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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 Bureau 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 Bureau 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 Bureau 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 Bureau most commonly supports bridge substructure components on piles, bridge piers are supported on drilled shafts where drilled shafts are economical and advantageous. In most cases the Bureau does not support abutments on drilled shafts because the Bureau 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 Bureau successfully experimented with integral abutments supported on H-piles inserted in drilled shafts. For situations involving shallow rock, where semi-integral abutments or stub abutments are used and where piles or spread footings on rock are not a good option, drilled shafts may be used.

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. For waterways, drilled shafts with permanent casings in a single shaft per frame pier column arrangement may be more economical in a shallow rock situation than a pier on pile footings or spread footings on rock since it may eliminate the need for coffer dams. Drilled shafts are also preferred over spread footings in

cases where the Soils Design Unit has determined that shallower depth shales may degrade when exposed to air. 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 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.

Multi-span bridge replacement projects whether using traditional construction or ABC have occasionally constructed drilled shafts for the replacement bridge just outside the footprint of the existing bridge before demolishing the existing bridge to allow the road to remain open to traffic for a longer period of time. In these situations, it is preferred the designer supply at least 18 inches of clearance between the perimeter of the drilled shaft and the closest edge of the existing superstructure, but a minimum clearance of 12 inches is acceptable. In some cases, it may be possible to increase clearance by removing a portion of the existing superstructure near the proposed shaft (e.g. remove a portion of a curb overhang on an existing bridge which is not structurally necessary).

Although a demonstration shaft typically is required for a bridge project involving drilled shafts 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 Unit and the supervising Unit Leader when Osterberg Load Cell instrumentation is required.

Typically, the Bureau requires that drilled shafts for bridge support be socketed into rock. Exceptions to tip-out in soil shall be approved by the Soils Design Unit and the Chief Structural Engineer. For ordinary bridges, drilled shafts may be considered when bedrock is within 40 to 75 feet 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 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. To minimize the effects of construction issues, drilled shafts socketed into rock shall extend an additional 12" into the rock beyond what is required for geotechnical capacity.

The Iowa DOT has accumulated test data for drilled shafts socketed in shale and limestone. The test data currently are available to designers from the Soils Design Unit.

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.

Bureau 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 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 Bureau considers it necessary to test each drilled shaft used for support of bridges, light towers, and sign structures. The Bureau requires crosshole sonic log (CSL) testing, with at least four 2-inch 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.

The Bureau 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. The clearance needed between drilled shafts for a replacement structure and the foundations of an existing structure must be carefully considered, particularly if the existing bridge is to remain in service during shaft construction. Interference between a shaft and battered pile should be avoided since it can affect both shaft constructability and battered pile capacity. Shafts installed near existing bridge foundations should ordinarily use temporary or permanent casing to prevent caving of the shaft hole and possible instability to existing adjacent foundations. Shafts installed through sand layers are particularly susceptible to caving and the designer should consult with the Soils Design Unit for guidance on how much clearance is needed between the shaft and existing foundation. For artesian conditions, the elevation of the top of the casing is increased until water no longer flows out of the top. 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].

Currently the Bureau 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 Unit 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 Unit. 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 Unit for appropriate information.

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

- Contracts and Specifications Bureau, *Standard Specifications for Highway and Bridge Construction*, Section 2433. Concrete Drilled Shafts (Available on the Internet at: <https://www.iowadot.gov/specifications/pdf/completebook.pdf>)
- Construction and Materials Bureau, *Construction Manual* (Available on the Internet at: <http://www.iowadot.gov/erl/current/CM/Navigation/nav.pdf>)
- Construction and Materials Bureau, *New Bridge Construction Handbook* (Available on the Internet at:

https://iowadot.gov/construction_materials/structures_foundations/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.

Construction and Materials Bureau. *Construction Manual*. Ames: Construction and Materials Bureau, 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: Construction and Materials Bureau, 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, dynamic load allowance generally should 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 with design 3-second gust wind speed at 70 mph

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 Unit, 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 Bureau 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 Unit 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 Bureau 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. The designer shall envelope the stiffness of the soil and shaft for analyses involving soil-shaft interaction. Consult the Soils Design Unit for an appropriate range of soil properties. The range of 28-day concrete strengths for shaft stiffness may vary from 4.0 to 8.0 ksi. Note that the structural capacity of the shaft design shall be based on 4.0 ksi unless a higher strength is specified.

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 Unit 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 smaller than the shaft diameter and should consider the development length for any reinforcing within the socket length. The depth of the rock socket shall be the maximum of the following two conditions:

- The depth of the rock socket shall be at least one and one-half shaft diameters.
- In order to minimize construction issues, the depth of the rock socket shall extend an additional 12" into the rock beyond what is required for geotechnical capacity.

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 at the service limit state, and
- The estimated settlement does not exceed 1 inch 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 Unit 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 Unit 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 13.8.2, 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 into rock.

Contractors often use temporary casings in the soil at the top of the shaft that are 10 to 15 feet in length and 6 to 12 inches larger in diameter than the nominal shaft dimension at that location. These larger diameter temporary casings are filled with concrete when the shaft is poured which increases the dead load on the shaft and potentially increases any downdrag forces that may be acting on the larger diameter. The designer shall calculate the dead load of the shaft, for portions of the shaft above the rock socket, based on the nominal diameter of the shaft above the rock socket plus an additional 12 inches. If a drilled shaft penetrates consolidating soil layers, the designer shall consider the effect of downdrag. The designer shall calculate the downdrag force based on a drilled shaft diameter equal to the nominal shaft

diameter in and above the consolidating soil layers plus 12 inches. Include CADD Note E745 and E750 as necessary. The designer may also need to consider the effect that a change in diameter has on the stiffness of the drilled shafts and the potential effects on the design. In general, if a shaft diameter increase is introduced over a relatively short length of the shaft it is typically not necessary to meet the minimum longitudinal reinforcement requirement for the larger diameter shaft in that region.

Minimum drilled shaft diameter shall be 24 inches. Larger drilled shaft diameters should be selected in increments of 6 inches. Drilled shafts for bridge support shall be at least 36 inches 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 larger than the diameter of the column.

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 [IDOT SS 2433.03, A, 1].

Drilled shaft concrete shall have a 28-day strength of 4.0 ksi, unless the supervising Unit Leader approves a higher value.

Drilled shaft reinforcement shall be Grade 60 with minimum yield strength of 60 ksi.

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 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 apart.

The Bureau prefers that a drilled shaft be designed as a tied column and detailed with both a spiral that has turns spaced at 12 inches and an alternate for ties at 12 inches anchored with laps to avoid reinforcement congestion and interference with concrete during placement. Spirals and ties shall be #4 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 | Uncoated Bar Splice Length, Inches | Epoxy-coated Bar Splice Length, Inches |
|------------------------|-------------------------------|------------------------------------|----------------------------------------|
| #4 | 1.5 | 25 | 30 |
| #5 | 1.875 ⁽¹⁾ | 32 | 38 |

Table note:

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

The tie lap shall be rotated 90 degrees from one tie to the next as indicated in Figure 6.3.5.

For aesthetic reasons, drilled shafts extending above the ground without permanent casing shall require a formed finish from the top of the shaft to at least 12 inches below the finished ground surface.

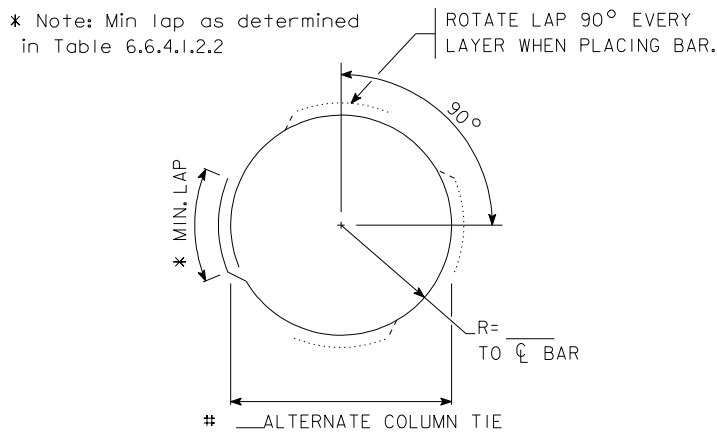


Figure note:

- Determine minimum lap from Table 6.3.5.

Figure 6.3.5. 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 less than the diameter of the casing to provide for flow of concrete between the cage and hole and to provide for adequate cover. In cases where the rock socket diameter is 6 inches less than the cased shaft diameter, the full height rebar cage shall have an outside diameter 6 inches less than the rock socket diameter which, in turn, is 12 inches less than the cased shaft diameter.

Drilled shafts with a rock socket shall include the following plan details:

- Estimated top of competent bedrock elevation
- Minimum rock socket length in feet
- Estimated bottom of drilled shaft elevation

Note that friction in the first 12 inches of the rock socket is typically ignored if casing is used since the casing is assumed to penetrate up to 12 inches into the rock socket. The estimated top of competent bedrock elevation is the elevation at which the rock socket is assumed to begin and, when applicable, should not exclude the assumed 12 inches of casing penetration.

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 diameter access pipe shall be provided per 1 foot 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.