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6 Bridge Substructure Design

6.1 General

The series of articles under Section 6, Bridge Substructure Design, is intended to fit together as a unit. As much as possible, cross references are used to avoid duplication.

In a following article [BDM 6.1.5], several references are listed for soils, driven piles, and integral abutments. Although the soils reference, *Foundation Soils Information Chart, Pile Foundation*, (a.k.a. Blue Book) has not been updated for LRFD, it provides some of the background on which the Iowa State University LRFD calibration for driven piles was based.

For driven pile design, in 2007 the Bureau moved to an interim LRFD procedure with a single resistance factor of 0.725 fitted to the Blue Book and to an approximate average load factor of 1.45. Since the LRFD statistical calibration to static pile load tests was completed by Iowa State University (ISU) in 2012, the pile section [BDM 6.2] of the LRFD Bridge Design Manual has been rewritten to adopt geotechnical and target driving resistance factors from the research discussed in *Volume IV of Development of LRFD Procedures for Bridge Pile Foundations in Iowa* and from subsequent discussions with the researchers regarding setup in cohesive soil. More basic information about the ISU research is available in earlier Volumes I - III [BDM 6.1.5].

In the past, designers were encouraged to obtain and use the 1987 integral abutment reference, *Final Report, Pile Design and Tests for Integral Abutment Bridges, HR-273, and Addendum*, for relatively long bridges. However, the Bureau no longer encourages use of the reference because the bridge length policy was revised to allow longer bridges, and the 2005 reference, *Field Testing of Integral Abutments, Final Report HR-399*, has modified the older recommended design procedures [BDM Table 6.5.1.1.1].

The two integral abutment references generally substantiate the present policy, and the designer may find them useful in understanding the various rules associated with the policy.

6.1.1 Policy overview

In the Bridges and Structures Bureau, the design of typical highway bridge substructures proceeds from preliminary to final design units. The preliminary design unit selects the abutment, pier, and foundation type based on bridge site information and criteria stated in *Bridge Design Manual* Section 3, Preliminary Design. In some cases, the preliminary design unit also considers aesthetic criteria in Section 9. Final design units then complete the structural design and detailing following policies in Section 5, Bridge Superstructure Design, and Section 6, Bridge Substructure Design. In some cases, the final design units in consultation with the Soils Design Unit may decide to change the substructure type and/or foundation type based on soils information or other factors that arise during the final design process.

For a bridge over a waterway a Corps of Engineers 404 permit is required, but there no longer is a need for a note on the bridge plans. For typical bridge projects the Design Bureau will provide notes and details for the 404 permit. If special permit conditions are identified in the submittal letter from the Location and Environment Bureau (Green Sheet), the Bridges and Structures Bureau will work with the Design Bureau to provide appropriate notes and details in the project plans.

The Bureau interprets the basic AASHTO LRFD specifications when designing foundations, abutments, and piers and specifies rules for detailing of those substructure components. This series of articles on substructure components covers most typical designs but does not cover special designs for signature bridges and long-span bridges.

In all cases substructure components need to be designed for vertical and lateral loads, settlement, stability, and economy considering the complete bridge structure. Pile, drilled shaft, footing, abutment, and pier design is affected by the choice of bearings [BDM 5.7] because bearings transmit loads from the superstructure. Abutment and pier design also is affected by the choice of foundations because foundations provide support and either partial or complete fixity.

For highway bridge foundations, the Bureau generally selects among three types: piles, drilled shafts, and spread footings. Because most Iowa bridge sites are in rural areas and because bedrock seldom is near the surface, site conditions and economy usually favor the use of piles for the support of substructure components. In cases where pile driving would disturb adjacent structures and where site conditions permit, substructure components may be supported on drilled shafts. In cases where bedrock is close to the planned bottom elevation of a substructure component, the component should be placed on a spread footing notched into the rock.

To eliminate expansion joints, wherever practical the Bureau selects integral abutments first and semi-integral abutments second over other abutment types. Based on research and testing for bridges without skew, the Bureau generally orients integral abutment steel H-piles for weak axis bending with respect to longitudinal expansion or contraction of the superstructure. For integral abutment bridges with skews of 30 degrees or less, H-piles are rotated to align the pile webs with the centerline of abutment bearings. However, at skews above 30 degrees, integral abutment piles shall be aligned with pile webs perpendicular to centerline of roadway.

Except for integral abutments, wherever practical the Bureau batters some of the foundation piles for a substructure component. Semi-integral abutments typically batter two lines of piles outward at a 1 horizontal to 6 vertical slope, however, designers may elect to design the abutments using a single row of vertical piles. Typically, the inner line of stub abutment piles, stub abutment wing wall piles, and the perimeter piles for pier foundations are battered at a 1 horizontal to 4 vertical slope. The end piles for pile bents are battered at a 1 horizontal to 12 vertical slope.

6.1.2 Design information

For each bridge site the Soils Design Unit in the Design Bureau provides to the Bridges and Structures Bureau a bridge soils package that typically includes three primary items: the boring logs, the soil profile sheet, and the supplemental. There may be other items or attachments as needed based on site conditions and other factors.

The supplemental is organized to provide the N-values for the standard penetration test, but the document typically provides additional information, requirements, and recommendations for three design factors: slope stability, settlement, and foundation. These three items can vary from very short to complex, can discuss work to be done by a grading contractor, and can discuss further coordination between design Bureaus.

For the foundation part of the supplemental, the Soils Design Unit typically recommends a foundation type, usually one of the following:

- Point-bearing piles driven to a rock formation,
- Friction or friction plus bearing piles driven to a specified load capacity, below any expected scour elevation,
- Drilled shafts, or
- Spread footings founded directly on a rock formation.

The Soils Design Unit does not necessarily make more specific recommendations, such as a pile type. If applicable, the section discusses downdrag and relates downdrag to design requirements and delay period. The settlement information on the supplemental includes consolidation time rate information.

The Soils Design Unit typically recommends pile driving points if soil conditions warrant, but the designer may discuss the need with the Unit if it appears that points are advisable.

The majority of Iowa bridge foundations are placed on piles that derive support from shear strength of surrounding soil and end bearing. Based on approximately 280 pile load tests in Iowa soils and experience with previous charts the Soils Design Unit prepared *Foundation Soils Information Chart, Pile Foundation* in 1989, updated the chart in 1994, and accepted charts updated to LRFD geotechnical resistance for trial use in 2006. The revised 2007 LRFD geotechnical resistance charts [BDM 6.2.7] shall be used for design of pile foundations for Iowa bridges.

6.1.3 Definitions

Substructure is any construction below the bearing seats or, in the absence of bearings, below the soffit of the superstructure.

6.1.4 Abbreviations and notation

N or N-value, standard penetration test number of blows per foot. N also may be given as **SPT NO**, the Standard Penetration Test Number, in the soils information chart reference.

6.1.5 References

AbdelSalam, S.S.,K.W. Ng, S. Sritharan, M.T. Suleiman, and M. Roling. *Development of LRFD Procedures for Bridge Pile Foundations in Iowa – Volume III: Recommended Resistance Factors with Consideration of Construction Control and Setup.* Ames: Institute for Transportation, Iowa State University, 2012. (Available on the Internet at: http://www.intrans.iastate.edu/research/documents/research-reports/lrfd_vol_iv_final_w_cvr.pdf)

Abendroth, R.E. and L.F. Greimann. *Field Testing of Integral Abutments, Final Report HR-399.* Ames: Center for Transportation Research and Education, Iowa State University, 2005. (Available on the Internet at http://www.iowadot.gov/operationsresearch/reports/reports_pdf/hr_and_tr/reports/hr399.pdf)

Dirks, Kermit and Patrick Kam. *Foundation Soils Information Chart, Pile Foundation*. Ames: Iowa Department of Transportation, Design Bureau, January 1989/September 1994. (a.k.a. **Blue Book**)

Generally with the move to LRFD, the ASD-based Blue Book is out-of-date, and its contents have been revised and moved to the BDM. The Blue Book is available from the Soils Design Unit in the Design Bureau.

Green, D., K.W. Ng, K.F. Dunker, S. Sritharan, and M. Nop. *Development of LRFD Procedures for Bridge Pile Foundations in Iowa – Volume IV: Design Guide and Track Examples.* Ames: Institute for Transportation, Iowa State University, 2012. (Available on the Internet at: http://www.intrans.iastate.edu/research/projects/detail/?projectID=-700958271)

Greimann, L.F., R.E. Abendroth, D.E. Johnson, and P.B. Ebner. *Final Report, Pile Design and Tests for Integral Abutment Bridges, HR-273, and Addendum.* Ames: Iowa Department of Transportation and College of Engineering, Iowa State University, 1987. (Available on the Internet athttp://www.iowadot.gov/operationsresearch/reports/reports_pdf/hr_and_tr/reports/hr273.pdf)

Ng, K.W., M.T. Suleiman, M. Roling, S.S. AbdelSalam, and S. Sritharan. *Development of LRFD Procedures for Bridge Pile Foundations in Iowa – Volume II: Field Testing of Steel H-Piles in Clay, Sand, and Mixed Soils and Data Analysis.* Ames: Institute for Transportation, Iowa State University, 2011. (Available on the Internet at: http://publications.iowa.gov/13626/)

Roling, M., S. Sritharan, and M. Suleiman. *Development of LRFD Procedures for Bridge Pile Foundations in Iowa – Volume I: An Electronic Database for Pile Load Tests in Iowa (PILOT-IA).* Ames: Institute for Transportation, Iowa State University, 2010. (Available on the Internet at: http://publications.iowa.gov/13624/)

Wang, S., L. C. Reese. *COM624P – Laterally Loaded Pile Analysis Program for the Microcomputer, Version 2.0*. Performed by Ensoft, Inc., Report No. FHWA-SA-91-048, June 1993.

6.1.6 Substructure and Foundation Selection

This article is intended to summarize the important factors affecting the selection of substructure and foundation types.

6.1.6.1 Abutments

For support of typical superstructures, the office generally selects between three types of abutments for shallow-slope embankments: integral, semi-integral and stub. Integral and semi-integral abutments with jointless bridge decks are preferred wherever feasible with integral abutments preferred over semi-integral abutments.

Integral and stub abutments have been used in Iowa for many years while the use of semi-integral abutments has been steadily growing. The most common application to date for semi-integral abutments has been to convert deteriorated stub abutments on older bridges to semi-integral abutments as part of a repair project to eliminate deck expansion joints and protect beam ends. Currently there are no published standard working details available for semi-integral abutments, however, the BSB does have a limited set of draft standards it can provide as a starting point.

Applications for semi-integral abutments on new bridges should generally include the following situations:

- bridge length and skew restrictions preclude the use of integral abutments (Note 1),
- end span limits for steel girders with integral abutments are exceeded,
- shallow bedrock precludes use of steel piling for integral abutments (or may require costly rock coring to make steel piling work with integral abutments),
- drilled shaft foundations at abutments preclude the use of integral abutments,
- wide bridges of 120 feet or more which benefit from the lateral flexibility of expansion bearings on semi-integral abutments,
- ABC, particularly for lateral slides and modular units, and
- high abutments.

Note 1: Iowa has not set a formal policy on limits for semi-integral abutments. However, with designer verification, the maximum permissible length limit for semi-integral abutments for skews up to 45 degrees are generally assumed to be equivalent to those given for integral abutments at a 0-degree skew.

The Bureau prefers to use the same abutment type at both ends of the bridge. However, in cases where a stub abutment is required at one end of the bridge, but not at the other end, consider using a semi-integral abutment to avoid the use of an additional deck joint. Additionally, on single span ABC projects over waterways the superstructure should be positively connected to the substructure on at least one abutment. In this case an integral abutment may be used to positively tie down the superstructure at one end while a semi-integral abutment may be used at the other end.

All three abutment types are typically supported by steel H piles, when practical, due to the low cost of that foundation type. Semi-integral abutments and stub abutments may also be supported by spread footings on rock or drilled shaft foundations. Spread footings are used when the rock is very shallow (see BDM 6.1.6.1.1). Drilled shafts are sometimes used for shallow rock situations (see BDM 6.1.6.1.1) but are more commonly selected for abutments when there are concerns with the noise and vibration that occur during pile driving. In one special case, the Bureau successfully experimented with integral abutments supported on H-piles inserted in drilled shafts.

Iowa is currently exploring the use of a semi-stub abutment type. The concept in this case is to tie the approach slab to the bridge superstructure and carry it over the abutment backwall such that the expansion joint resides at the end of the approach slab. The main benefits of this abutment type are to retain earth against the backwall rather than a movable superstructure while moving the deck joint away from the ends of the bridge beams.

6.1.6.1.1 Shallow Bedrock

Shallow bedrock at an abutment may be conservatively defined as rock, regardless of type (e.g. shale, limestone, etc.) and quality (e.g. solid, hard, broken, weathered, highly weathered, etc.), that is 50 feet or less from the bottom of the superstructure beams. In the absence of shallow rock, abutments are typically supported on steel H piles, regardless of abutment type. When shallow rock is present the designer should consider abutment type and foundation options more closely.

As part of the geotechnical field investigation for bridge foundations, the Soils Design Unit generally specifies boring drill hole locations as discussed in the Design Bureau’s Design Manual 200I-1, Appendix A, 6.C and Table 1. A minimum of one drill hole is required at each substructure unit. The borings at each substructure unit are typically staggered from side to side of the bridge along the length of the bridge to establish a longitudinal and transverse soil profile. Ideally, for a suspected shallow rock situation at an abutment, a minimum of two borings should be taken, one at each edge of the abutment to establish the depth of rock along the abutment. In some cases, it may not be possible to obtain two borings, or even one boring, at the new abutment location due to issues with site access. In cases where soil/rock information is minimal at an abutment, the designer, in consultation with the Soils Design Unit, will need to use engineering judgment with respect to depth of rock at the abutment.

6.1.6.1.1.1 Integral Abutments

Integral abutments, when feasible, are the preferred abutment option. The use of integral abutments in shallow rock situations is largely dependent not only on the depth of the rock, but also the depth of prebore required. Prebored holes for integral abutments need not be used for bridges 130 feet or less in length. All abutment piles for bridges longer than 130 feet are placed in prebored holes a minimum of 10 feet deep. Prebored holes of up to 15 feet are commonly used in situations where pile downdrag is expected. Prebored holes are filled with bentonite slurry to maintain the hole opening.

Integral abutments rely on the ability of the pile to develop fixity at both ends of the pile. Rotational fixity at the top of the pile is achieved with sufficient embedment of the pile into the abutment concrete footing. Fixity of the pile at the lower end is typically achieved with sufficient embedment of the pile into the soil. The length of pile embedment in the soil required to achieve fixity can vary significantly depending on several factors (e.g. soil characteristics, pile size, pile loading conditions, top of pile head condition). For the pile to have a point of fixity the pile must penetrate the soil sufficiently so that there are at least two points of zero deflection below ground [Wang and Reese 1993]. If the pile does not penetrate far enough the bottom of the pile will deflect laterally in a "fence-posting" mode of behavior. [Note that even with two points of zero deflection below ground, selecting the location of the point of fixity itself seems to be open to engineering judgment.]

Shallow rock, combined with depth of prebore, limits the length of pile embedment available to develop at least two points of zero deflection in the soil to establish pile fixity. While pile penetration into the rock during driving would help establish pile fixity, the amount of pile penetration into different types of rock and different quality of rock is difficult to predict in the design phase and difficult to confirm in the construction phase. In some cases, driven piles may penetrate several feet below some rock surfaces, but only bite into or rest on top of other rock surfaces. Additionally, the amount of contact between the sides of the pile surface and the rock is not easily determined and may not be sufficient to help develop lateral resistance. Due to the uncertainty involved, the BSB does not rely on pile penetration into rock to develop fixity of the pile during the design phase. Note, however, that the designer shall include a reasonable amount of additional pile contract length in the bid item to account for the possibility that the pile will penetrate the rock prior to reaching refusal. Doing so will help avoid costly pile field splices. See BDM Table 6.2.4.2-2 for additional pile length to include in the bid item.

The following table indicates the minimum depth of soil overburden required to select integral abutments if no additional analysis is performed.

Table 6.1.6.1.1.1-1. Minimum Depth of Soil Overburden for Integral Abutments (1)

H-pile section	Depth of Prebore, feet(2)	Minimum depth from bottom of beams to top of rock, feet	Minimum depth from bottom of 3-foot thick abutment cap to top of rock, feet	Minimum pile length in direct contact with soil, feet(3)
HP 10	0	30	27	27
	10	37	34	24
	15	40	37	22
HP 12	0	33	30	30
	10	41	38	28
	15	43	40	25
HP 14	0	37	34	34
	10	45	42	32
	15	48	45	30

Table notes:

(1) The designer may subtract 5 feet from the minimum requirements when there are two borings at an abutment, one on each side near the gutterlines. The depth to rock along the abutment should be well-established with two borings and concerns due to a sloping rock surface should be minimal.

(2) Only the most common prebore depths were considered.

(3) Among other assumptions, the pile length required assumed soft clay/loose sand as the overburden. Designers may override the table requirements based on an LPile evaluation of a particular project.

The limits in the table above may be modified if studies demonstrate piles can adequately penetrate rock and develop fixity to prevent fence-post type failures. The use of pile points may be beneficial in penetrating shallow rock but is currently not used for that purpose in shallow rock situations.

Prior to 2021, in cases of shallow rock Iowa often relied upon rock coring combined with at least 3 feet of concrete confinement for piles to establish pile fixity for integral abutments as integral abutments were seen to be a better option than stub abutments even though rock coring is costly. The policies outlined in this article are designed to encourage the use of semi-integral abutments over integral abutments requiring rock coring. In cases where the use of integral abutments is questionable due to shallow rock concerns, designers are encouraged to use semi-integral abutments.

6.1.6.1.1.2 Semi-integral Abutments

When an integral abutment cannot be used due to shallow rock conditions alone the designer shall use a semi-integral abutment.

Where there are two borings at a semi-integral abutment, one on each side near the gutterlines, then the abutment may be supported on piles so long as each pile has at least 10 feet of pile in direct contact with the soil. Where there is only one boring at an abutment the abutment may be supported on piles so long as each pile has at least 15 feet of pile in direct contact with the soil. The additional 5 feet of pile length in cases where only one boring is present is designed to mitigate the possibility of installed piles being shorter than 10 feet due to a sloping rock surface. Designers shall ensure the piles have adequate lateral resistance to resist lateral loads. In shallow rock conditions, the semi-integral abutment shall be supported on two rows of piles when piles are the foundation choice. The piles in each row are typically battered outwardly in opposite directions with a 1 horizontal to 6 vertical slope (1:6 batter). The pile batter may be increased to 1:4 if lateral forces pose a significant design concern. Pile uplift, if present, should also be considered in the design. The use of pile points for battered piles is recommended for shallow rock conditions. If battered piles cannot be used due to downdrag, then the designer may need to consider the use of a deadman anchor to resist lateral forces. Alternatively, a drilled shaft foundation may be the better option.

Semi-integral abutments are suitable for use with spread footings on sound rock. Spread footings on rock are typically selected as the foundation option for an abutment when suitable rock, as defined by the Soils Design Unit, is 6 feet or less from the bottom of the superstructure beams. Establishing the depth to suitable rock on each end of the abutment, at the abutment, is particularly important for spread footings since excavation costs and plan modification costs can significantly increase if the rock surface is not adequately defined.

Semi-integral abutments are suitable for use with drilled shafts socketed into rock. Drilled shafts are typically selected as a possible foundation option when the rock is too deep for a spread footing, but too shallow for driven piles. Typically, a few 3-foot diameter shafts socketed into rock will provide enough axial and lateral capacity for the abutment. The desirability of using drilled shafts generally increases if the piers are also using drilled shafts. The designer shall consult with the Chief Structural Engineer when drilled shafts are being considered at an abutment. Including two viable foundation design options in the plans may be a benefit.

6.1.6.1.1.3 Stub Abutments

When integral and semi-integral abutments cannot be used, the designer shall use a stub abutment.

Where there are two borings at a stub abutment, one on each side near the gutterlines, then the abutment may be supported on piles so long as each pile has at least 10 feet of pile in direct contact with the soil. Where there is only one boring at an abutment the abutment may be supported on piles so long as each pile has at least 15 feet of pile in direct contact with the soil. The additional 5 feet of pile length in cases where only one boring is present is designed to mitigate the possibility of installed piles being shorter than 10 feet due to a sloping rock surface. Designers shall ensure the piles have adequate lateral resistance to resist lateral loads. Stub abutments on piles are always supported by two rows of piles. The piles in the back row are driven vertically while the piles in the front row are battered outwardly with a 1 horizontal to 4 vertical slope (1:4 batter). Pile uplift, if present, should also be considered in the design. The use of pile points for battered piles is recommended for shallow rock conditions. If battered piles cannot be used due to downdrag, then the designer may need to consider the use of a deadman anchor to resist lateral forces. Alternatively, a drilled shaft foundation may be the better option.

Stub abutments are suitable for use with spread footings on sound rock. Spread footings on rock are typically selected as the foundation option for an abutment when suitable rock, as defined by the Soils Design Unit, is 6 feet or less from the bottom of the superstructure beams. Establishing the depth to suitable rock on each end of the abutment, at the abutment, is particularly important for spread footings since excavation costs and plan modification costs can significantly increase if the rock surface is not adequately defined.

Stub abutments are suitable for use with drilled shafts socketed into rock. Drilled shafts are typically selected as a possible foundation option when the rock is too deep for a spread footing, but too shallow for driven piles. Typically, a few 3-foot diameter shafts socketed into rock will provide enough axial and lateral capacity for the abutment. The desirability of using drilled shafts generally increases if the piers are also using drilled shafts. The designer shall consult with the Chief Structural Engineer when drilled shafts are being considered at an abutment. Including two viable foundation design options in the plans may be a benefit.

6.1.6.2 Piers

For support of typical superstructures, the office generally selects between frame piers, T-piers, pile bents, and diaphragm (wall) piers. The reader is directed to BDM 6.6.1.1 for common considerations when determining the choice of substructure type. When feasible, driven pile foundations are normally selected for frame piers and T-piers due to their low cost and ease of installation. Driven piles are used explicitly for pile bents. When bedrock is close to the surface, spread footings on rock are often selected for frame piers, T-piers and diaphragm piers. Drilled shafts are used for frame piers, T-piers and diaphragm piers. In most cases, a single shaft per column is used for frame piers. Diaphragm piers and T-piers may use a single line of shafts with a common footing. T-piers may also use an array of shafts with a common footing. Drilled shafts are commonly used where space considerations may exclude other foundation types, where noise and vibration due to pile driving are undesirable, where large lateral resistances may be needed, and where the use of cofferdams in a river is undesirable.

6.1.6.2.1 Shallow Bedrock

Shallow bedrock at a pier may be conservatively defined as rock, regardless of type (e.g. shale, limestone, etc.) and quality (e.g. solid, hard, broken, weathered, highly weathered, etc.), that is 30 feet or less from the lowest of the ground line, stream bed, or design scour elevation. In the absence of shallow rock, piers are often supported on steel H piles. When shallow rock is present the designer should consider pier foundation options more closely.

As part of the geotechnical field investigation for bridge foundations, the Soils Design Unit generally specifies boring drill hole locations as discussed in the Design Bureau’s Design Manual 200I-1, Appendix A, 6.C and Table 1. A minimum of one drill hole is required at each substructure unit. The borings at each substructure unit are typically staggered from side to side of the bridge along the length of the bridge to establish a longitudinal and transverse soil profile. Ideally, for a suspected shallow rock situation at a pier, a minimum of two borings should be taken, one at each edge of the pier to establish the depth of rock along the pier. In some cases, it may not be possible to obtain two borings, or even one boring, at the new pier location due to issues with site access. In cases where soil/rock information is minimal at a pier, the designer, in consultation with the Soils Design Unit, will need to use engineering judgment with respect to depth of rock at the pier.

6.1.6.2.1.1 Pile Bents

Pile bents are primarily used for low-level, short-span CCS, PPCB, or RSB bridges in small stream applications. The use of pile bents in shallow rock situations is largely dependent not only on the depth of the rock, but also the depth of scour. Pile bents rely on the ability of the pile to develop fixity at the lower end of the pile through sufficient embedment of the pile into the soil. The length of pile embedment in the soil required to achieve fixity can vary significantly depending on several factors (e.g. soil characteristics, pile size, pile loading conditions, top of pile head condition). For the pile to have a point of fixity the pile must penetrate the soil sufficiently so that there are at least two points of zero deflection below ground

[Wang and Reese 1993]. If the pile does not penetrate far enough the bottom of the pile will deflect laterally in a “fence-posting” mode of behavior.

While pile penetration into the rock during driving would help establish pile fixity, the amount of pile penetration into different types of rock and different quality of rock is difficult to predict in the design phase and difficult to confirm in the construction phase. In some cases, driven piles may penetrate several feet below some rock surfaces, but only bite into or rest on top of other rock surfaces. Additionally, the amount of contact between the sides of the pile surface and the rock is not easily determined and may not be sufficient to help develop lateral resistance. Due to the uncertainty involved, the BSB does not rely on pile penetration into rock to develop fixity of the pile during the design phase. Note, however, that the designer shall include a reasonable amount of additional pile contract length in the bid item to account for the possibility that the pile will penetrate the rock prior to reaching refusal. Doing so will help avoid costly pile field splices. See BDM Table 6.2.4.2-2 for additional pile length to include in the bid item.

The following table indicates the minimum depth of direct pile to soil contact to use a pile bent if no additional analysis is performed.

Table 6.1.6.2.1.1-1. Minimum Depth of Pile to Soil Contact for Pile Bents (1)

H-pile section	Minimum soil penetration(2),(3)
HP 10	23
HP 12	26
HP 14	29

Table notes:

(1) This table is based on BDM Table 6.6.4.2.1.1. An additional 5 feet has been added to the values from Table 6.6.4.2.1.1. The designer may subtract 5 feet from the minimum requirements of the table above when there are two borings at a pier, one on each side near the gutterlines. The depth to rock along the pile bent should be well-established with two borings and concerns due to a sloping rock surface should be minimal.

(2) Among other assumptions, the minimum soil penetration assumed soft clay or loose sand. Designers may override the table requirements based on an LPile evaluation of a particular project.

(3) This distance from ground line, stream bed, or design scour elevation to bottom of pile is required for the pile to have a point of fixity. If the pile has less embedment it may fail by “fence-post” action.

The limits in the table above may be modified if studies demonstrate piles can adequately penetrate rock and develop fixity to prevent fence-post type failures. The use of pile points may be beneficial in penetrating shallow rock but is currently not used for that purpose in shallow rock situations.

Prior to 2021, in some rare shallow rock cases Iowa would rely upon rock coring combined with at least 3 feet of concrete confinement for piles to establish pile fixity for pile bents. The policies outlined in this article are designed to encourage the use of pile bents only when pile can be driven without rock coring.

6.1.6.2.1.2 T-Piers

T-piers are used for grade separation structures and for bridges in waterways.

Where there are two borings at a pier, one on each side near the gutterlines, then the pier may be supported on piles so long as each pile has at least 10 feet of pile in direct contact with the soil accounting for loss of soil due to scour as appropriate. Where there is only one boring at a pier the pier may be supported on piles so long as each pile has at least 15 feet of pile in direct contact with the soil accounting for loss of soil due to scour as appropriate. The additional 5 feet of pile length in cases where only one boring is present is designed to mitigate the possibility of installed piles being shorter than 10 feet due to a sloping rock surface. Designers shall ensure the piles have adequate lateral resistance to resist lateral loads. Pile uplift, if present, should be considered in the design. Perimeter pier piles are typically battered as discussed in BDM 6.6. The use of pile points for battered piles is recommended for shallow rock conditions. The designer must ensure the pier piles can resist lateral loads particularly when pier piles cannot be battered.

T-piers are suitable for use with spread footings on sound rock. Spread footings on rock are typically selected as the foundation option for a pier when suitable rock, as defined by the Soils Design Unit, is 10 feet or less from ground line or stream bed. Establishing the depth to suitable rock on each end of the pier, at the pier, is particularly important for spread footings since excavation costs and plan modification costs can significantly increase if the rock surface is not adequately defined.

T-piers are suitable for use with drilled shafts socketed into rock. Drilled shafts are typically selected as a possible foundation option when the rock is too deep for a spread footing, but too shallow for driven piles. In most cases, a single line or small array of drilled shafts connected by a common footing is sufficient for the foundation.

6.1.6.2.1.3 Frame Piers

Frame piers are commonly used for grade separation structures. Frame piers with one drilled shaft per column are becoming more common for bridges in waterways.

Where there are two borings at a pier, one on each side near the gutterlines, then the pier may be supported on piles so long as each pile has at least 10 feet of pile in direct contact with the soil accounting for loss of soil due to scour where appropriate. Where there is only one boring at a pier the pier may be supported on piles so long as each pile has at least 15 feet of pile in direct contact with the soil accounting for loss of soil due to scour as appropriate. The additional 5 feet of pile length in cases where only one boring is present is designed to mitigate the possibility of installed piles being shorter than 10 feet due to a sloping rock surface. Designers shall ensure the piles have adequate lateral resistance to resist lateral loads. Pile uplift, if present, should be considered in the design. Perimeter pier piles are typically battered as discussed in BDM 6.6. The use of pile points for battered piles is recommended for shallow rock conditions. The designer must ensure the pier piles can resist lateral loads particularly when pier piles cannot be battered.

Frame piers are suitable for use with spread footings on sound rock. Spread footings on rock are typically selected as the foundation option for a pier when suitable rock, as defined by the Soils Design Unit, is 10 feet or less from ground line or stream bed. Establishing the depth to suitable rock on each end of the pier, at the pier, is particularly important for spread footings since excavation costs and plan modification costs can significantly increase if the rock surface is not adequately defined.

Frame piers are suitable for use with drilled shafts socketed into rock. Drilled shafts are typically selected as a possible foundation option when the rock is too deep for a spread footing, but too shallow for driven piles. In most cases, one drilled shaft per frame pier column is used for the foundations.

In some cases, involving waterways, a frame pier with a single shaft per column is more desirable than a T-pier with drilled shafts or driven piles. Drilled shafts with temporary or permanent casing extending above the water can be less expensive than installing cofferdams for footing caps. Additionally, when the drilled shaft casing extends above the water, work on the bridge can continue without risk of floods impeding the work.

6.1.6.2.1.4 Diaphragm Piers

Solid concrete diaphragm piers (wall piers) are the preferred choice for low-level, short-span slab or PPCB bridges where bedrock is near the surface, and it is impractical to drive piles.

Spread footings on rock are typically considered when suitable rock, as defined by the Soils Design Unit, is 10 feet or less from ground line or stream bed. Establishing the depth to suitable rock on each end of the pier, at the pier, is particularly important for spread footings since excavation costs and plan modification costs can significantly increase if the rock surface is not adequately defined.

Diaphragm piers are suitable for use with drilled shafts socketed into rock. Drilled shafts are typically selected as a possible foundation option when the rock is too deep for a spread footing and a wall pier is still desired as the substructure option. In most cases, a line of drilled shafts with a common footing is used for the foundations.

6.1.7 Construction and Staging Considerations for Substructures

This article addresses factors related to the construction and staging of substructures.

6.1.7.1 Driven Pile Conflicts

For most bridge replacement projects, the abutment and pier foundations for new bridges are located to avoid interference with the foundations of current bridges being replaced since the existing foundations are typically left in place just below the surface. However, some projects may still have conflicts that must be addressed. The most common cases involve interference between driven steel HP piles for new bridges and timber piles from existing bridges. [Note: Some bridge replacement project locations may have had a previous bridge replacement project which could indicate the presence of additional foundations left in place from a past bridge removal. Designers should review previous bridge plan sets to determine whether there may be additional foundations that could interfere.] There are two approaches that should be avoided when addressing pile conflicts:

- Designers should not assume the existing timber piles will be removed nor should a note be included in the plans calling for removal. The condition of existing timber piling can vary significantly. The heads of the piles may be deteriorated enough to make it difficult to extract the timber piling. Also, removing a timber pile may leave a void which can reduce the lateral and axial capacity of the new steel pile.
- Designers should not assume that new steel piles can be driven through the existing timber piling. The condition of existing timber piling below the surface may be intact enough to deflect a driven steel pile causing misalignment.

Generally, there are two methods which may be used to mitigate interference.

- The first is to design the new foundation to span across the existing foundation where interference could occur.
- The second is to place the new piles in between the existing piles with a clearance that is the larger of 2.5 feet or 2.5 times the pile size. Because not all the existing piles are likely to be located per the original plan, the designer will need a plan note indicating how far the piles should be spaced from existing piling and how far each pile can be shifted in the field to avoid interference. Designers should design their foundation piles to allow for 6 to 12 inches of shift when interference is a concern. The note should also indicate that the Engineer should be contacted if the limits as given in the plan need to be exceeded. Note that Standard Specification 2501.02 L.1 automatically allows for up to 3 inches of deviation for each pile.

Existing substructure concrete can also lead to conflicts and may need to be addressed with concrete removal or other approaches.

6.1.7.2 Shoring and Cofferdam Considerations

The location of new pier foundations relative to existing foundations should take into consideration the most likely means and methods for construction. Constructing new pier pile foundations often requires installation of temporary sheet pile shoring to maintain the excavated hole for foundation construction. In waterways, sheet pile cofferdams are often used to allow for dewatering the excavated hole. As discussed in BDM 6.6.4.1.4, seal coats are occasionally needed at the bottom of a cofferdam to facilitate dewatering. For deeper excavations, struts and walers may need to be employed inside the enclosure to brace and strengthen the sheet pile walls.

IDOT SS 2405.03.A.4 specifies providing a clear space of at least 36 inches on all sides between the footing and the inside edge of the cofferdam sheet pile (i.e. width of walers does not need to be considered). The designer should conservatively assume a sheet pile cross-sectional shape of 20 inches in width for cofferdams. New and existing battered bridge piles shall be a minimum of 12 inches clear from the face of the assumed bottom of sheet pile. For the purposes of estimating clearance between battered bridge pile and sheet pile, the sheet pile should generally be assumed to penetrate 25 feet below the bottom of the new footing unless shallower bedrock is present. The 25 feet of sheet pile embedment should generally be assumed even in cases where seal course details are included in the contract plans since their installation is optional.

In cases where it is difficult to meet the above spacing requirements, the designer should discuss options with the Construction and Materials Bureau and Soils Design Unit. Some potential solutions might include:

- Eliminating or reducing pile batter on new bridge foundations.
- Assuming the bridge contractor may need to encompass both the new and existing foundation footprints within the shoring/cofferdam.
- Reviewing soil properties to better estimate depth to bottom of sheet pile.
- Selecting drilled shafts for the foundations.

6.1.7.3 Downdrag Considerations for Existing Pile Foundations

Downdrag occurs when soil around a pile settles more than the pile. This relative settlement between the soil and pile results in negative skin friction, or drag load, on the pile. Under certain conditions, new construction near an existing bridge can produce drag loads on existing bridge piling. The effects of downdrag on an existing bridge which is to remain in service during or after new construction should be considered and addressed by the designer. For purposes of this article, downdrag most commonly occurs under the following scenarios:

- New fill placed on top of soil that has a compressible soil layer, usually a relatively soft cohesive soil layer, that consolidates and settles under the added load thereby causing downdrag load on pre-installed piles.
- Construction activities producing vibrations in relatively loose, poorly graded granular soil which consolidates and settles leading to downdrag loads on pre-installed piles.

Types of construction near existing bridges having the potential to cause soil settlement include:

- Bridge widening projects which require additional fill.
- Staged bridge replacements which require construction of a wider bridge, a bridge just off alignment, and/or a bridge with a grade raise any of which requires additional fill.
- Projects which place box culverts or pipe culverts under existing bridges over waterways or abandoned railroads and after which the space between the structures are filled in.
- Installation of new H-pile, sheet pile, cofferdam or drilled shaft casing near an existing bridge using methodologies that result in significant vibration.

The remainder of this article will only address downdrag on existing piles produced by settlement due to placement of new fill. See BDM Article 6.1.7.4 for additional discussion related to settlements caused by vibration.

Mitigating downdrag effects on existing bridges can have significant cost implications. When the Soils Report indicates downdrag potential for the existing structure (or new structure) or if the bridge designer suspects downdrag is possible then it is incumbent on the designer to meet as early as possible with the DB Soils Design Section and the CMB Foundations and Structures Group to address downdrag concerns. There are several approaches to address concerns related to downdrag on existing pile foundations, such as:

- Evaluate capacity of existing piles based on calculating pile loads and determining pile capacities from as-built pile driving logs (or project plans if logs not available) to resist downdrag loads.
- In some situations, simple monitoring for bridge settlement may suffice. In these cases, the typical mitigation technique is to add an asphalt overlay to the existing bridge deck for better rideability if settlement occurs. This technique is typically reserved for low risk situations involving short bridges with signalized one-way traffic (i.e. low traffic volumes and speeds).

- Isolate the existing pile foundation from negative skin friction effects either in part or altogether. Temporary or permanent sheet pile, where there is room to install it, may be used to isolate existing bridge piling. Using split CMP sleeves could be used around piles in pile bents when fill, causing downdrag, is needed in the region. The depth to the compressible soil layer may affect how deep the isolation technique should extend. (Pile coatings that reduce pile friction, such as bitumen, are generally discouraged.)
- Use expanded polystyrene (EPS) foam (geofoam) blocks, lightweight cellular (foamed) concrete, or other lightweight fill materials to reduce or eliminate downdrag effects.
- Strengthen existing pile foundations typically by driving additional piles that are tied to the substructure unit for additional resistance.
- Remove or core-out compressible soil layers before adding fill.
- Various ground improvement techniques may be applicable.

Subjecting existing (or new) foundations with battered piles to downdrag should be avoided.

6.1.7.4 Bridge Displacement Due to Construction Generated Vibration Effects

A staged bridge replacement project or bridge widening project may have conditions conducive to vibration induced settlement of the existing bridge during construction of the new bridge. Vibration induced settlement can lead to significant displacements affecting the structural integrity of a bridge and the safety of the traveling public. The following three conditions all need to be present for vibration induced settlement to occur:

1. Bridge foundations located in an existing soil mass consisting of loose, poorly graded granular soils (e.g. sands) especially in a saturated condition.
2. Relatively short foundation piles that tip out in the soil mass described in No. 1.
3. Construction methods which induce enough vibration into the soil mass surrounding the existing bridge foundation to cause settlement (compaction/densification/liquefaction) of the bridge foundation in the soil mass. Common construction methods involving the potential for vibration include the use of impact or vibratory hammers to install sheet pile, cofferdams, foundation pile and drilled shaft casings. Using vibratory methods to remove foundation elements can also have the same effect.

Even though the general conditions leading to settlement are known the precise conditions are not well-defined. Additionally predicting how a bridge will displace and what displacements are unacceptable for any given bridge is not easily determined. Differential settlements between substructure units or within the same substructure unit can lead to translations and rotations of the substructure which in turn lead to displacement effects in the superstructure. Overstress of bridge members, functionality of bridge bearings and other components, and rideability can all be affected.

In fiscal year 2025 there were several projects let that included a Special Provision (SP) for Vibration Monitoring. The SP included vibration, tilt, and displacement monitoring programs with alert thresholds. The cost for these monitoring programs is significant. Designers shall discuss any projects with conditions conducive to vibration induced settlement with the Chief Structural Engineer. Any project which includes an SP for Vibration Monitoring of an existing bridge must be approved by the Chief Structural Engineer.