and complexity of the structural model. The solution's accuracy is primarily 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 is not so dependent on the pile itself. Simple beam column elements are usually adequate for modeling pile behavior. SCDOT uses a computer program such as LPILE or FB-Pier to model equivalent soil springs.



METHODS OF REPRESENTING PILE FOUNDATION STIFFNESS

Figure 19.4-1

19.5 SPREAD FOOTINGS AND PILE/SHAFT-SUPPORTED FOOTINGS

This Section applies to both spread footings supported on soil and to pile/shaft-supported footings.

19.5.1 Usage

As noted in Section 12.5, SCDOT rarely uses spread footings. Spread footings may be used at grade separations where suitable soils or rock are located at a relatively shallow depth (less than 10 ft). They are prohibited:

- at stream crossings where they may be susceptible to scour,
- on fills, and
- beneath bents that are located within the reinforced soil mass associated with MSE walls.

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.

Pile/shaft-supported footings distribute loads among two or more piles or drilled shafts that support a single column or group of columns.

19.5.2 Dynamic Load Allowance (IM)

Dynamic load allowance (IM), traditionally termed impact, shall be applied to the proportioning of footings to resist moment and shear, if any portion of the footing is above ground. Dynamic load allowance need not be applied to proportion spread footings to resist bearing, sliding, or overturning.

19.5.3 Minimum Dimensions/Materials

The following minimum criteria shall apply:

1. Footing Thickness:
    - Spread Footings: 2′-6″
    - Pile/Shaft-Supported Footings: 3′-6″
2. Compressive Strength: 28 day (for structural design): 4 ksi
3. Reinforcing Steel: $f_y = 60$ ksi

19.5.4 Footing Thickness and Shear Design

Reference: LRFD Articles 5.8.3, 5.13.3.6, and 5.13.3.8

The footing thickness may be governed by the development length of the footing dowels (footing to wall or column) or by concrete shear requirements. Generally, shear reinforcement in footings should be avoided. If concrete 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.

19.5.5 Footing Elevation

The following will apply:

1. For grade-separation projects, the footing elevation shall be set to maintain a minimum of 2 ft of backfill above the top of the footing. When setting the footing elevation, consideration should also be given to future widenings.
2. For “waterline” footings, the bottom of the footing elevation shall be set a minimum of 1 ft below the mean low-water elevation.
3. At shallow stream crossings, the top of the footing should be set at or below the streambed elevation to minimize the potential for debris buildup.
4. For footings in navigable waters, the top of the footing shall be set either low enough to not present a hazard to the waterway traffic or high enough to be clearly visible to the waterway traffic.

19.5.6 Bearing Resistance and Eccentricity

Reference: LRFD Article 10.6.3

The required ultimate bearing and the geotechnical resistance factor shall be shown in the plans. See Section 6.3.

19.5.6.1 Soils Under Footings

Reference: LRFD Article 10.6.3.1.5

In contrast to the approach in the AASHTO *Standard Specifications*, a reduced effective footing area based upon the calculated eccentricity is used to include these effects. Uniform design bearing pressure is assumed over the effective area. This uniform-pressure model acknowledges the plastic nature of soil. An example is provided in Figure 19.5-2.

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

19.5.6.2 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.

19.5.7 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 very effective, and their economic justification is often over estimated. However, when it becomes necessary to use a key, the designer shall prepare studies early in project design to evaluate this issue.

19.5.8 Settlement

Reference: LRFD Articles 3.12.6, 10.6.2.2, and 10.7.2.3

Differential settlement (SE) is considered a superstructure load in the *LRFD Specifications*. Generally, due to the methods used by SCDOT to proportion foundations, settlements are within a tolerable range and, therefore, force effects due to differential settlement need not be investigated. If varying conditions exist, settlement will be addressed in the Bridge 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 settlement may create a feeling of lack of safety.

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.

19.5.9 Reinforcement

Reference: LRFD Articles 5.10.8 and 5.13.3

Unless other design considerations govern, the reinforcement in footings should be as follows:

1. Steel in Top of Footing. For pile/shaft-supported footings, 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 the footing in both directions shall be #6 bars at 12 in on center.

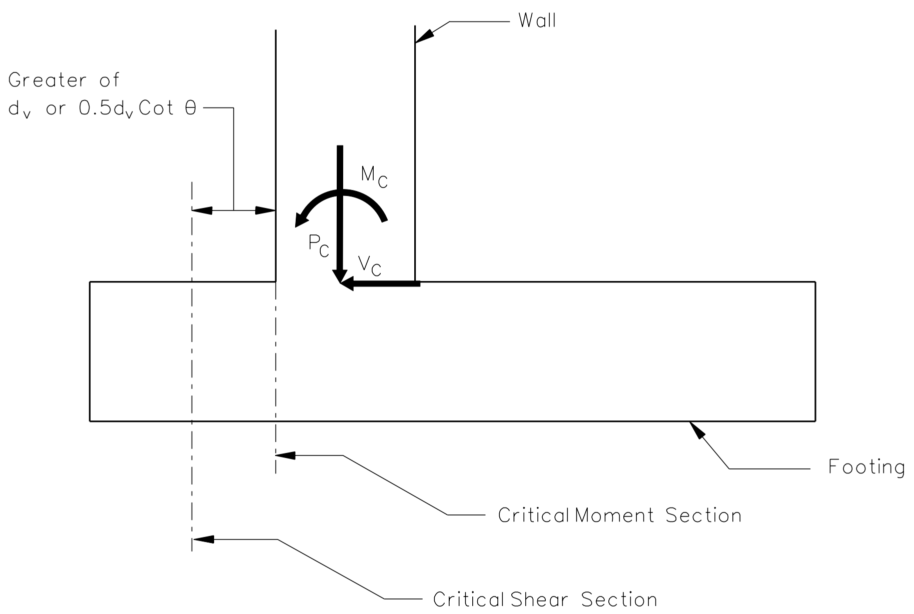
2. Embedment Length. Vertical steel extending upwards out of the footing shall also extend down to the bottom footing steel and shall be hooked on the bottom end regardless of the footing thickness. Bar embedment lengths shall be shown on the plans.

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. 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. See Figure 19.5-1. 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.

19.5.10 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 placed in the joint.



CRITICAL SECTIONS FOR MOMENT AND SHEAR FOR WALLS OR WALL-LIKE PIERS

Figure 19.5-1

19.5.11 Stepped Footings

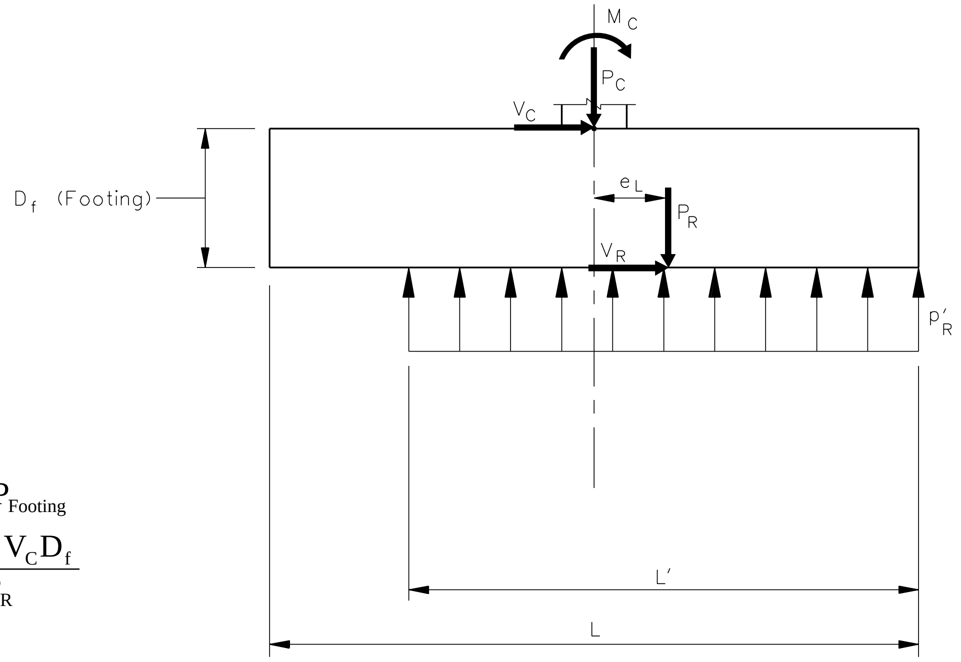
The difference in elevation of adjacent stepped footings should not be less than 6 in. The lower footing should extend at least 2 ft under the adjacent higher footing.

19.5.12 Example Analysis of a Spread Footing on Competent Soil

See Figure 19.5-2 for a schematic example of a spread footing on soil to support an interior bent at a grade separation.

19.5.13 Example Analysis of Pile-Supported Footings

See Figure 19.5-3 for a schematic example of the analysis of a pile-supported footing to support an interior bent at a stream crossing (fixed-pile connection). See Figure 19.5-4 for a similar footing assuming a pinned pile connection.



SECTION

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

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

$$V_R = V_C$$

$$L' = L - 2e_L$$

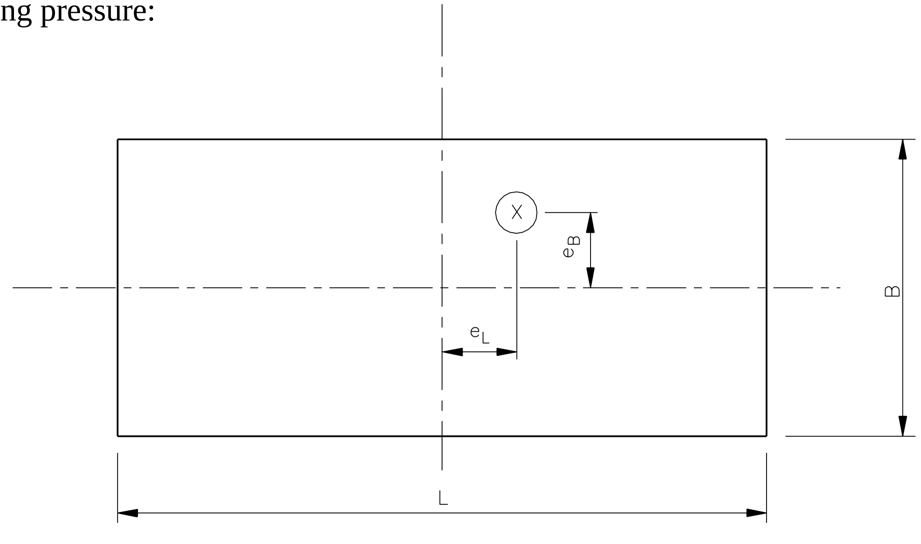
In two dimensions, bearing pressure:

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

Where:

$L' = L - 2e_L$

$B' = B - 2e_B$

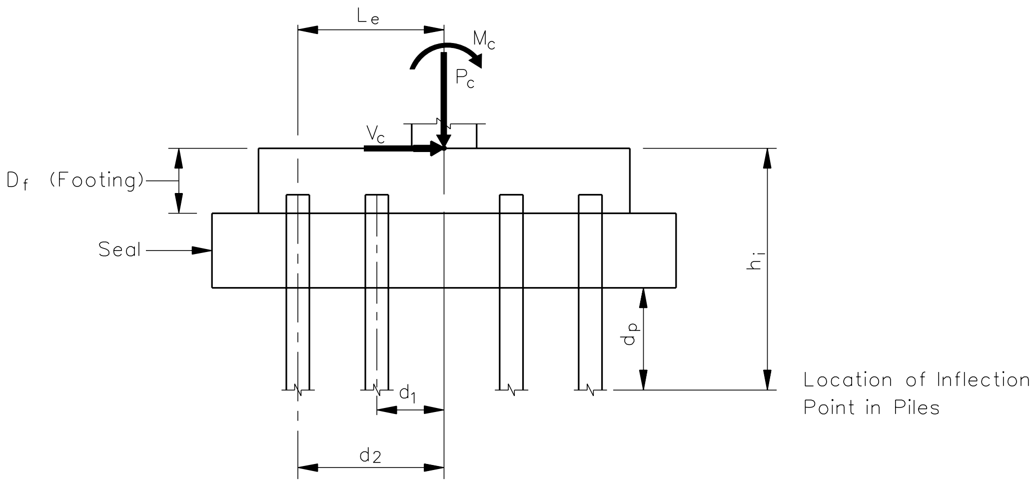


PLAN

Note: See LRFD Article 10.6.3.1.5.

EXAMPLE ANALYSIS OF SPREAD FOOTING ON COMPETENT SOIL

Figure 19.5-2



$P_R = P_c + P_{footing} + P_{seal} - \text{Buoyancy}$

Assumptions: Pile footing is rigid (footing is considered rigid if $L_e/D_f \le 2.2$). Pile connections are fixed and shear forces per pile are significant.

To obtain forces in piles, sum moments about inflection point:

$$P_{max} = \frac{P_R}{\#\text{ of piles}} + \frac{(V_c h_i + M_c)\, d_2}{I_z}$$

$$P_{min} = \frac{P_R}{\#\text{ of piles}} - \frac{(V_c h_i + M_c)\, d_2}{I_z}$$

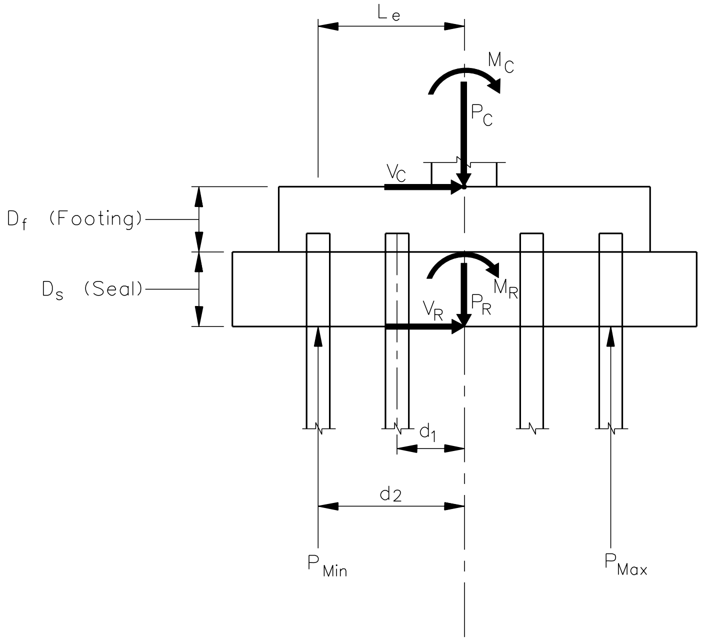
$$I_z = 2\left(d_1^2 + d_2^2\right)$$

$$V_{pile} = \frac{V_c}{\#\text{ of piles}}$$

$$M_{pile} = V_{pile}\, d_p$$

EXAMPLE ANALYSIS OF PILE-SUPPORTED FOOTING
(Fixed-Pile Connection)

Figure 19.5-3



$P_R = P_c + P_{footing} + P_{seal} - \text{Buoyancy}$

Assumptions: Pile footing is rigid (footing is considered rigid if $L_e/D_f \le 2.2$). 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 PILE-SUPPORTED FOOTING
(Pinned-Pile Connection)

Figure 19.5-4