17. Foundations

17.1. General

A critical consideration for the satisfactory performance of any structure is the proper selection and design of a foundation that will provide adequate support. This chapter discusses Alaska-specific criteria that supplement Section 10 of the *LRFD Specifications* for the design of spread footings, driven piles, and drilled shafts. Although primarily focused on bridge foundations, this chapter addresses other transportation structure foundations.

Section 11.7 of this *Manual* presents DOT&PF criteria for selecting an appropriate foundation type within the context of structure-type selection. The *Alaska Geotechnical Procedures Manual* discusses the geotechnical considerations for bridge and transportation structure foundation design.

17.1.1. Design Methodology

The following summarizes the concepts in the *LRFD Specifications* for the design of foundations for bridges and structures.

Considering basic design principles for foundations, the *LRFD Specifications* implemented a major change when compared to the traditional principles of the AASHTO *Standard Specifications for Highway Bridges (Standard Specifications)*. 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 *LRFD Specifications* emphasize the distinction by addressing in-situ materials in Section 10 "Foundations" and structural components in Sections 5 and 6, which specify requirements for concrete and steel elements. The structural engineer applies the appropriate provisions from these sections in the structural design of footings, steel and concrete piles, and drilled shafts.

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

17.1.2. LRFD Resistance Factors for Foundations

LRFD Article 10.5.5.1 presents resistance factors for the Service limit states, which are typically 1.0. LRFD Articles 10.5.5.2.2, 10.5.5.2.3, and 10.5.5.2.4, present resistance factors for the Strength limit state for spread footings, driven piles, and drilled shafts respectively.

17.1.3. Arctic Engineering

Some areas of Alaska have ground conditions that include permafrost, which is ground that has remained at or below 32°F for two or more years. The active layer is the surficial layer of soil that undergoes seasonal freeze/thaw cycles.

Two methods are usually recommended for installing deep foundations in permafrost. For warm permafrost (31°F), drive piles through the permafrost layer. For cold permafrost (less than 27°F), cut or drill a hole, set the pile into the hole, and then fill the annulus with slurry. The project-specific installation method will be identified in the Structural Foundation Engineering Report (SFER).

After installation, isolate piles from the soils in the active layer. DOT&PF prohibits thermal piles.

For seismic design, consider both the thawed and frozen conditions.

17.1.4. Differential Settlement

Reference: LRFD Articles 3.12.6, 10.6.2.2, and 10.7.2.3.

Differential settlement is the difference between the settlements of two adjacent foundations. In the *LRFD Specifications,* differential settlement (SE) is a superstructure load.

DOT&PF Practice

Generally, due to the methods used by DOT&PF to proportion foundations, settlements are within a tolerable range and, therefore, force effects due to differential settlement need not be investigated.

The general DOT&PF practices on the acceptable limits for settlement are:

1. **Estimated Differential Settlement**. If Statewide Materials estimates that the differential settlement is less than one-half of the total estimated settlement, the bridge engineer 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.

   DOT&PF does not use the LRFD limits for design, which are related to structural distress, because these angular distortions yield unacceptable impacts on ride-ability and aesthetics. Typically, meeting the requirements of Item 1. Estimated Differential Settlement should preclude exceeding the angular distortions allowed by the *LRFD Specifications*.
3. **Piers**. Consider deep foundations where differential settlement is a concern between columns within a pier.

Foundation Settlement Effects

If varying site conditions exist, the Final SFER will address settlement. Consider the following effects:

1. **Structural**. The differential settlement of substructures causes the development of force effects in continuous superstructures. These force effects are directly proportional to structure depth and inversely proportional to span length, indicating a preference for shallow, long-span structures.

   The force effects from settlement are normally smaller than expected and tend to be reduced in the inelastic phase. Nevertheless, these force effects 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 joint 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 perception of lack of safety.

Foundation Settlement Mitigation

Use ground modification techniques to improve the soil to address differential settlement concerns. Some available techniques include:

- chemical grouting
- over-excavation and replacement
- surcharging
- installation of stone columns
- compaction grouting
- deep dynamic compaction

17.2. Structural Foundation Engineering Report

Use the following procedures to assist the foundation engineer in developing the Structural Foundation Engineering Report (SFER) and to provide support for bridge design and construction activities.

17.2.1. Overview and Objectives

The Department designs and constructs bridges in conformance with the *AASHTO LRFD Bridge Design Specifications (AASHTO)* and other DOT&PF documents. These specifications provide requirements for field exploration, foundation analysis, and field monitoring of bridge foundations, and aid in the development of the SFER.

SFER development requires coordination among several functional groups. The objective of this section is to:

- outline the interaction among the design team members,
- define the process for developing and implementing the SFER recommendations, and
- describe the support activities commonly required during bridge construction projects.

17.2.2. Bridge Foundation Design Process

The regional project manager (PM) requests support from the Statewide Materials Section (Geotech) to aid in developing site selection and roadway alignment options during the Preliminary Design Phase (pre-environmental document).

The PM requests support from the Bridge Section (Bridge) to develop bridge type alternatives. The PM uses Geotech and Bridge recommendations to support the identification of a preferred project alternative. Based upon the project objectives, the PM determines the preferred bridge alternative and site selection. Once selected, Bridge will send the preferred bridge alternative and site selection information (including preliminary plans in AutoCAD format) to the PM. The PM will arrange for a geotechnical investigation and foundation design recommendations by Geotech.

Note: *Geotech and Bridge typically communicate directly with each other. However, the PM is the primary contact and should be copied in most correspondence, especially matters addressing project scope, schedule, or budget. Comply with all of the requirements of the Alaska Highway Preconstruction Manual (e.g., Section 450.9.1 "Bridge Design" and Section 450.9.6 "Geotechnical Investigations").*

Geotech prepares a subsurface exploration plan based on the preferred bridge alternative(s). This typically occurs during the Preliminary Design Phase. Bridge reviews and comments on the plan. PM approval is required prior to executing the subsurface exploration plan.

Geotech and Bridge use the subsurface exploration findings to generate the Foundation Geology Report (refer to the *Alaska Geotechnical Procedures Manual* for additional information). This report helps to generate the Preliminary SFER and the Final SFER.

Geotech prepares the Preliminary SFER during the Preliminary Design Phase to identify feasible foundation types and design parameters. The preliminary subsurface information serves as the basis of the Preliminary SFER that Bridge uses to determine the most economically feasible foundation.

Once Bridge has identified the preferred bridge foundation, Geotech generates the Final SFER. The Final SFER is prepared during the Design Phase, prior to generating the final stamped bridge plans.

Note: *The preceding sequence requires Geotech to conduct the field exploration during the Preliminary Design Phase of the project. However, funding and other issues (e.g., environmental permitting) may preclude the execution of field explorations during the Preliminary Design Phase. If the field exploration is postponed until the Design Phase, the time allotted for preparing the SFER may be compressed.*

Preliminary Design Phase Interaction

Bridge and Geotech collaborate to generate the Foundation Geology Report and Preliminary SFER. Key components of this collaboration are detailed below.

Geotech Needs/Bridge Provides:

- the proposed bridge configuration (i.e., the preliminary General Layout and Site Plan drawings for the bridge options)
- the foundation locations (typically, the centerline support station and skew are shown on the Site Plan drawings)
- the total estimated factored loads (Strength I) to the foundation elements that will be used in determining reasonable sizes of foundation elements and requisite subsurface testing depths
- the total estimated Service I loads to the foundation elements

- the average unfactored pile dead load for each substructure unit, used for neutral plane method analysis
- a list of special bridge needs and concerns, if any (e.g., “limit support settlements for the proposed structure to approximately one inch under Service Load combinations” or “the existing bridge has shown signs of frost jacking at Pier 2”)
- an estimate of the scour depth at in-water piers (a method for estimating local pier scour is provided in Figure 17-1 to facilitate preliminary design in advance of a formal bridge hydraulic study); and
- historic subsurface and pile driving data (Bridge may have historic pile driving records or other relevant information in its files that may aid in the development of foundation recommendations. If such data exists, send copies to Geotech).

Bridge Needs/Geotech Provides:

- the subsurface exploration plan (the PM, responsible for controlling the project’s scope, schedule, and budget, must formally approve the plan; a copy of the plan is typically sent to Bridge for comment); and
- the Preliminary SFER, described in Section 17.2.3, containing an array of deep and shallow foundation options (feasible foundation types are examined to determine the most cost-effective structure. It is important that an ample variety of foundation recommendations be prepared to allow for meaningful cost comparisons).

Design Phase Interaction

Ideally, Bridge receives the Final SFER two months before the stamped PS&E due date. Collaboration between Bridge and Geotech is required to generate the Final SFER. Key components of this exchange are as follows:

Geotech Needs/Bridge Provides:

- the review of PS&E documents (typically distributed by PM to Geotech as part of the Review PS&E process)
- the final total factored loads (Strength I) to the foundation (these values will be provided in the foundation Data Table on the Site Plan drawing)
- the final total Service I loads to the foundation for settlement analysis, if necessary
- the final scour depth (these values will be provided in the Hydraulic and Hydrologic Summary table on the Site Plan drawing); and
- The final average pile dead load per substructure unit for neutral plane method analysis

Bridge needs/Geotech provides:

- the stamped Final SFER containing the final Foundation Geology Report as described in Section 17.2.3;
- the final pile driving special provisions, if necessary (e.g., field monitoring requirements, pile driving concerns such as hard driving, pile tip reinforcement requirements, pre-boring requirements, etc., that are not addressed in the *Alaska Standard Specifications*; and
- comments on the foundation design shown in the plans (Geotech will verify that the bridge foundation agrees with the Final SFER recommendations).

17.2.3. Content Requirements of the SFER

The Preliminary SFER and Final SFER contain the information presented in the following subsections. The Preliminary SFER focuses on design recommendations such as foundation capacity charts and feasible foundation types. The Final SFER is a fully developed report with supporting analysis and documentation.

Requirements of the Preliminary SFER

The Preliminary SFER provides geotechnical design data and recommendations for deep and/or shallow foundations.

Geotechnical Data

The Preliminary SFER contains the following geotechnical data:

- the preliminary Foundation Geology Report, including test hole locations, geological description of soils and rock, Standard Penetration Test (SPT) data, ground water table locations, temperature data, permafrost depth, and other data as applicable;

- the description of bedrock properties when present, including planes of weakness, joints, faults, rock type, Rock Quality Designation

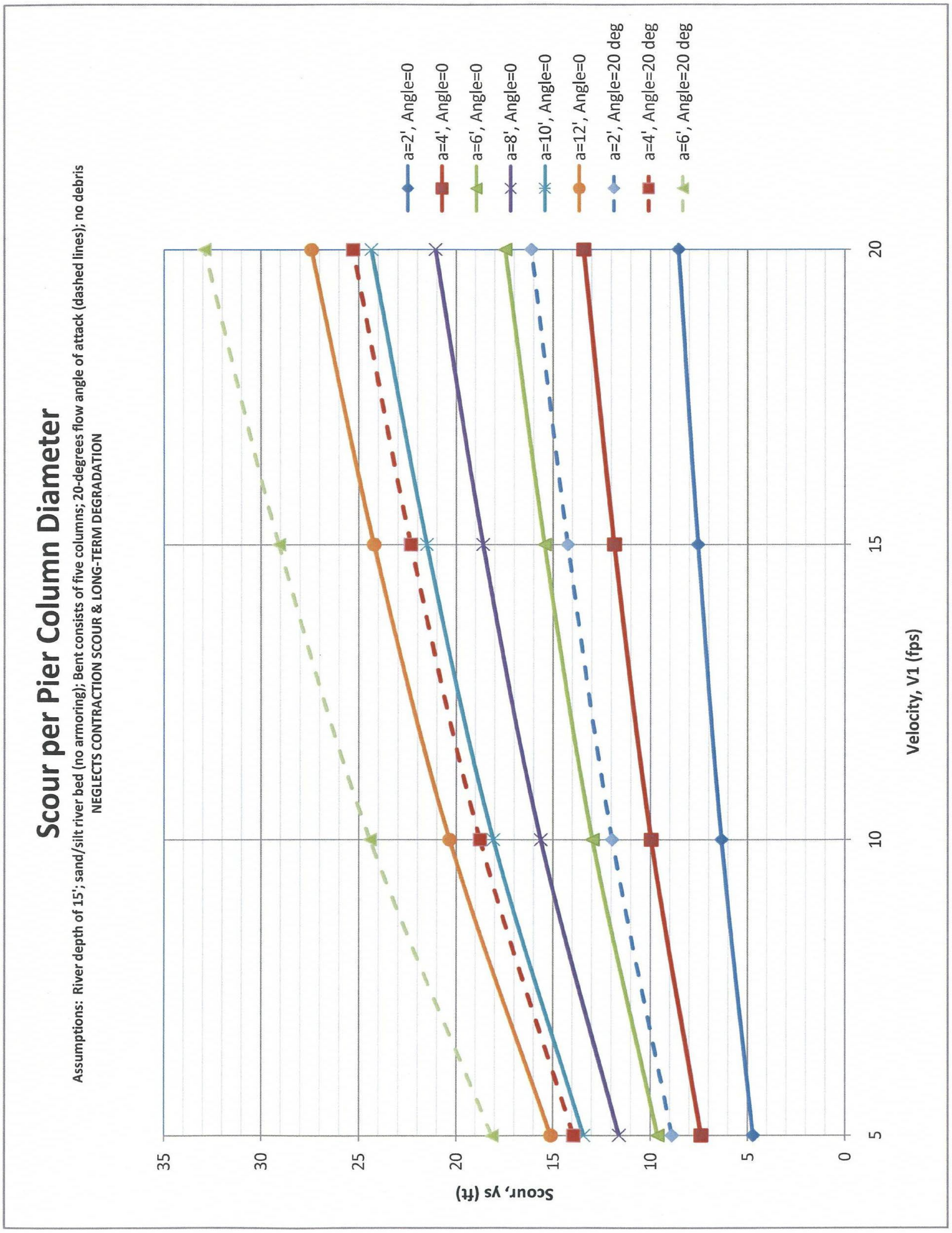


Figure 17-1
Preliminary Pier Scour Estimation Graph

(RQD), etc., as they relate to the foundation recommendations;

- the subsurface soil description, including unit weight, relative density, moisture content, phi angle, and lateral stiffness parameters and modeling recommendations for each layer of soil (Bridge will perform the lateral pile/shaft analysis);
- the presence of permafrost, high ground water table, and soil stability considerations; and
- the AASHTO seismic site class designation (i.e., "A" through "E" and, in special cases, "F") and the applicability of code-specified seismic response spectra (i.e., are there local faults that would result in seismic demands greater than those provided in the *AASHTO LRFD Bridge Design Specifications*?).

Deep Foundation Data

Typically, use deep foundations (e.g., steel H-piles, steel pipe piles, drilled shafts) at water crossings, in poor soils, and in other locations where shallow foundations are inappropriate. Preliminary design recommendations on a variety of driven pile and shaft sizes are required to determine the most cost-effective bridge foundation and bridge type. The Preliminary SFER contains deep foundation recommendations including:

- capacity tables and charts presenting the axial and uplift vertical resistance, including scour effects, as a function of embedment depth (this data is used to establish the Estimated Pile Tip Elevation for piles or the Tip Elevation for drilled shafts);
- capacity tables and charts presenting the axial and uplift vertical resistance, excluding scour effects, as a function of embedment depth (this data is used for establishing the vertical resistance at the time of construction, without regard to scour or other reductions in vertical resistance);
- capacity tables and charts presenting the axial and uplift vertical resistance, including liquefaction effects, as a function of embedment depth (the effects of scour and liquefaction may act concurrently);
- capacity tables and charts presenting the non-seismic nominal downdrag load (e.g., settlement, consolidation) either as a single value or as a function of embedment, as appropriate; and
- capacity tables and charts presenting the nominal seismic-induced downdrag load (primarily due to liquefaction effects) presented as either a single value or as a function of embedment, as appropriate.

For driven pile foundations, use the unfactored nominal resistance when preparing the vertical capacity with depth tables or charts. For drilled shafts, use the factored nominal resistance when preparing the vertical resistance with depth tables or charts. Deep foundation recommendations account for the following:

- Scour effects that reduce the amount of soil around the pile or shaft, reducing the member's vertical and lateral resistance. The Hydraulic and Hydrologic Report addresses scour effects and are summarized in the Hydraulic and Hydrologic Summary table on the bridge Site Plan drawing. For the Preliminary SFER, use the graph provided in Figure 17-1 to estimate scour effects. Figure 17-1 relates stream velocity and depth to estimated scour depth. In lieu of more accurate information, assume that the water flow velocity, V_1, is 15 feet/second. For multiple-column, pile-extension piers, assume a 20-degree water flow angle of attack (labeled "Angle = 20" on the chart). For single-column piers, assume a 0-degree water flow angle of attack (labeled "Angle = 0." The value "a" is the pile or shaft diameter). For the Final SFER, use the scour values provided in the Hydraulic and Hydrologic Summary table as the basis of the design.
- Liquefaction effects caused by seismic-induced ground motion that reduce the member's vertical and lateral resistance. The Preliminary SFER includes the soil's liquefaction potential (i.e., high, medium, low), liquefied soil properties, deformations due to lateral soil flow and settlement, and subsequent downdrag loads. (Bridge does not typically use steel H-piles or shallow foundations in liquefiable soils where lateral spread is possible).

- Downdrag loads that reduce the member's vertical and lateral resistance. Geotech shall provide recommendations for addressing downdrag (e.g., "sleeve the uppermost 10 feet of the pile" or "as required in Section 505-3.09 of the *Alaska Standard Specifications*").

- Address the spacing and group effects that would have a tendency to reduce the vertical and lateral capacity of the piles or shafts and/or minimum pile spacing.

- Rock socket length that may be required to develop vertical or lateral resistance. Provide the minimum rock socket length. (Collaboration between Bridge and Geotech may be required in establishing the rock socket length in high seismic hazard areas where the development of the member's overstrength capacity is required).

- The Preliminary SFER shall address other foundation demands such as those associated with frost jacking and heave and shall provide design recommendations.

All DOT&PF projects require field monitoring of pile driving operations. For driven pile foundations, the DOT&PF will specify the use of either:

- the "Wave equation analysis without pile dynamic measurements," or
- a "Driving criteria established by dynamic test with signal matching."

Use the corresponding dynamic analysis resistance factors, φ_{dyn}, from the most current edition of the *AASHTO LRFD Bridge Design Specifications* (currently, φ_{dyn}= 0.50 and φ_{dyn} = 0.65, for "Wave equation analysis without pile dynamic measurements" and "Driving criteria established by dynamic test with signal matching," respectively). The Preliminary SFER should include recommendations for field monitoring. In the absence of field monitoring recommendations, Bridge will determine field-monitoring requirements based on the most cost-effective option.

Shallow Foundation Data

Shallow foundations are typically used for non-water crossings (e.g., highway interchanges) where the underlying soil has good bearing capacity. The Preliminary SFER contains shallow foundation design recommendations including:

- nominal soil bearing resistance at the Service, Strength, and Extreme Event limit states as a function of effective footing width;

- minimum embedment depth required due to frost penetration and other factors affecting the nominal soil bearing resistance (in most cases, Bridge will require that the bottom of the footing be at least 3 feet below the finished ground line);

- need for replacement of the existing soil with engineered material (in some cases, the existing soil may be replaced with the structural fill material identified in the *Alaska Standard Specifications*); and

- ground water table location and its effects on the nominal soil bearing capacity (use the highest anticipated ground water table when determining the nominal bearing resistance).

Requirements of the Final SFER

The recommendations in the Final SFER are the same as those in the Preliminary SFER, except that the Final SFER addresses only the bridge foundation elements used in the final bridge design. Develop the full body of the text in the Final SFER, expounding upon:

- geotechnical data and interpretation
- discussion of foundation recommendations
- seismic conditions and liquefaction
- analysis methods and limitations
- construction issues and recommendations
- sealed and signed test hole location and boring log plan sheets
- references

Bridge cannot submit the stamped PS&E to the PM before receiving the Final SFER.

17.2.4. Plan Set Information

Provide the following information on either the bridge Site Plan drawing or, if present, the Foundation Plan drawing.

Foundation Data Tables

Bridge will provide the following table in all bridge plans using piles as a foundation element. The special provisions provide the level of field monitoring, and

Table 17-1
Pile Data Example Table

PILE DATA TABLE							
		Driving Criteria			Design Data		
Location	Pile Type	Minimum Penetration (FT)	Estimated Pile Tip Elevation (FT)	Minimum Driving Resistance (K)	Strength I Factored Load (K)	Nominal Resistance (K)	Resistance Factor, φ
Abut. 1	HP14 × 117	40.0	1415.0	600	350	550	0.65
Pier 2	4′-0″ × 1″ Pipe	60.0	1400.0	1400	800	1250	0.65

Table 17-2
Drilled Shaft Data Table Example

DRILLED SHAFT DATA TABLE							
		Installation Criteria			Design Data		
Location	Shaft Diameter	Tip Elevation (FT)	Minimum Rock Socket Length (FT)	Minimum Top of Rock Socket Elevation (FT)	Strength I Factored Load (K)	Nominal Resistance (K)	Resistance Factor
Pier 2	8′-0″	1624.0	16.0	1640.0	2100	4200	0.5

Table 17-3
Footing Pressure Table Example

FOOTING PRESSURE TABLE			
Location	Strength I Factored Load (KSF)	Nominal Bearing Resistance (KSF)	Bearing Resistance Factor, φ
Abut. 1	4.2	12.0	0.45
Abut. 3	4.9	12.0	0.45

provide the associated Resistance Factor in the Pile Data (see Table 17-1 for an example). Currently, a Resistance Factor value of 0.50 indicates that “Wave equation analysis without pile dynamic measurements” will be used. A Resistance Factor value of 0.65 indicates that a “Driving criteria established by dynamic test with signal matching” is required.

Minimum penetration of the pile is typically based upon lateral resistance requirements (e.g., seismic or ice demands). Base the Estimated Pile Tip Elevation upon the factored estimated resistance after scour, downdrag, liquefaction, and all other pile resistance conditions have been considered. Because scour, downdrag, and other pile resistance reductions are not present during pile driving, the Minimum Driving Resistance, in most cases, will be greater than the Nominal Resistance.

The Nominal Resistance of the pile is the anticipated pile capacity after all applicable pile resistance reductions have occurred. The Strength I Factored Load must be less than the Nominal Resistance multiplied by the Resistance Factor.

Bridge will provide a Drilled Shaft Data table (see Table 17-2 for an example) in all bridge plans that use drilled shaft foundations.

Provide the drilled shaft Tip Elevation and Minimum Rock Socket Length in the SFER. Do not include the material that is encountered above the specified Minimum Top of Rock Socket Elevation in the

Minimum Rock Socket Length (e.g., in Table 17-2, rock encountered above elevation 1640.0 does not contribute towards the 16.0-foot Minimum Rock Socket Length). If rock is not anticipated, then the table will be provided with "NA."

The Nominal Resistance of the drilled shaft is the anticipated shaft capacity after all applicable reductions have occurred. The Strength I Factored Load must be less than the Nominal Resistance multiplied by the appropriate Resistance Factor(s).

Bridge will provide the level of field inspection for drilled shafts (e.g., down-hole inspection and bottom cleanliness) in the special provisions.

Bridge will provide a Footing Pressure table (see Table 17-3 for an example) in all bridge plans that use shallow foundations.

Seismic Parameters

Bridge will provide the seismic design parameters, as shown in Figure 17-2, in the "GENERAL NOTES" of the Site Plan drawing. Provide the spectral acceleration values in the *AASHTO LRFD Bridge Design Specifications* and the *AASHTO Guide Specifications for LRFD Seismic Bridge Design*. Provide the Site Class and Liquefaction Potential in the SFER

For Site Class F soils or other situations where a site-specific response spectra is used in the bridge design, include the site-specific spectra on the bridge plans sheets.

Log of Test Hole Borings

Bridge will incorporate the sealed and signed test hole location and boring log plan sheets in the final bridge plans.

17.2.5. Construction Support

Both Geotech and Bridge must be available during construction to address construction-related foundation and geotechnical questions and problems and to provide technical advice to the Construction Project Engineer.

For pile foundations, Geotech will be required to:

- review the adequacy of the Contractor's proposed pile driving plan;
- review the adequacy of the Contractor's proposed pile driving hammer;
- provide the pile driving acceptance criteria (also known as the inspector's chart) when a "*Wave equation analysis without pile dynamic measurements*" is specified;
- provide preliminary pile driving acceptance criteria when *"Driving criteria established by dynamic test with signal matching"* is specified; and
- generate the scope of services for the Construction Project Engineer when a *"Driving criteria established by dynamic test with signal matching"* is specified and interact with the PDA consultant once its services have been acquired.

For drilled shaft foundations, both Geotech and Bridge will be required to:

- review the adequacy of the Contractor's proposed shaft installation plan; and
- review field inspection reports (e.g., shaft cleanliness, cross-hole-sonic logs).

For shallow foundations, Geotech may be required to evaluate foundation adequacy when the actual soils deviate from those presented in the Foundation Geology Report and Final SFER (e.g., groundwater table, rock characteristics, soil type).

SEISMIC PARAMETERS PGA = 0.25
S_s = 0.65
S_1 = 0.20
Site Class = C
Liquefaction Potential = Low
AASHTO 7% probability of exceedence in 75 years

Figure 17-2
Seismic Parameters

17.3. Footings and Caps

17.3.1. Terms

Spread Footing: A slab of concrete directly transferring load to the soil beneath it.

Pile Caps: A strip of concrete transferring load to a single row of piles.

Pile Footings: A slab of concrete transferring load to multiple rows of piles.

17.3.2. General

The following criteria apply to both footings and caps.

Basic Design Criteria
Reference: LRFD Articles 5.12.8.6 and 5.12.8.7.

The footing or cap thickness may be governed by the development length of the column or wall reinforcement, or by seismic requirements.

Construction Joints
Footings and caps do not generally require construction joints. Where used, offset construction joints 2 feet from expansion joints or construction joints in walls, and construct the joints with keyways.

Stepped Footings/Caps
Stepped footings and caps are only used occasionally. Where used, the difference in elevation of adjacent stepped footings or caps should not be less than 4 feet. See Figure 17-3.

Depth
Locate pile caps or footings above the lowest anticipated scour level if the piles are designed for this condition. Construct caps or footings to neither pose an obstacle to water traffic nor be exposed to view during low flow. Construct caps or footings to pose a minimum obstruction to water and debris flow if exposed during high flows.

17.3.3. Spread Footings

Embed spread footings a sufficient depth to provide the greatest of the following:

- adequate bearing, scour, and frost heave protection (typically defined in the SFER);
- 3 feet to the bottom of the footing; or
- 2 feet of cover over the footing.

Sliding Resistance
Reference: LRFD Article 10.6.3.4.

Except for unusual cases, do not use keys in footings to develop passive pressure against sliding. When it becomes necessary to use a key, the bridge engineer should consult with the Statewide Materials Section.

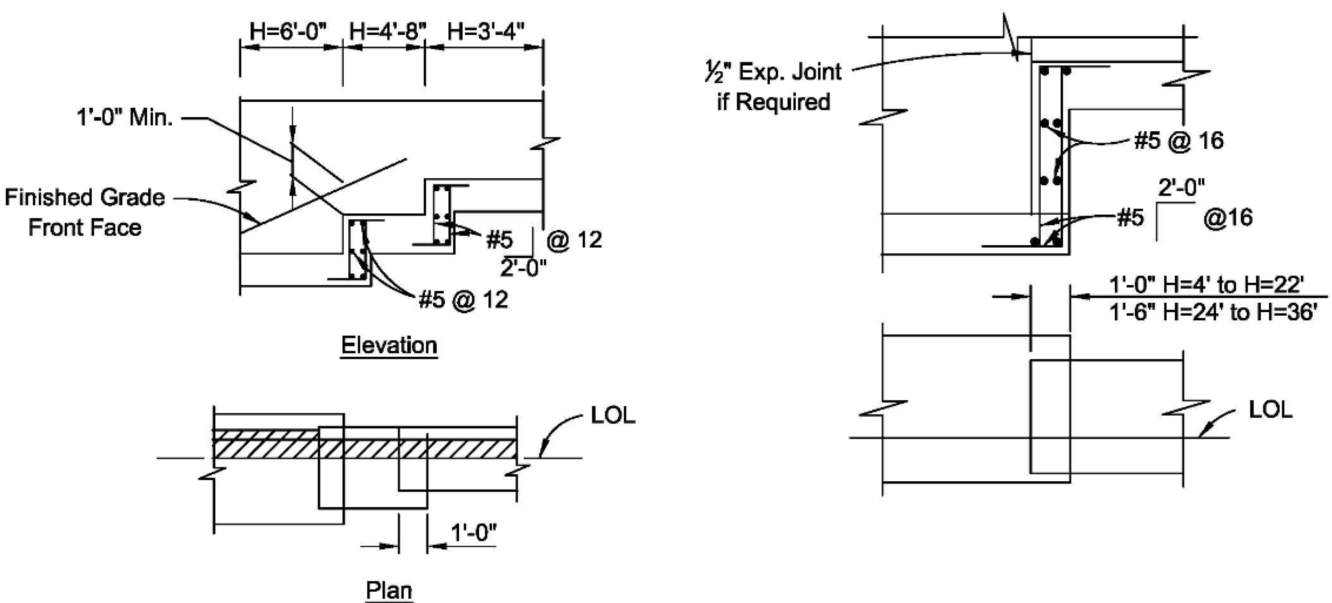


Figure 17-3
Stepped Footings/Caps Pile Caps/Footings

17.4. Driven Piles

Piles serve to transfer loads to deeper suitable strata. Piles may function through skin friction, through end bearing, or a combination of both.

17.4.1. Pile Types/Selection

See Section 11.7.4 for DOT&PF practices for selecting driven piles as the foundation type. Minimize the use of differing pile types and sizes.

Steel H-Piles

DOT&PF uses steel H-piles to support abutments protected against scour, where a competent bearing layer is available. The steel H-pile shape most commonly used by DOT&PF is HP14x117. Other sizes may be acceptable. Where a significant savings may be realized by using non-typical sizes or where the design dictates, use other standard AISC sizes.

Steel Pipe Piles

Reference: LRFD Articles 6.9.5 and 6.12.2.3.

DOT&PF uses steel pipe piles in waterways where the predicted scour is deep and driving conditions are favorable, and at sites prone to liquefaction. Use pipe pile extension piers to speed construction compared to the use of pile footings with CIP concrete columns. Conventionally, use open-ended piles where cobbles and boulders may be encountered during driving. This allows use of a down hole hammer to break up obstructions.

Use the following specifications for structural steel pipe piles:

- DOT&PF Special Provisions for spiral welded pipe piles.
- American Petroleum Institute (API) Specification 5L X52 PSL2, Specification for Line Pipe.
- API 2B using ASTM A709 Grade 50T3.
- ASTM A53 Grade B.

Serious shortcomings in the traditionally applied ASTM A252 standard have been identified when attempting to specify steel pipe piles adequate for current bridge design and construction practices.

The following also applies:

1. **Diameter**. DOT&PF uses pipe pile diameters of 12 inches to 48 inches. The wall thickness typically is not less than 1:48 of the pipe diameter.
2. **Interior Filler**. Typically, fill steel pipe piles with reinforced concrete to strengthen and stiffen the pipe and as a means of connecting the pile to the cap/footing.

Pile Selection

The Bridge Section selects the pile type based on the SFER. Figure 17-4 provides guidance in selecting pile types based on their typical usage by DOT&PF.

17.4.2. Design Details

Reference: LRFD Article 10.7.1.

Pile Length

Determine pile length based on the SFER. All piles for a specific pier or abutment should be the same length where practical. Show pile lengths in whole-foot increments.

The estimated pile tip elevations and minimum penetration will be shown on the Pile Data Table in the contract documents. Ensure that the estimated pile tip elevations reflect the elevation where the required ultimate pile capacity is anticipated to be obtained. The minimum penetration should 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 feet in depth require pre-drilling. The size of the pre-drilled hole is 2 inches larger than the diameter or largest dimension of the pile.

Reinforced Pile Tips

Use reinforced pile tips to minimize pile damage where hard layers are anticipated and as recommended in the SFER. Where rock is anticipated, designate that the pile tips will be equipped with teeth designed to penetrate into the rock. Show the type of pile tip reinforcing on the plans.

Battered Piles

Do not use battered piles due to their past poor performance in moderate to high seismic areas.

Pile Footing and Cap Details

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

1. **Steel H-Piles**. See Figure 17-5.

2. **Steel Pipe Piles**. Always extend longitudinal column bars to the top of the cap. Fully develop the reinforcing steel through adequate development length or standard hooks. See Figure 17-6.

17.4.3. Force Effects

Uplift Forces

Lateral loads can cause uplift forces (e.g., seismic forces, buoyancy, frost jacking). Check piles intended to resist uplift forces for resistance to pullout and for structural resistance to tensile loads. Check the connection of the pile to the cap or footing.

Laterally Loaded Piles

Section 17.6 discusses pile analysis for lateral loading and resistance.

17.4.4. Pile Loads

Show applicable pile loads on the plans. This information will help ensure that pile driving efforts will result in a foundation adequate to support the design loads; see Section 17.2.4 for Foundation Data Table requirements.

Pile Type	Soil Conditions and Structural Requirements
Steel H-pile	Rock or dense soil where end bearing is desirable and lateral flexibility in one direction is not critical. Common at abutments and for pile footings, but not typically used in liquefiable soils.
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 or liquefaction is anticipated and high lateral stiffness is needed.

Figure 17-4
Driven Pile Selection

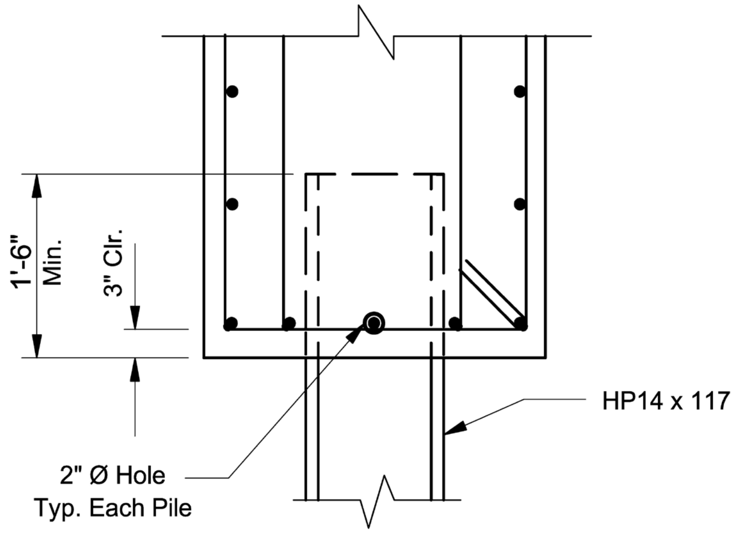


Figure 17-5
Steel H-Pile Connection

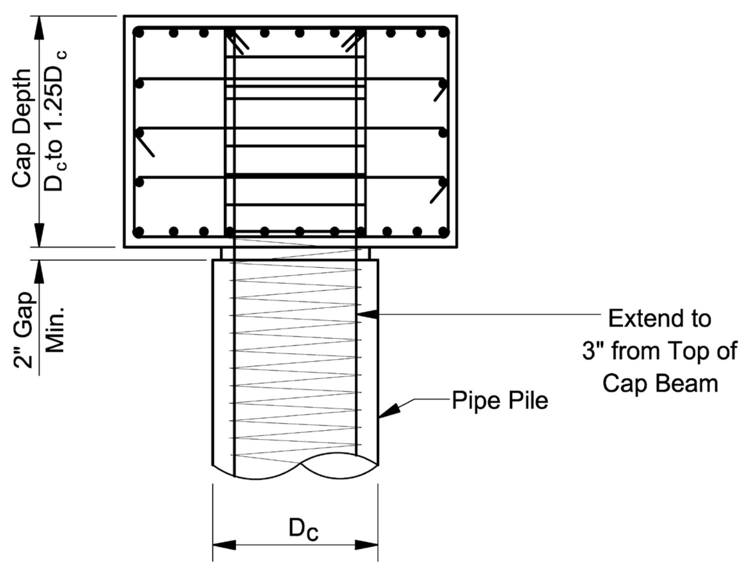


Figure 17-6
Steel Pipe Pile Connection

17.5. Drilled Shafts

17.5.1. Usage

Guidance for selecting drilled shafts as the foundation type can be found in Chapter 11 of this Manual.

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.

17.5.2. Drilled Shaft Axial Compressive Resistance at the Strength Limit State

The *LRFD Specifications* provide procedures to estimate the axial resistance of drilled shafts in cohesive soils and cohesionless soils in 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.

17.5.3. Structural Design

Column Design. Because even soft soils provide sufficient support to prevent lateral buckling of the shaft, design drilled shafts surrounded by soil according to the criteria for short columns in LRFD Article 5.6.4.4 when soil liquefaction is not anticipated. If the drilled shaft is extended above ground to form a pier, design the shaft as a column. Similarly, consider the effects of scour around the shafts in the analysis.

Casing. DOT&PF almost always uses a permanent casing to maintain the excavation, especially when placing a shaft within the groundwater table. Use the casing in the determination of the structural resistance of the shaft, depending on the thickness of the casing. In seismic analysis and design, use a strain compatibility method to determine the stiffness and strength of the cased shaft.

Lateral Loading. Section 17.6 discusses drilled shaft analysis for lateral loading and resistance.

17.5.4. Design Details

1. **Diameter**. The diameter of a drilled shaft supporting a single column should be at least 18 inches greater than the greatest dimension of the column cross section. Shaft diameters up to 120 inches have been used in Alaska.
2. **Location of Top of Shaft**. Typically, terminate drilled shafts 6 inches above the finished grade or at 12 inches above the water elevation anticipated during construction.
3. **Reinforcement**. Section 14.2 discusses DOT&PF practices for the reinforcement of structural concrete, which apply to the design of drilled shafts. Additional reinforcement criteria include:

   a. For the shaft, provide a minimum reinforcement of 1 percent of the gross concrete area. Extend the shaft reinforcement from the bottom of the shaft into the footing, if present.

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

   c. The design and detailing of drilled shafts must provide clearances of 4 inches to 6 inches for reinforced steel cages. Maintain the annular space around the cage with non-corrosive spacers.

   d. Detail drilled shafts and columns to accommodate concrete placement considering the multiple layers of reinforcing steel including lap splices. Maximize lateral reinforcement spacing.

   e. Strive to provide windows about 5-inch square between longitudinal and transverse bars.

   Figures 17-7 and 17-8 illustrate the typical drilled shaft and column longitudinal and transverse reinforcement.

4. **Class DS Concrete**. Construct all drilled shafts with Class DS Concrete, Concrete for Drilled Shaft Foundations. See Section 501 of the *Alaska Standard Specifications for Highway Construction* for these concrete material requirements. Class DS Concrete includes smaller aggregates and provides greater slump, among other features, to facilitate placement of the concrete into the drilled shaft.
5. **Construction Joints**. Do not use construction joints for drilled shafts except with approval by the Chief Bridge Engineer.
6. **Casing**. DOT&PF typically uses permanent metal casings for drilled shafts.

7. **Constructability**. 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. The objective is to provide windows between horizontal and vertical bars equal to 5-inch squares.

8. **Rock-Socketed Shafts**. Where casing through overburden soils is required, design the shaft as one size and, if necessary, step down (reduce the diameter) when going into a rock socket.

9. **Specialized Contractors**. Use specialized contractors for drilled shafts greater than 6 feet in diameter.

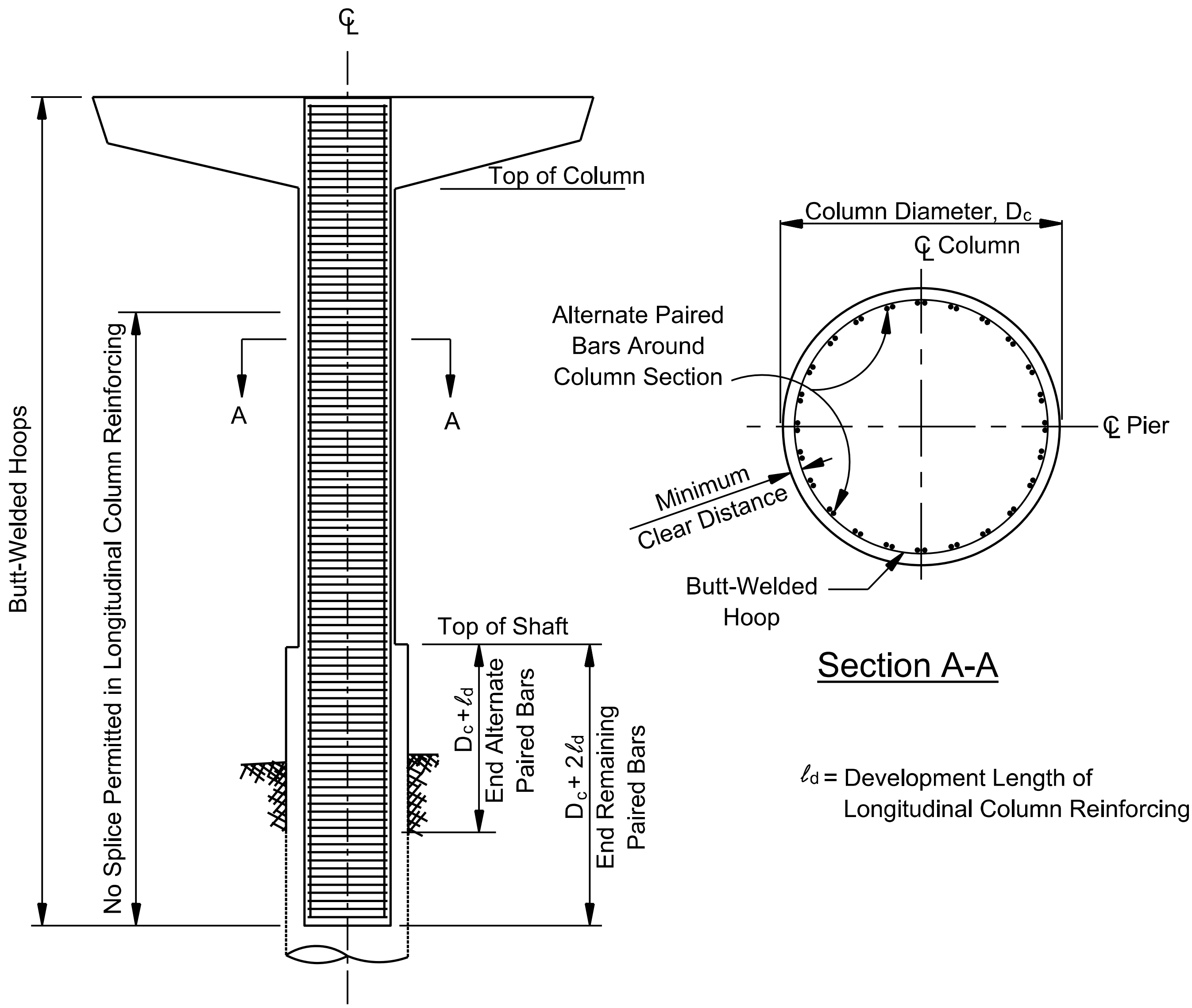


Figure 17-7
Typical Drilled Shaft

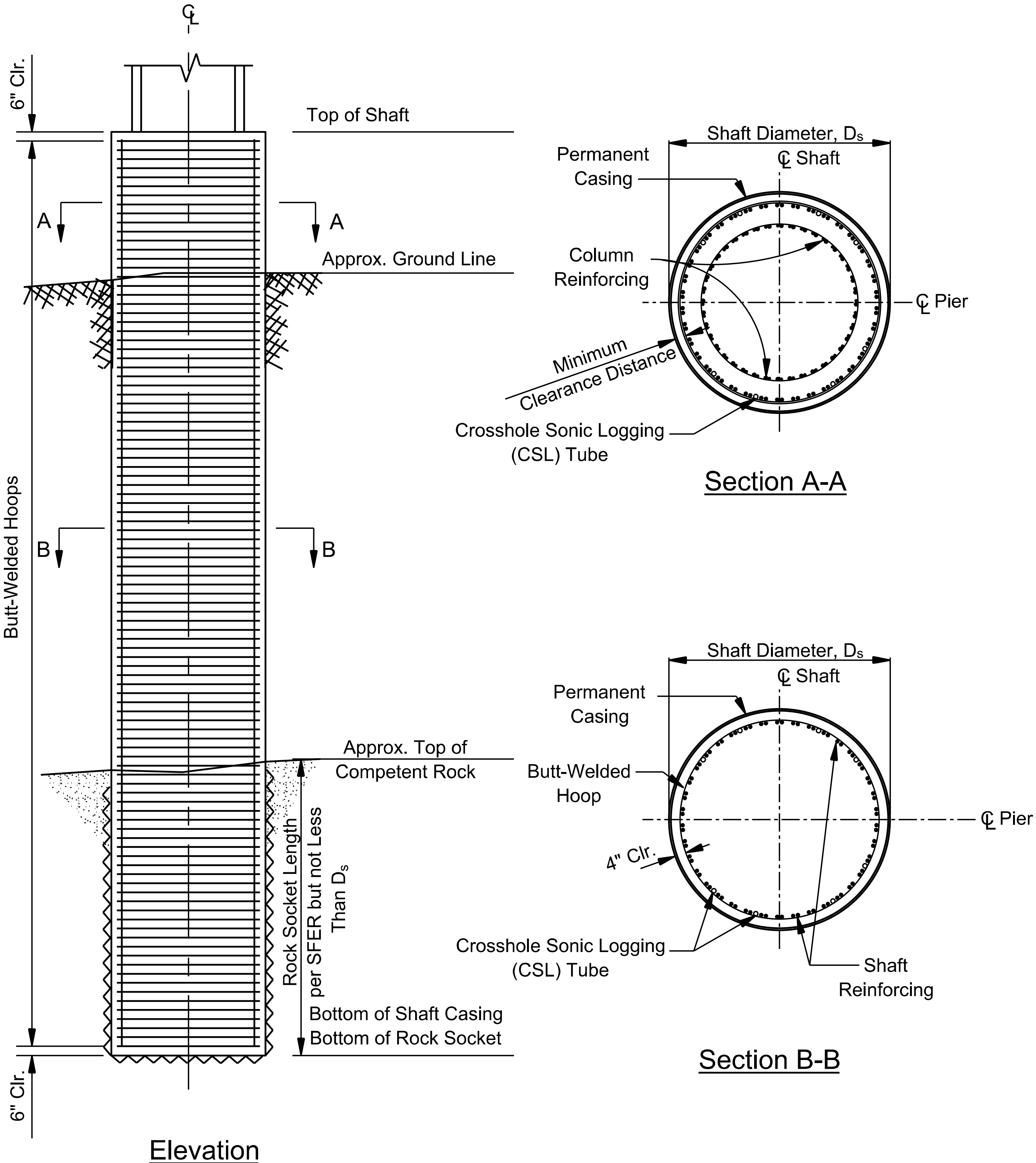


Figure 17-8
Drilled Shaft
(Socketed in Rock)

17.6. Lateral Loading of Deep Foundation Elements

17.6.1. Pile/Shaft Supported Footings

Pile and shaft supported footings typically behave as fixed supports, and the lateral stiffness of deep foundation elements does not typically need to be considered in the non-seismic design of these elements. Lateral stiffness of the deep foundation elements may need to be included in the seismic analysis of the bridge when the bridge engineer anticipates soft soils, liquefaction, or other factors that affect the lateral stiffness of the footing. Use the modeling techniques presented in Section 17.6.2 to determine the lateral stiffness of deep foundation elements.

17.6.2. Pile/Shaft Extension Piers

Include the lateral stiffness of deep foundations in both the non-seismic (small lateral deflection) and seismic (large lateral deflection) of pile/shaft extension piers. Include the effects of scour, liquefaction, and frozen soil, when applicable, in the lateral stiffness analysis.

Several methods of analysis are available for calculating the lateral stiffness of deep foundation elements. Not all of the methods discussed below are applicable to all situations, and the bridge engineer should be aware of each method's limitations.

Closed-Form Linear Models

For small lateral deflections, closed-form solutions have been developed based upon a "beam on an elastic foundation" model. These methods provide a depth to effective fixity for moment (l_m) and deflection (l_s) wherein the actual soil-pile system is replaced by an equivalent fixed-base cantilever. LRFD Article C10.7.3.13.4 and Figure 17-9 provide the equations describing these systems for both cohesive and cohesionless soils. These equations are often referred to as the "fourth-root" or "fifth-root" equation, depending upon the soil type. These equations typically provide sufficiently accurate results for most situations where the deflections are small and the response is elastic.

Closed-form solutions also exist for large-deflection stiffness determination but, like most hand methods, are not readily capable of addressing soil layering and other "real-world" variability. Nonetheless, these methods provide a good means of checking the more sophisticated, computer-generated results.

Non-Linear Models

As the lateral demands increase, the soil and pile/shaft may behave in a non-linear manner. In these situations, numerical modeling of the soil-pile/soil-shaft interaction is often required. These numerical approaches are capable of incorporating the non-linear soil and structure response, but they rely upon computer software. The most commonly used software programs are FB-Pier, the DOT&PF "Pushover Program," and L-Pile. Use the results of these methods to provide a depth to effective fixity, such as that described in Section 17.6.2, or to develop an equivalent soil spring model, such as that shown in Figure 17-9.

The use of non-linear models is often required for seismic analysis.

17.6.3. Minimum Penetration

The Estimated Pile Tip Elevation is determined from the maximum vertical pile/shaft demands and the expected vertical pile capacity presented in the SFER. Verify the vertical pile capacity in the field by using either wave equation analysis or dynamic pile monitoring (PDA/CAPWAP).

Embed piles and shafts into the soil so that the deflected shape of the pile subjected to lateral loads crosses a zero deflection point at two places. This point may be determined by using three times the depth to effective fixity (l_s) as calculated in Section 17.6.2, or as numerically determined in the non-linear approaches described in Section 17.6.2.

In addition to crossing the zero deflection point two times, for bridges in seismic design category (SDC) B, C, and D, embed the pile sufficiently to develop the overstrength plastic hinging moment (M_{po}) of the pile or shaft unless it is otherwise capacity protected from developing below-ground hinges.

17.6.4. Effects of Frozen Soil on Structural Response

The upper layers of soils with high moisture content and those below the ground water table are subject to seasonal freezing. The depth of seasonally frozen ground varies around the state but is typically between two feet and ten feet. Frozen soil may be up to several orders of magnitude stiffer and stronger than unfrozen soil. Include frozen soil effects in the foundation analysis when all the following conditions apply:

- The applied loads are dynamic, including seismic, vehicle collision or other Extreme Event load combinations
- Locations where temperatures at the site could remain below 32 °F continuously for more than two weeks
- Sites where the ground water table may be present within 10 feet of the ground surface.

The structural engineer should be aware that variations in the applicability of frozen soil effects are possible between different piles or substructure units of the bridge (i.e., not all substructure units may be frozen at one time). Bents with short pile extensions are particularly susceptible to frozen soil effects and should be designed to meet the requirements of Seismic Design Category D in both the unfrozen and frozen soil conditions.

The effects of frozen soil have been found to have a negligible effect on the seismic response spectra (Yang et al 2010). Do not consider the increased frozen soil stiffness when determining the site classification.

Include frozen soil stiffness in the lateral analysis of foundations and substructures. Frozen soil stiffness such as p-y curves can be provided by the foundation engineer. When subjected to quasi-static loads, such as thermal expansion or contraction, the effects of frozen soil are often negligible due to the high creep associated with frozen soils. When subjected to rapidly applied loads such as earthquake or collision, the effects of frozen soil may significantly stiffen the bridge response.

For seismic considerations and pushover analysis of pile extension bents in frozen soil, a depth to effective fixity approach (see LRFD Article 17.6) may be used (Yang et al 2012). The effective fixity for moment (L_m) and deflection (L_s) may be taken as:

$$L_m = 0.25\ D_c$$

$$L_s = 4\ D_c$$

where:

D_c = pile or shaft diameter

In lieu of a more detailed pushover analysis, the following approximate force-displacement relationships for a single free-head pile or shaft may be used:

$$P_{yi} = \frac{M_{yi}}{H + L_m}$$

$$\Delta_{yi} = \frac{\varphi_{yi}\,(H + L_s)^2}{3}$$

$$P_u = \frac{M_u}{H + L_m}$$

$$\Delta_u = \Delta_y\left(\frac{M_u}{M_{yi}}\right) + L_p(\varphi_u - \varphi_{yi})\,(H + L_m)$$

where:

P_{yi} = idealized lateral yield force

M_{yi} = idealized yield moment

H = pile or shaft height measured from the ground line to the top of the section

Δ_{yi} = idealized lateral yield displacement

Δ_y = idealized yield displacement

ϕ_{yi} = idealized yield curvature

P_u = maximum lateral force

M_u = ultimate moment

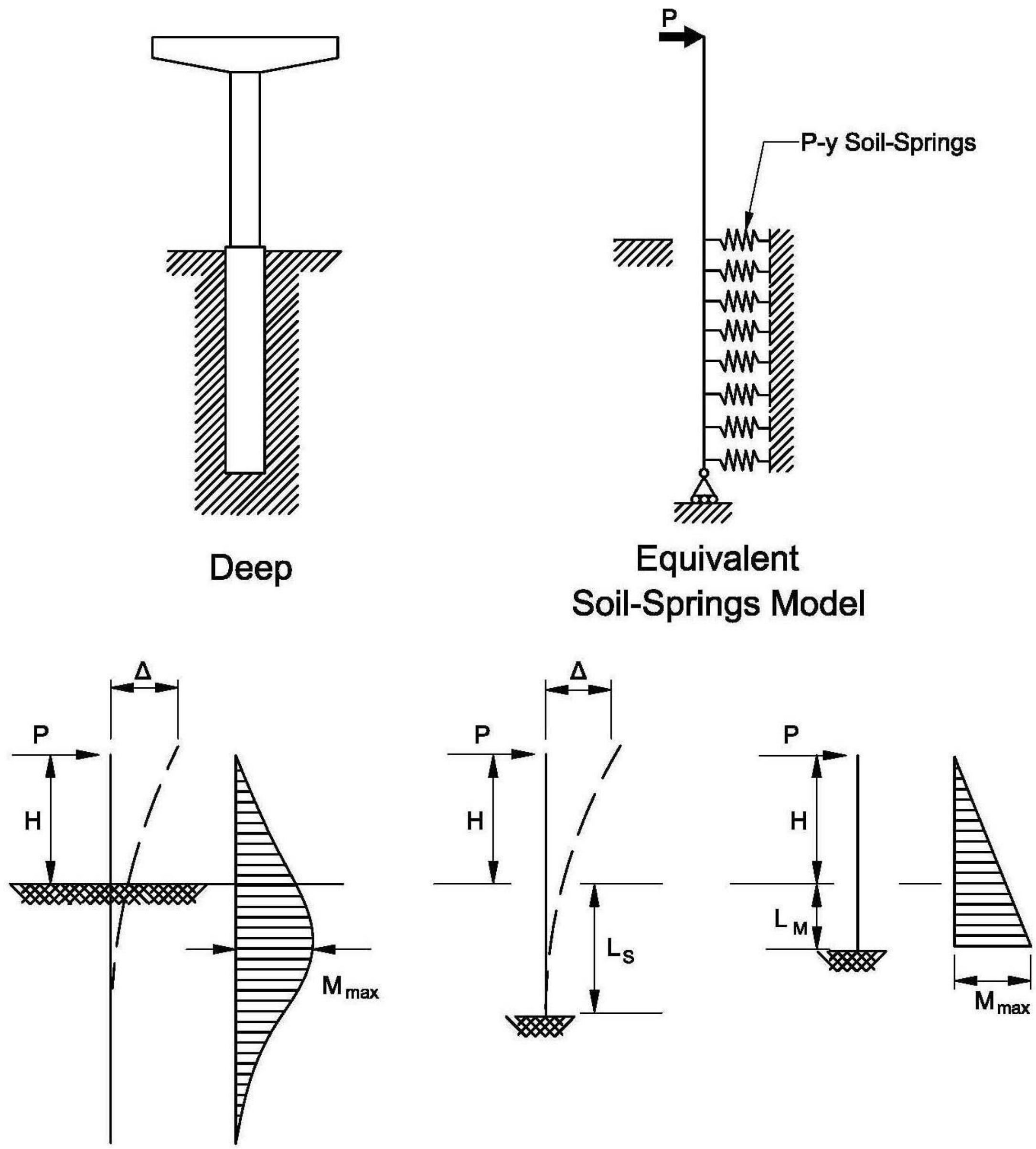
Δ_u = maximum lateral displacement capacity

L_p = analytical plastic hinge length = 2 D_c

ϕ_u = ultimate curvature

Similar equations can be developed for fixed-head piles and shafts recognizing that the height, H, can be replaced by the distance from the plastic hinge to the point of contraflexure.

Refer to the *AASHTO Guide Specifications for LRFD Seismic Bridge Design* for the generation of the moment-curvature relationship for reinforced concrete and concrete filled steel pipe sections



Coefficient n_h (Kips per cubic feet)			
Relative Density	**Loose**	**Medium**	**Dense**
Above Ground Water	14	42	112
Below Ground Water	8	28	68

	L_S	L_M
Cohesive Soil Constant k_h	$1.4\sqrt[4]{\frac{EI}{k_h}}$	$0.44\sqrt[4]{\frac{EI}{k_h}}$
Cohesionless Soil Constant n_h	$1.8\sqrt[5]{\frac{EI}{n_h}}$	$0.78\sqrt[5]{\frac{EI}{n_h}}$

k_h = Coefficient of horizontal subgrade reaction for fine-grained soil

$$= \frac{160\overline{m}c}{\overline{b}}\left(\text{in k / ft}^2\right)$$

In which $\overline{m}$ = 0.32 for $c < 1$ ksf
= 0.36 for $1 < c < 4$ ksf
= 0.40 for $c > 4$ ksf
b = width of pile (ft)
c = soil cohesion

Figure 17-9
Method of Modeling Deep Foundation Stiffness

This page intentionally left blank.