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6.3 Drilled shafts

6.3.1 General

Drilled shafts directly support bridge substructure components, light towers, sign structures, and other transportation structures. In addition to this series of articles the designer should review the design manual articles for specific substructure components and sign supports: abutments [BDM 6.5], piers [BDM 6.6], and sign supports [BDM 10.2].

With few exceptions the office has used drilled shafts only for highway bridge foundations, and those foundations now are being designed by load and resistance factor design (LRFD). In the future the office may use drilled shafts for light tower and sign structure foundations more often, but the AASHTO specifications for those structures and their foundations presently are based on allowable stress design (ASD). Those ASD specifications, however, are being rewritten for LRFD. In view of the present office use of drilled shafts and the coming changes, the more general articles [BDM 6.3.1.1 - 6.3.1.5] are written to cover both LRFD and ASD drilled shaft foundations, but the remaining articles [BDM 6.3.2 through 6.3.5] cover only LRFD drilled shafts for highway bridges.

6.3.1.1 Policy overview

Although the office most commonly supports bridge substructure components on piles, the office recently began supporting bridge piers on drilled shafts where drilled shafts are economical and advantageous. In most cases the office does not support abutments on drilled shafts because the office routinely uses integral abutments, for which drilled shafts do not have the lateral flexibility necessary to accommodate the thermal movements. In one special case, however, the office successfully experimented with integral abutments supported on H-piles inserted in drilled shafts.

Drilled shafts are reinforced concrete columns poured in relatively large diameter holes drilled into soil and rock. For support of bridge substructures drilled shafts provide compact foundations that are more likely than pile foundations to fit within divided highway medians and adjacent to existing structures. Drilled shafts can be installed relatively quickly with less noise and vibration than pile foundations, which often is an important consideration for urban sites or sites adjacent to buildings or sensitive structures. Compared to piles, drilled shafts have relatively large lateral load resistances.

Drilled shafts may function as bridge supports without or with separate footings. Without footings, drilled shafts may simply be extensions of the columns of frame piers or narrow column T-piers. A drilled shaft should be about 6 inches (150 mm) larger in diameter than a column above to accommodate construction tolerances. In cases where drilled shafts need to be grouped it is necessary to provide footings as for piles. Closely spaced drilled shafts require consideration of loss of capacity and increased settlement due to group effects.

Although a demonstration shaft typically is required for a bridge project involving drilled shafts in order to check the equipment and methods of the contractor, the requirement is waived for experienced contractors. In cases where soil design parameters need to be confirmed, a demonstration or production shaft may be instrumented with an Osterberg Load Cell. The designer should consult with the Soils Design Section and the supervising Section Leader when Osterberg Load Cell instrumentation is required.

Typically the office requires that drilled shafts for bridge support be socketed into rock. Exceptions to tip-out in soil shall be approved by the Soils Design Section and the Chief Structural Engineer. For ordinary bridges, drilled shafts may be considered when bedrock is within 40 to 75 feet (12 to 23 m) of the existing ground surface. In the most common design condition, a drilled shaft is designed to carry load by side friction in a rock socket. The rock socket should have a diameter 6 inches (150 mm) less than the shaft diameter and may be grooved or smooth depending on the type of rock encountered. If estimated settlements are small, end bearing capacity on bedrock may be added to the side friction capacity. Otherwise, the drilled shaft should be extended into the rock for additional side friction capacity.

The Iowa DOT has accumulated test data for drilled shafts socketed in shale and limestone, and researchers are using the data to assemble a local database. The test data currently are available to designers from the Soils Design Section, and the eventual goal is to have a locally calibrated load and resistance factor design process so that drilled shafts will be more economical than if designed using the general information in the AASHTO LRFD Specifications.

Drilled shafts should not be battered because construction of non-vertical drilled shafts is difficult. In cases where lateral loads are large, drilled shafts may be thickened to increase lateral load capacity. If thicker shafts have insufficient lateral load capacity, more shafts should be placed and tied together with a footing to carry the lateral loads.

Office policy is to reinforce drilled shafts over the full height, and the designer should note that a reinforcing cage will require splicing of longitudinal bars if the cage is more than 60 feet (18.252 m) in length. The typical reinforcing cage is similar to the cage for a round reinforced concrete column, with equally spaced vertical bars and a spiral. Ties, if used in place of the spiral, are developed with laps rather than hooks so that there are no obstructions within the cage.

Due to lack of redundancy in many applications, quality control of drilled shafts is important. The office considers it necessary to test each drilled shaft used for support of bridges, light towers, and sign structures. The office requires crosshole sonic log (CSL) testing, with at least four 2-inch (50-mm) diameter pipes equally spaced inside the reinforcing cage. The testing is covered in the Iowa DOT Standard Specifications [IDOT SS 2433], which are applicable for bridge foundations, and in a developmental specification [IDOT DS-09032] for support structure foundations.

The office generally permits use of cased or uncased shafts as appropriate for soil, water, and adjacent structure conditions at the site. Casing is required where soil conditions promote caving, where artesian conditions exist, and where caving would damage adjacent foundations. Also, where drilled shafts are located within close proximity to rail lines the designer shall investigate the need for and depth of temporary casing.

Uncased shafts may be constructed dry or with slurry depending on soil conditions. The Iowa DOT Standard Specifications and the developmental specification permit use of either mineral or polymer slurry.

In all cases the designer shall consider existing foundations, utilities, and drainage when locating drilled shafts.

Structural design of drilled shafts for bridge foundations is governed by the *AASHTO LRFD Bridge Design Specifications*, and the designer should consult *Drilled Shafts: Construction Procedures and LRFD Design Methods* by Brown, et al. for design information [BDM 6.3.1.5]. However, structural design of drilled shafts for light tower and sign support foundations is governed by *Standard Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals, Fifth Edition*, which are based on allowable stress design. For those structures the designer should consult *Drilled Shafts: Construction Procedures and Design Methods* by O'Neil and Reese [BDM 6.3.1.5].

At this time the office has no standard sheets available for drilled shaft foundations.

6.3.1.2 Design information

The soils design package provided for each bridge site by the Soils Design Section contains the soil logs and rock coring information needed for bridge foundation design [BDM 6.1.2], and the preliminary situation plan locates the borings. Although crews make every effort to take borings at proposed drilled shaft locations, on some sites drilled shaft locations will be inaccessible. If the designer needs to interpolate between widely separated borings, the designer should recognize that actual site conditions may require deeper drilled shafts than the interpolation would suggest. The designer also may consult with and request recent local test data for drilled shafts socketed in shale and limestone from the Soils Design Section. When using the data, the designer shall ensure that test shaft conditions are duplicated in the new design (for example, rock socket grooving).

Soils information for light tower and sign structure sites may be available in a less formal manner. As needed the designer shall consult with the Soils Design Section for appropriate information.

For specification or construction information beyond the information in this manual the designer should consult the following sources.

- Office of Specifications, *Standard Specifications for Highway and Bridge Construction, Series 2009*, Section 2433. Concrete Drilled Shaft (Available on the Internet at: http://www.iowadot.gov/erl/current/GS/Navigation/nav.pdf)
- Office of Specifications, "Developmental Specifications for Concrete Drilled Shaft for Support Structures" (DS-09032)
- Office of Construction, *Construction Manual* (Available on the Internet at: http://www.iowadot.gov/erl/current/CM/Navigation/nav.pdf)
- Office of Construction, *New Bridge Construction Handbook* (Available on the Internet at: http://www.iowadot.gov/construction/structures/bridge_construction_handbook.pdf)

6.3.1.3 Definitions

Reserved.

6.3.1.4 Abbreviations and notation

ASD, allowable stress design
CSL, crosshole sonic logging
LRFD, load and resistance factor design

6.3.1.5 References

American Association of State Highway and Transportation Officials (AASHTO). *Standard Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals, Fifth Edition.* Washington: AASHTO, 2009.

Brown, D.A., J.P. Turner, and R.J. Castelli. *Drilled Shafts: Construction Procedures and LRFD Design Methods, Publication No. FHWA-NHI-10-016.* Washington: Federal Highway Administration (FHWA), 2010.

Office of Construction. *Construction Manual.* Ames: Office of Construction, Iowa Department of Transportation, 2006. (Available on the Internet at: http://www.iowadot.gov/erl/current/CM/Navigation/nav.pdf)

O'Neill, M.W. and L.C. Reese. *Drilled Shafts: Construction Procedures and Design Methods, Publication No. FHWA-IF-99-025.* Washington: Federal Highway Administration (FHWA), 1999.

Sunday, W. and K. Frame. *New Bridge Construction Handbook.* Ames: Office of Construction, Iowa Department of Transportation, 2000. (Available on the Internet at: http://www.iowadot.gov/construction/structures/bridge_construction_handbook.pdf)

6.3.2 Loads [AASHTO-LRFD 3.6.2.1]

Loads are transmitted directly to drilled shafts from bridge substructure components such as stub abutments, pier columns, and pier footings. Live, dead, and other loads transmitted to a drilled shaft shall be determined from the design manual articles for the component or structure supported by the footing as follows: abutments [BDM 6.5.2] and piers [BDM 6.6.2].

Lateral loads and eccentric loads applied to a bridge substructure component or structure, as well as frame action, will cause shear and moment, and those effects need to be considered in addition to axial loads in the design of the supporting drilled shafts.

For the design of drilled shafts entirely below ground ~~for piers and abutments~~, dynamic load allowance generally should~~shall~~ be excluded from the vertical loads [AASHTO-LRFD 3.6.2.1]. However, if a column is integral with a drilled shaft that is entirely below ground, as a conservative design simplification the designer may choose to include the dynamic load allowance on the drilled shaft.

In cases where drilled shafts are placed below the water table, loads due to buoyancy shall be considered.

6.3.3 Load application

6.3.3.1 Load modifier [AASHTO-LRFD 1.3.2, 3.4.1]

Load factors shall be adjusted by the load modifier, which accounts for ductility, redundancy, and operational importance [AASHTO-LRFD 1.3.2, 3.4.1]. For typical drilled shaft foundations for bridges the load modifier shall be taken as 1.0.

6.3.3.2 Limit states [AASHTO-LRFD 3.4.1, 3.4.2]

For a typical drilled shaft foundation for a bridge, the designer shall consider the following load combinations for the supported structural component, as applicable [AASHTO-LRFD 3.4.1]. However, the designer should be alert to design conditions in which additional strength limit load combinations may control. For design of abutment foundations the designer should use judgment to exclude any combinations that will not control.

- Strength I, superstructure with vehicles but without wind
- Strength IV, superstructure with very high dead to live load ratio, which often controls for long-span bridges
- Extreme Event II, superstructure with reduced vehicles and vehicular collision, ice, or hydraulic events
- Service I, superstructure with vehicles and wind at 55 mph (89 kph)

Except for unusual situations, such as eccentric loads during staged construction, the designer need not investigate construction load combinations for bridges [AASHTO-LRFD 3.4.2].

Design of the drilled shaft foundation shall be based on the resulting critical combinations for maximum axial force, maximum moment, and maximum shear.

6.3.4 Analysis and design

For structural and geotechnical design of drilled shafts for bridge foundations the designer shall use the LRFD method.

For geotechnical design of drilled shafts the designer should use local information available from the Soils Design Section, if the local information is appropriate for the project site and structure. Otherwise the designer shall use the information in the AASHTO LRFD Specifications.

The office recommends that the designer use *Drilled Shafts: Construction Procedures and LRFD Design Methods, Publication No. FHWA-NHI-10-016* by Brown et al. as a design guide [BDM 6.3.1.5]. If any of the guidelines contained in the FHWA publication conflict with guidelines in this section [BDM 6.3] or the AASHTO LRFD Specifications, the designer shall consult with the supervising Section Leader.

Drilled shafts used as supports for bridge substructure components will be subject to frame action that extends below the ground line into the shafts. The office prefers that the frame action be considered by means of an iterative solution rather than by arbitrary selection of points of fixity. The designer shall consider the shear and moment caused by frame action in design of both the substructure component and drilled shafts.

If the lateral load at the top of a drilled shaft is greater than the capacity of the shaft, the shaft should be thickened to provide the needed capacity, or additional shafts should be placed and tied together with a footing. Battered shafts are not permissible.

Drilled shafts for bridge foundations generally should be spaced no closer than three diameters center-to-center. If shafts are spaced less than six diameters center-to-center, the designer shall check interaction with adjacent shafts for vertical and lateral load. Depending on type of load, pile spacing, soil type, and other factors there may be a reduction in resistance for some or all of the shafts.

Unless a drilled shaft tipped in soil is approved by the Soils Design Section and the Chief Structural Engineer, a drilled shaft for support of bridge substructure components shall be socketed into rock. The socket should have a diameter 6 inches (150 mm) smaller than the shaft diameter, should be a depth of at least one and one-half shaft diameters, and should consider the development length for any reinforcing within the socket length. Generally the drilled shaft design for axial load will be based on the side friction capacity in the socket, but the contribution from end bearing may be added to the side friction capacity under the following two conditions:

- The estimated settlement does not exceed 0.25 inches (6 mm) at the service limit state, and
- The estimated settlement does not exceed 1 inch (25 mm) at the strength limit state, which is defined as a load 2.5 times the service load.

If either settlement limitation is exceeded, the needed bearing may be obtained by side friction from a deeper socket.

Grooving of the sidewalls of rock sockets for drilled shafts is typically desired and specified in softer rocks such as Pennsylvanian age shale, siltstone, mudstone, and sandstone, including Pennsylvanian age rocks that include limestone stringers, etc. The Soils Design Section has several load tests on drilled shafts with grooved rock socket sidewalls in Pennsylvanian age rock material, and the results of those load tests are frequently used for design of drilled shafts in similar material. Therefore, grooving in Pennsylvanian age rock materials is necessary when previous load test results have been used as a basis for a current design.

However, grooving is not to be specified in harder rocks such as limestone or dolomite/dolostone because grooving in these harder materials is simply not possible. The designer always should consult the Soils Design Section to discuss and determine grooving of the rock sockets in drilled shafts.

The Iowa DOT Standard Specifications [IDOT SS 2433.03, E] require grooving and brushing of the sidewalls of a rock socket, effective October 2011. Therefore, grooving and brushing is the standard, and the designer shall include a note on the project plans when grooving is not required [BDM 11.8.2, E740/M740]. All rock sockets, whether grooved or not, shall be brushed.

Grooving is not to be specified for any portion of a drilled shaft in soil.

If permanent or temporary casing is required, the designer shall not consider any side friction capacity over the length of the casing. Permanent casing shall not extend more than 1 foot (300 mm) into rock.

If a drilled shaft socketed into rock penetrates consolidating soil layers, the designer shall consider the effect of downdrag.

Minimum drilled shaft diameter shall be 24 inches (610 mm). Larger drilled shaft diameters should be selected in increments of 6 inches (150 mm). Drilled shafts for bridge support shall be at least 36 inches (910 mm) in diameter to accommodate inspection. In cases where the drilled shaft is a direct extension of a bridge column, the diameter of the drilled shaft shall be a minimum of 6 inches (150 mm) larger than the diameter of the column. Preferably the diameter of a drilled shaft should be one of the following: 24, 36, 48, or 60 inches (610, 910, 1220, or 1520 mm).

The designer shall consider the permissible construction tolerance for the plan position of a drilled shaft. The current specifications for drilled shafts specify the plan tolerance as 3 inches (75 mm) [IDOT SS 2433.03, A, 1 and DS-09032.03, A, 1].

Drilled shaft concrete shall have strength of 3.5 ksi (24 MPa), unless the supervising Section Leader approves a higher value.

Drilled shaft reinforcement shall be Grade 60 with minimum yield strength of 60 ksi (400 MPa).

Drilled shafts shall be reinforced full height.

6.3.5 Detailing [AASHTO-LRFD 10.8.3.9]

For drilled shafts used for bridge support, reinforcement cover, spacing, and development shall meet the AASHTO LRFD Specifications [AASHTO-LRFD 10.8.3.9]. Longitudinal bars shall be #8 (#25) or larger. When a large amount of longitudinal steel is required the designer may use bundled bars. Longitudinal reinforcement should be a minimum of eight bars or bundles. The designer should avoid use of double cages. Longitudinal bar splices shall be staggered. The designer shall not splice more than 50% of the bars at any location, and splice locations shall be a minimum of 10 feet (3 m) apart.

The office prefers that a drilled shaft be designed as a tied column and detailed with both a spiral that has turns spaced at 12 inches (300 mm) and an alternate for ties at 12 inches (300 mm) anchored with laps to avoid reinforcement congestion and interference with concrete during placement. Spirals and ties shall be #4 (#13) or larger. An extra 1½ turns of the spiral shall be used at the top and bottom. At a spiral splice location, the splice length shall be the Class B splice length required for the bar size, minimum cover, top bar condition, and coating condition given in Table 6.3.5.

Under bent bar details, the tie alternate for the spiral shall be given. The tie size shall match the spiral bar size. The tie lap shall be the Class B splice length required for the bar size, minimum cover, top bar condition, and coating condition given in Table 6.3.5.

Table 6.3.5. Splice length for shaft spirals and ties

Spiral or Tie Bar Size	**Minimum Concrete Cover Inches (mm)**	**Uncoated Bar Splice Length, Inches (mm)**	**Epoxy-coated Bar Splice Length, Inches (mm)**
#4 (#13)	1.5 (40 mm)	18 (445)	21 (535)
#5 (#16)	1.875 (50 mm) (1)	22 (560)	27 (670)

Table note:

(1) The cover larger than required for corrosion protection is necessary to reduce the #5 (#16) splice lengths shown in the table.

The tie lap shall be rotated 90 degrees from one tie to the next as indicated in Figure 6.3.56.4.1.2.2-1.

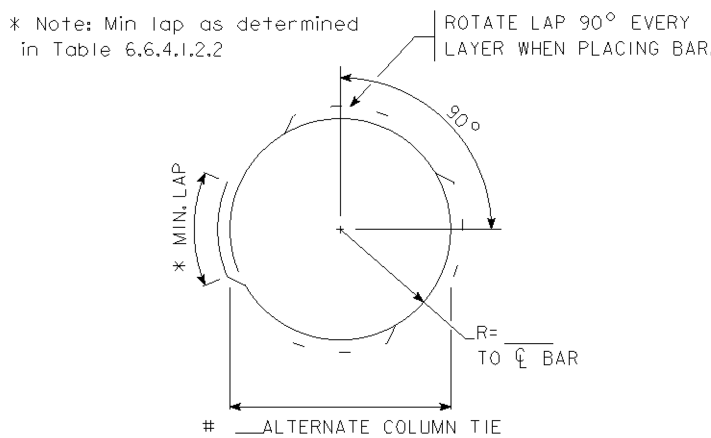

Figure note:

- Determine minimum lap from Table 6.3.5.

Figure 6.3.5 6.4.1.2.2-1. Alternate shaft tie detail

If a drilled shaft is placed with temporary or permanent casing, the outside diameter of the rebar cage should be at least 6 inches (150 mm) less than the diameter of the casing to provide for flow of concrete between the cage and hole and to provide for adequate cover.

All drilled shafts shall have provisions for crosshole sonic logging (CSL), and the designer shall show on the plans a CSL access pipe layout for each unique drilled shaft. One 2-inch (50-mm) diameter access pipe shall be provided per 1 foot (300 mm) of shaft diameter, but there shall be a minimum of four access pipes per shaft. The access pipes shall be equally spaced around the inside perimeter of the reinforcing cage. The layout should provide adequate space around CSL access pipes for concrete consolidation. The layout should avoid congested areas, especially between column and drilled shaft reinforcing cages and should avoid placing reinforcing bars in a direct line between any two access pipes.