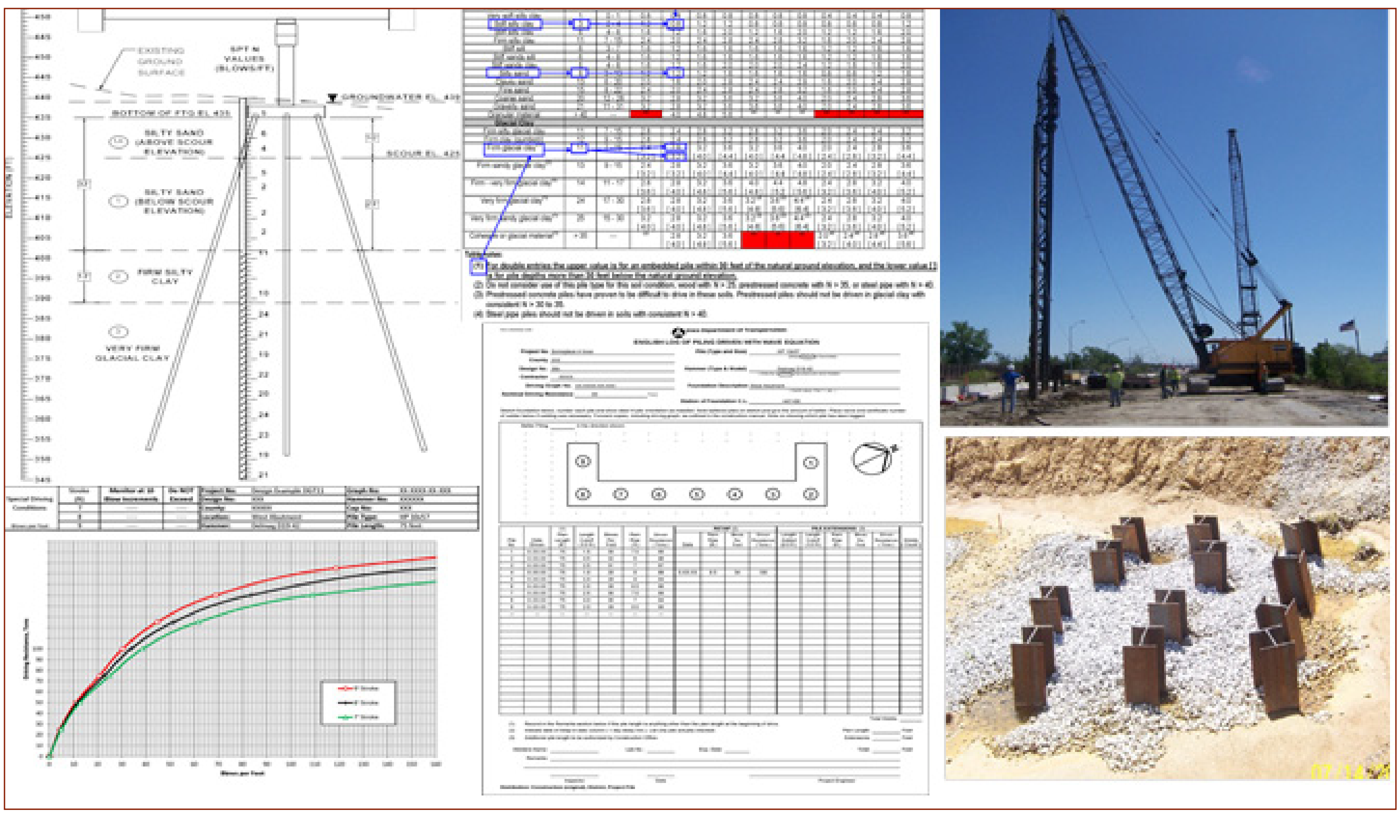
Development of LRFD Procedures for Bridge Pile Foundations in Iowa

Volume IV: Design Guide and Track Examples

BRIDGE ENGINEERING CENTER

Final Report
May 2012



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Iowa Department of Transportation
(InTrans Projects 07-294, 08-312, and 08-313)

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16. Abstract

With the goal of producing engineered foundation designs with consistent levels of reliability as well as fulfilling the Federal Highway Administration (FHWA) mandate that all new bridges initiated after October 1, 2007 be designed according to the Load and Resistance Factor Design (LRFD) approach, the Iowa Highway Research Board (IHRB) sponsored three research projects on driven piles (TR-573, -583 and -584). The research outcomes are presented in three reports entitled Development of LRFD Design Procedures for Bridge Piles in Iowa, Volumes I, II, and III, and other research information is available on the project web site at http://srg.cce.iastate.edu/lrfd/.

Upon incorporating the regional LRFD recommendations from the completed research into the Iowa DOT Bridge Design Manual (2010) as it is being rewritten under the new title of LRFD Bridge Design Manual (December 2011), and adopting the American Association of State Highway and Transportation Officials (AASHTO) LRFD Bridge Design Specifications (2010), this Volume IV for driven piles in Iowa was developed.

Following the layout of a design guide, the application of the LRFD approach is demonstrated using various pile design examples in three different tracks, which depend on the construction control method used for establishing the pile driving criteria. Piles are designed using the Iowa Blue Book method. The pile driving criteria are established using the Wave Equation Analysis Program (WEAP) in Track 1, the modified Iowa Engineering News Record (ENR) formula in Track 2, and the combination of WEAP and the Pile Driving Analyzer (PDA) with a subsequent pile signal matching analysis using the CAse Pile Wave Analysis Program (CAPWAP) in Track 3.

The track examples cover various pile types, three different soil profiles (cohesive, non-cohesive, and mixed) and special design considerations (piles on rock, scouring, downdrag, and uplift).

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Development of LRFD Procedures for Bridge Piles in Iowa – Volume IV: Design Guide and Track Examples

Final Report
May 2012

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ACKNOWLEDGMENTS

This report is the culmination of three Iowa Highway Research Board (IHRB) Load and Resistance Factor Design (LRFD) projects (TR-573, -583, and -584). The researchers would like to thank the IHRB and the Iowa Department of Transportation (DOT) for funding these projects and the technical advisory committee (TAC) for their guidance.

The following individuals served on the TAC: Ahmad Abu-Hawash, Dean Bierwagen, Lyle Brehm, Ken Dunker, Kyle Frame, Steve Megivern, Curtis Monk, Michael Nop, Gary Novey, John Rasmussen, and Bob Stanley.

Using input from selected members of the TAC and Donald Green from Michael Baker Jr., Inc., this volume was developed to assist with LRFD implementation in future bridge foundations in Iowa.

EXECUTIVE SUMMARY

With the goal of producing engineered designs with consistent levels of reliability, the Federal Highway Administration (FHWA) issued a policy memorandum on June 28, 2000 requiring all new bridges initiated after October 1, 2007, to be designed according to the Load and Resistance Factor Design (LRFD) approach. To improve the economy of bridge foundations, the American Association of State Highway and Transportation Officials (AASHTO) allows the development of regional LRFD recommendations that reflect local soil conditions and practices in accordance with the AASHTO LRFD framework.

In response to the FHWA mandate and AASHTO recommendations, the Iowa Highway Research Board (IHRB) sponsored three research projects on driven piles (TR-573, -583, and -584). This research was undertaken by researchers with the Bridge Engineering Center and the Department of Civil, Construction, and Environmental Engineering at Iowa State University.

Complete research outcomes are presented on the project web site at http://srg.cce.iastate.edu/lrfd/ and in the following three volumes entitled Development of LRFD Procedures for Bridge Pile Foundations in Iowa:

- Volume I: An Electronic Database for PIle Load Tests (PILOT)
- Volume II: Field Testing of Steel Piles in Clay, Sand, and Mixed Soils and Data Analysis
- Volume III: Recommended Resistance Factors with Consideration of Construction Control and Setup

Incorporating the LRFD resistance factors developed in Volume III, and adopting the AASHTO LRFD Bridge Design Specifications (2010), design for driven piles in Iowa is presented in this volume. The application of the LRFD approach is demonstrated using several pile design examples in three different tracks, depending on the construction control method chosen for verifying the pile resistance in the field.

In all cases, piles are designed using the Iowa “Blue Book” method as recommended in Volume III. The pile driving criteria are established using the Wave Equation Analysis Program (WEAP) in Track 1, the modified Iowa Engineering News Record (ENR) formula in Track 2, and the combination of WEAP and Pile Driving Analyzer (PDA) with a subsequent pile signal matching analysis using the CAse Pile Wave Analysis Program (CAPWAP) in Track 3.

These three options were identified as acceptable construction control methods from the completed LRFD research project. The different track examples cover various pile types, three different soil profiles (cohesive, non-cohesive, and mixed), and special design considerations (piles on rock, scouring, downdrag, and uplift). In each case, all steps required to complete the design and construction control are presented.

CHAPTER 1. INTRODUCTION

The Allowable Stress Design (ASD) philosophy has been used for the design of pile foundations for decades in Iowa and the nation. However, this approach does not ensure sufficiently consistent reliability for pile design and installation. Since the mid-1980s, the Load and Resistance Factor Design (LRFD) approach has been progressively developed to ensure an improved and more uniform reliability of bridge design in the US.

Due to the high variation in soil properties, complexity in soil-pile interaction, and difficulty in accurately predicting pile resistance and driving stresses, the integration of the LRFD approach in pile foundation design and its construction control poses more challenges than those associated with the superstructure elements.

With the goal of producing engineered designs with consistent levels of reliability for both superstructure and substructure, the Federal Highway Administration (FHWA) issued a policy memorandum on June 28, 2000 requiring all new bridges initiated after October 1, 2007 to be designed according to the LRFD approach. Meanwhile, the American Association of State Highway and Transportation Officials (AASHTO) recommended an LRFD framework and permitted the use of regionally calibrated resistance factors so that the economy of bridge foundations can be improved.

As the first step toward implementing the FHWA mandate, and to ensure a smooth transition from the ASD to the LRFD approach, the Iowa Department of Transportation (DOT) implemented an interim procedure as a short-term solution to the LRFD mandate.

Next, the regional LRFD procedure was developed for steel H- and timber piles driven into cohesive, non-cohesive, and mixed soils in Iowa. Adequacy of these procedures were verified through three research projects (TR-573, -583, and -584) supported by the Iowa Highway Research Board (IHRB).

In addition to giving consideration to the regional soil conditions, the LRFD approach developed for Iowa also paid attention to the local design and construction practices, so that the familiar approaches could be retained even if they are not the most efficient methods. Consideration was also given to timber piles because of interest in using this pile type in several counties in Iowa for low-volume bridges.

Details can be found at http://srg.cce.iastate.edu/lrfd/ and in the following reports:

- Volume I: An Electronic Database for PIle LOad Tests (PILOT) (Roling et al. 2010)
- Volume II: Field Testing of Steel Piles in Clay, Sand, and Mixed Soils and Data Analysis (Ng et al. 2011)
- Volume III: Recommended Resistance Factors with Consideration of Construction Control and Setup (AbdelSalam et al. 2012a)

Volume I describes the development of PILOT, the user-friendly, quality-assured, electronic database of historical pile load tests conducted in the Iowa from 1966 through 1989. A strict acceptance criterion for each of the three hierarchical pile load test dependability classifications (reliable, usable-static, and usable-dynamic) was imposed to ensure that the resulting data available in PILOT for LRFD regional calibration is of superior quality.

Of the 164 historical steel H-pile records contained within PILOT, 80 were usable for investigations dealing with static analysis methods, while 34 were usable for evaluating the dynamic analysis methods as well as dynamic pile driving formulas. For each pile in the database, the pile capacity was defined using the Davisson's criterion (1972).

In Volume II, the 10 full-scale field tests on the most commonly used steel H-piles (e.g., HP 10 × 42) conducted throughout Iowa to cover all five geological regions are summarized. These field tests involved detailed site characterization using both in situ subsurface investigations and laboratory soil tests.

Test piles were instrumented with strain gauges and monitored, using the Pile Driving Analyzer (PDA), during pile installations and restrikes that were performed to investigate the influence of pile setup. After completing all re-strikes on the test piles, vertical static load tests were performed on test piles following the "Quick Test" procedure of ASTM D1143 (2007), and the pile capacity in each case was defined using the Davisson's criterion (1972).

Pile resistances were analyzed using static analysis methods, dynamic driving formulas, the Wave Equation Analysis Program (WEAP), and the CAse Pile Wave Analysis Program (CAPWAP). Detailed data analyses and the development of pile setup quantification methods are described in Volume II and all data from the field tests were also incorporated in PILOT.

Volume III describes the development of regional LRFD resistance factors following the AASHTO LRFD framework and the incorporation of the construction control aspects and soil setup into the pile design and construction processes. Using the PILOT database and the field test results, resistance factors were calibrated for various static analysis methods.

Among the various methods, the in-house Iowa "Blue Book" method, based on the Geotechnical Resistance Charts (Appendix A), was recommended for design of steel H-piles. Similarly, resistance factors were calibrated for various dynamic formulas, WEAP, and CAPWAP. Following the examination of efficiencies of different methods, the modified Iowa Engineering News Record (ENR) formula, WEAP, and CAPWAP are recommended for the construction control of steel H-piles, while the modified Iowa ENR formula is recommended for the construction control of timber piles.

Given the scope of these three projects and the lack of available data, the following special topics were not covered in Volume III:

1. Resistance factors for other pile types, such as prestressed concrete piles and pipe piles
2. Resistance factors for end bearing piles or driven piles on rock
3. LRFD consideration to scour
4. LRFD consideration to downdrag load
5. LRFD recommendation for piles subjected to uplift

However, adopting the AASHTO LRFD Bridge Design Specifications (2010) and the Iowa DOT Bridge Design Manual (2010) as it is being rewritten under the new title of LRFD Bridge Design Manual (December 2011), these special topics are incorporated in this volume to the extent possible, and their design steps are demonstrated in selected examples. It should be expected that these resistance factors are not as efficient as those developed for steel H-piles, summarized in Appendix C, through the completed comprehensive research program.

In addition to these three volumes of reports, additional information with more emphasis on theoretical aspects can be found in a master's thesis by Roling (2010) and doctoral dissertations by AbdelSalam (2010) and Ng (2011). The research outcomes have also been published in journal papers, including the following:

- AbdelSalam et al. (2010b). Current Design and Construction Practices of Bridge Pile Foundations with Emphasis on Implementation of LRFD.
- Roling et al. (2011a). Introduction to PILOT Database and Establishment of LRFD Resistance Factors for the Construction Control of Driven Steel H-Piles.
- Roling et al. (2011b). Load and Resistance Factor Design Calibration for Bridge Pile Foundations-Investigation of Design and Construction Practices in Iowa County, Iowa, Jurisdictions.
- AbdelSalam et al. (2011). LRFD Resistance Factors for Design of Driven H-Piles in Layered Soils.
- AbdelSalam et al. (2012b). Modeling Axially Loaded Friction Steel H-Piles using the Load-Transfer Approach Based on a Modified Borehole Shear Test.
- Ng et al. (2012a). Pile Setup in Cohesive Soil with Emphasis on LRFD: An Experimental Investigation.
- Ng et al. (2012b). Pile Setup in Cohesive Soil with Emphasis on LRFD: Analytical Quantifications and Design Recommendations.
- Ng et al. (2012c). Verification of Recommended Load and Resistance Factor Design Approach to Pile Design and Construction in Cohesive Soils.
- Ng et al. (2012d). A Procedure for Incorporating Pile Setup in Load and Resistance Factor Design of Steel H-Piles in Cohesive Soils.

The scope of this volume is to present the newly developed LRFD method for bridge foundations consisting of driven piles in Iowa with considerations to past practice and design simplifications, as well as to demonstrate the application of the method through examples presented in three tracks (in Chapters 3, 4, and 5).

Piles are designed using the Iowa “Blue Book” method, and the pile driving criteria are established using the WEAP, modified Iowa ENR formula, and combination of WEAP and PDA, with a subsequent pile signal matching analysis using CAPWAP. Chapter 2 outlines the concept of the three tracks, includes pile design flow charts, provides the standardized templates and instructions for the Computer-Aided Design and Drafting (CADD) design and driving notes for abutment piles and pier piles, and briefly describes each design example included in the following three chapters and tracks.

Track 1, which makes up Chapter 3, consists of seven design examples that use WEAP as the construction control method to define the pile driving criteria. The applications of LRFD in three different soil categories (cohesive, non-cohesive, and mixed soils, as defined in Appendix B) are illustrated in Track 1.

Track 2, which is detailed in Chapter 4, consists of two examples that use the modified Iowa ENR formula as the construction control method to define pile driving criteria. The LRFD application to timber piles is also demonstrated in this track.

Track 3, which makes up Chapter 5, demonstrates two design examples for projects that require special construction control procedures using PDA/CAPWAP, WEAP, and/or planned retaps.

Chapter 6 presents a summary of this volume. And, supplementary materials, design formulation, resistance factors, and other recommendations are included in Appendices A through H.

CHAPTER 2. DESIGN GUIDANCE AND OVERVIEW OF TRACK EXAMPLES

2.1. General

The background and basis for the resistance factors used in this volume are presented in the Development of LRFD Procedures for Bridge Pile Foundations in Iowa – Volume III: Recommended Resistance Factors with Consideration of Construction Control and Setup (AbdelSalam et al. 2012a).

Volume III includes a discussion of the rationale considered to calibrate resistance factors statistically and to adjust the calibrated resistance factors to maintain uniformity with Iowa DOT pile design practice. Volume III also includes a discussion about how pile setup and construction control are accommodated in the overall design process.

2.2. Track Concept

The design examples in this volume focus on issues related to geotechnical design (and not structural issues) of the pile foundations. The examples present the general procedures for pile foundation design.

Pile setup in cohesive soils (as outlined in Appendix B) and other special considerations, such as scour, downdrag, uplift, and end bearing in bedrock, are addressed in the design examples.

Given driven steel H-piles are mostly used in Iowa, steel H-piles were primarily considered in this volume, while other pile types, such as timber, prestressed concrete, and steel pipe piles, are included in the track examples. For other pile types, the general design procedures remain the same.

The LRFD examples cover three tracks for geotechnical design in Chapters 3 through 5 as summarized in Table 2.1.

Table 2.1. Overview of LRFD examples organized by track in Chapters 3 through 5

Chapter	Track	LRFD Using	Description
3	1	WEAP construction control (present design method for typical bridges)	The designer determines pile length based on plan-specified WEAP construction control. Only the pile length on the plans (contract length) will be provided and used. Any setup will be included in the original design. The Iowa DOT inspector will be provided a driving graph determined by a WEAP analysis. Retaps will be used within 24 hours only if bearing is not achieved with contract pile length at end of driving (EOD).
4	2	Modified Iowa ENR formula construction control (similar to WEAP for typical bridges)	The designer determines pile length based on plan-specified Iowa DOT ENR formula construction control. Only the pile length on the plans (contract length) will be provided and used. Any setup will be included in the original design. The inspector and/or contractor will use the formula to determine driving blow count. Retaps will be used within 24 hours only if bearing is not achieved with contract pile length at EOD.
5	3	Site load test, PDA/CAPWAP, WEAP, planned retaps, or special procedures (for large bridges and other bridges for which special procedures are appropriate)	Permits the designer to use a full range of special procedures to manage a large or special project. Eventually some branch of this track may become common for typical bridges.

2.3. Pile Design and Construction Steps

All of the design examples in this volume generally follow the same steps, which reflect the real-world design and construction procedures for an Iowa DOT driven pile foundation, as presented in Table 2.2.

Table 2.2. Summary of pile design and construction steps

Design Step	
1	Develop bridge situation plan (TS&L)*
2	Develop soils package, including soil borings and foundation recommendations*
3	Determine pile arrangement, pile loads, and other design requirements*
4	Estimate the nominal geotechnical resistance per foot of pile embedment**
5	Select resistance factor(s) to estimate pile length based on the soil profile and construction control**
6	Calculate the required nominal pile resistance, R_n**
7	Estimate contract pile length, L**
8	Estimate target nominal pile driving resistance, R_{ndr-T}**
9	Prepare CADD notes for bridge plans
10	Check the design depending on bridge project and office practice
Construction Step	
11	Prepare bearing graph
12	Observe construction, record driven resistance, and resolve any construction issues

* These steps determine the basic information for geotechnical pile design and vary depending on bridge project and office practice
** These steps are modified in Track 1 Example 5 for piles that are end bearing in bedrock

Figure 2.1 shows the construction control flow chart describing the process to be followed during construction to achieve the required nominal bearing resistance for construction control involving the following:

- End bearing pile embedded in all soil types as well as bedrock
- Friction pile embedded in non-cohesive and mixed soil types (no setup effect).

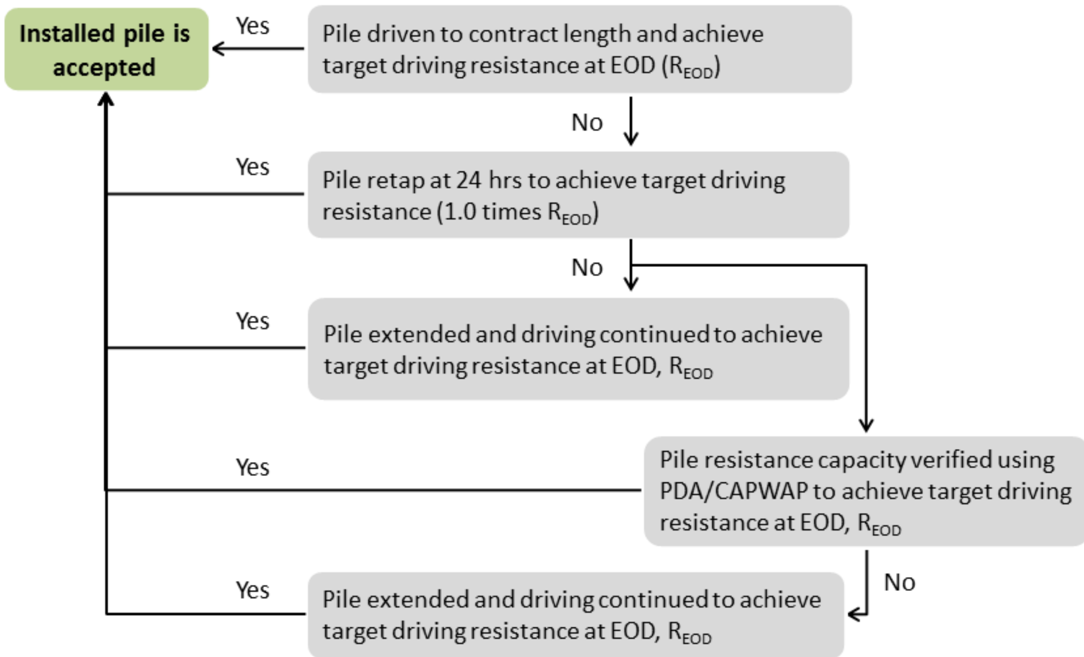


Figure 2.1. Construction control flow chart for end bearing piles in all soil types and friction piles embedded in non-cohesive and mixed soil types

Figure 2.2 shows the construction control flow chart describing the process to be followed during construction to achieve the required nominal bearing resistance for construction control involving friction pile embedded in cohesive soil with setup.

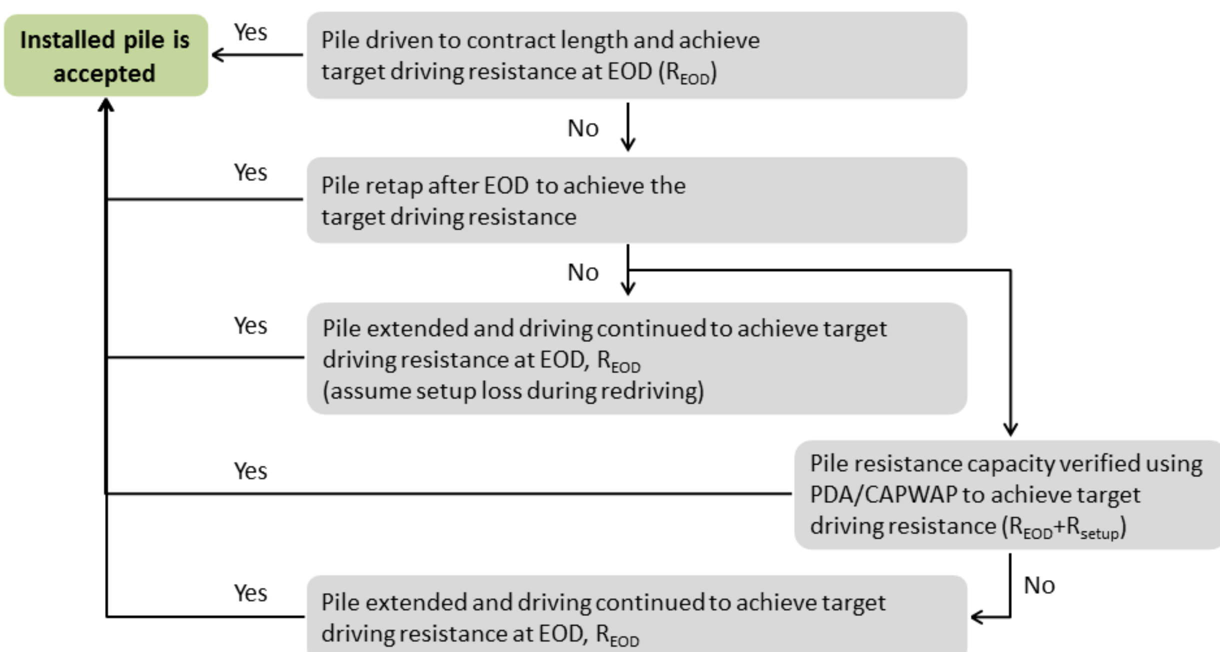


Figure 2.2. Construction control flow chart for friction piles embedded in cohesive soil and retap performed after EOD

2.4. Standardized CADD Note Templates

The Iowa DOT prepared standardized CADD note templates for use in summarizing and presenting pile design requirements and driving criteria on drawings and plans. The final design engineer selects the appropriate CADD notes and adds the specific pile load values to the notes.

The Iowa DOT presents pile design and driving notes in all capital letters (as shown below), and the authors of this volume replicate these notes using the same typeface as the Iowa DOT throughout the remainder of this volume.

The instructions to complete the CADD notes are also provided below (numbered, rather than bulleted).

A list of pertinent notations is included after the References for this volume and before the appendices.

2.4.1 Abutment Piles: Design Note and Instructions

THE CONTRACT LENGTH OF ___ FEET FOR THE ___ ABUTMENT PILES IS BASED ON A ___ SOIL CLASSIFICATION, A TOTAL FACTORED AXIAL LOAD PER PILE (P_U) OF ___ KIPS, AND A GEOTECHNICAL RESISTANCE FACTOR (PHI) OF ___ FOR SOIL AND ___ FOR ROCK END BEARING. TO ACCOUNT FOR SOIL CONSOLIDATION UNDER THE NEW FILL, THE FACTORED AXIAL LOAD INCLUDES A FACTORED DOWNDRAG LOAD OF ___ KIPS. ABUTMENT PILES ALSO WERE DESIGNED FOR A FACTORED TENSION FORCE OF ___ KIPS.

THE NOMINAL AXIAL BEARING RESISTANCE FOR CONSTRUCTION CONTROL WAS DETERMINED FROM A ___ SOIL CLASSIFICATION AND A GEOTECHNICAL RESISTANCE FACTOR (PHI) OF ___ FOR SOIL AND ___ FOR ROCK END BEARING. DESIGN SCOUR (100-YEAR) WAS ASSUMED TO AFFECT THE UPPER ___ FEET OF EMBEDDED PILE LENGTH AND CAUSE ___ KIPS OF DRIVING RESISTANCE.

1. Fill in the contract length (ft).
2. Fill in abutment location (north, east, south, or west) or delete the blank if the note covers both abutments.
3. Fill in soil classification for design (cohesive, mixed, or non-cohesive).
4. Fill in the total factored axial load per pile (Pu, kips).
5. Fill in the resistance factor (phi) for design in soil. If piles are to be driven to rock, add the resistance factor (phi) for rock; otherwise, delete the end of the sentence beginning with “for”.
6. If piles are subject to downdrag, fill in the factored downdrag load (kips).
7. Fill in soil classification for construction control (cohesive, mixed, or non-cohesive).
8. Fill in the resistance factor for construction control (phi).
9. If piles were designed for scour, fill in the affected embedded length (ft); otherwise, delete the sentence.

2.4.2 Abutment Piles: Driving Note and Instructions

THE REQUIRED NOMINAL AXIAL BEARING RESISTANCE FOR ___ ABUTMENT PILES IS ___ TONS AT END OF DRIVE (EOD). IF RETAPS ARE NECESSARY TO ACHIEVE BEARING, THE REQUIRED NOMINAL AXIAL BEARING RESISTANCE IS ___ TONS AT ONE-DAY RETAP, ___ TONS AT THREE-DAY RETAP, OR ___ TONS AT SEVEN-DAY RETAP. THE PILE CONTRACT LENGTH SHALL BE DRIVEN AS PER PLAN UNLESS PILES REACH REFUSAL. IN NO CASE SHALL A PILE BE EMBEDDED LESS THAN ___ FEET. CONSTRUCTION CONTROL REQUIRES A WEAP ANALYSIS WITH BEARING GRAPH.

1. Fill in abutment location (north, east, south, or west) or delete the blank if the note covers both abutments.
2. Fill in end of drive bearing (tons).
3. For clay or mixed sites, fill in retap blanks; for sand sites or piles driven to rock, delete the retap sentence. If retap is required for construction control, substitute the following sentence:
    - Piles must be retapped at ___ days with a required nominal axial bearing resistance of ___ tons.
4. For timber piles, replace the contract length sentence with the following:
    - The pile contract length shall be driven as per plan unless piles reach a driving limit of 110 tons.
5. If piles are subject to tension, scour, or other condition requiring a minimum embedment length, fill in the length (ft); otherwise, delete the sentence.
6. Replace the construction control sentence if a method other than WEAP without planned retap is to be used. Alternate sentences are as follows:
    - Construction control requires a modified Iowa DOT formula.
    - Construction control requires PDA/CAPWAP and a WEAP analysis with bearing graph.
    - Construction control requires a WEAP analysis with bearing graph and a retap at ___ days after EOD.

2.4.3 Pier Piles: Design Note and Instructions

THE CONTRACT LENGTH OF ___ FEET FOR THE ___ PIER PILES IS BASED ON A ___ SOIL CLASSIFICATION, A TOTAL FACTORED AXIAL LOAD PER PILE (P_U) OF ___ KIPS, AND A GEOTECHNICAL RESISTANCE FACTOR (PHI) OF ___ FOR SOIL AND ___ FOR ROCK END BEARING. TO ACCOUNT FOR SOIL CONSOLIDATION, THE FACTORED AXIAL LOAD INCLUDES A FACTORED DOWNDRAG LOAD OF ___ KIPS. PIER PILES ALSO WERE DESIGNED FOR A FACTORED TENSION FORCE OF ___ KIPS.

THE NOMINAL AXIAL BEARING RESISTANCE FOR CONSTRUCTION CONTROL WAS DETERMINED FROM A ___ SOIL CLASSIFICATION AND A GEOTECHNICAL RESISTANCE FACTOR (PHI) OF ___ FOR SOIL AND ___ FOR ROCK END BEARING. DESIGN SCOUR (100-YEAR) WAS ASSUMED TO AFFECT THE UPPER ___ FEET OF EMBEDDED PILE LENGTH AND CAUSE ___ KIPS OF DRIVING RESISTANCE.

1. Fill in the contract length (ft).
2. Fill in abutment location (north, east, south, or west) or delete the blank if the note covers both abutments.
3. Fill in soil classification for design (cohesive, mixed, or non-cohesive).
4. Fill in the total factored axial load per pile (Pu, kips).
5. Fill in the resistance factor (phi) for design in soil. If piles are to be driven to rock, add the resistance factor (phi) for rock; otherwise, delete the end of the sentence beginning with "for".
6. If piles are subject to downdrag, fill in the factored downdrag load (kips).
7. Fill in soil classification for construction control (cohesive, mixed, or non-cohesive).
8. Fill in the resistance factor for construction control (phi).
9. If piles were designed for scour, fill in the affected embedded length (ft); otherwise, delete the sentence.

2.4.4 Pier Piles: Driving Note and Instructions

THE REQUIRED NOMINAL AXIAL BEARING RESISTANCE FOR PIER ___ PILES IS ___ TONS AT END OF DRIVE. IF RETAPS ARE NECESSARY THE REQUIRED NOMINAL AXIAL BEARING RESISTANCE IS ___ TONS AT ONE-DAY RETAP, ___ TONS AT THREE DAY RETAP, OR ___ TONS AT SEVEN DAY RETAP. THE PILE CONTRACT LENGTH SHALL BE DRIVEN AS PER PLAN UNLESS PILES REACH REFUSAL. IN NO CASE SHALL A PILE BE EMBEDDED LESS THAN ___ FEET. CONSTRUCTION CONTROL REQUIRES A WEAP ANALYSIS AND BEARING GRAPH.

1. Fill in pier number (1, 2…) or delete the blank if the note covers all piers.
2. Fill in end of drive bearing (tons).
3. For clay or mixed sites, fill in retap blanks; for sand sites delete retap sentence.
4. For clay or mixed sites, fill in retap blanks; for sand sites or piles driven to rock, delete the retap sentence. If retap is required for construction control, substitute the following sentence.
    - Piles must be retapped at ___ days with a required nominal axial bearing resistance of ___ tons.
5. For timber piles replace the contract length sentence with the following:
    - The pile contract length shall be driven as per plan unless piles reach a driving limit of 110 tons.
6. If piles are subject to tension, scour, or other conditions requiring a minimum embedment length, fill in the length; otherwise delete the sentence.
7. Replace the construction control sentence if a method other than WEAP without planned retap is to be used. Alternate sentences are as follows:
    - Construction control requires a modified Iowa DOT formula.
    - Construction control requires PDA/CAPWAP and a WEAP analysis with bearing graph.
    - Construction control requires a WEAP analysis with bearing graph and a retap at ___ days after EOD.

Discussion item for Department policy concurrence: Consider setting the minimum embedment length due to scour equal to at least 2/3 the Iowa DOT “Blue Book” nominal capacity, plus the 100 percent of the capacity lost over the scour zone. Also, consider a minimum penetration of five pile diameters to develop end bearing in a stratum.

2.5. Overview of Design Examples

This volume currently consists of 11 design examples, which are arranged into three tracks as listed in Table 2.3.

Table 2.3. Summary of track examples

<table>
<tr><th rowspan="2">Track</th><th rowspan="2">Pile Type</th><th rowspan="2">Example</th><th rowspan="2">Sub-structure Type</th><th rowspan="2">Soil Type</th><th rowspan="2">Special Consider-ations</th><th colspan="2">Construction Controls</th></tr>
<tr><th>Driving Criteria Basis</th><th>Planned Retap 3 Days after EOD</th></tr>
<tr><td rowspan="7">1</td><td rowspan="5">H-Pile</td><td>1</td><td>Integral Abutment</td><td>Cohesive</td><td>---</td><td rowspan="7">Wave Equation</td><td rowspan="10">No</td></tr>
<tr><td>2</td><td>Pier</td><td>Mixed</td><td>Scour</td></tr>
<tr><td>3</td><td>Integral Abutment</td><td>Cohesive</td><td>Downdrag</td></tr>
<tr><td>4</td><td>Pier</td><td>Non-Cohesive</td><td>Uplift</td></tr>
<tr><td>5</td><td>Integral Abutment</td><td>Cohesive</td><td>End Bearing in Bedrock</td></tr>
<tr><td>Pipe Pile</td><td>6</td><td>Pile Bent</td><td>Non-Cohesive</td><td>Scour</td></tr>
<tr><td>Prestressed Concrete Pile</td><td>7</td><td>Pile Bent</td><td>Non-Cohesive</td><td>Scour</td></tr>
<tr><td rowspan="2">2</td><td>H-Pile</td><td>1</td><td>Integral Abutment</td><td>Cohesive</td><td>---</td><td rowspan="2">Modified Iowa ENR Formula</td></tr>
<tr><td>Timber</td><td>2</td><td>Integral Abutment</td><td>Non-Cohesive</td><td>---</td></tr>
<tr><td rowspan="2">3</td><td rowspan="2">H-Pile</td><td>1</td><td>Integral Abutment</td><td>Cohesive</td><td>---</td><td>PDA/ CAPWAP and Wave Equation</td></tr>
<tr><td>2</td><td>Integral Abutment</td><td>Cohesive</td><td>---</td><td>Wave Equation</td><td>Yes</td></tr>
</table>

The Office of Bridges and Structures policies regarding LRFD for piles are still evolving. In some cases, the design examples in this volume may not illustrate current policies. The designer is responsible for determining up-to-date policies. Each design example is a standalone document.

The soil classification in this volume (as listed in Table 2.3), as well as throughout the LRFD study, including PILOT, was defined using a 70 percent rule. Accordingly, a site is classified as sand or clay if the corresponding soil type is present more than 70 percent of the pile embedded length, where the soil type for each layer is identified as per the Unified Soil Classification System (USCS). If the percentage of the predominant soil along the pile length is less than 70 percent sand or clay, that site is taken as a mixed soil site.

A brief description of each design example follows.

Track 1 Example 1

As the first example in this volume, this example provides detailed calculations that might not be included in the other examples, such as the following:

- Selection of unit nominal resistance based on soil type and SPT N-value
- Determination of setup factor for cohesive soil based on average SPT N-value
- Determination of nominal driving resistance from blow count during construction
- Determination of generalized soil category based on the ratio of pile penetration in cohesive and non-cohesive layers
- Incorporation of setup into driving resistance estimation for cohesive soils
- Discussion on pile retap 24 hours after EOD for piles with driving resistance at EOD less than the required nominal driving resistance

Track 1 Example 2

This example illustrates that for friction pile subject to scour, the contribution to side resistance from the soil above the scour interval should be neglected to estimate the nominal bearing resistance (Design Step 7), while this contribution should be included to estimate driving resistance (Design Step 8). The increase in the length of the friction pile to account for scour will result in additional driving resistance that must be accounted for when the piles are driven.

Track 1 Example 3

This example highlights the effects of downdrag on pile design: 1) the soil above the neutral plane does NOT contribute to side resistance; 2) downward relative movement of soil above the neutral plane exerts drag load to the pile. This example also demonstrates how prebored holes can be used to relieve part of the drag load.

Track 1 Example 4

This design example includes an uplift resistance calculation, in addition to the routine pile axial compression resistance calculation. Resistance factors for uplift are taken as 75 percent of the resistance factors for axial compression resistance.

Track 1 Example 5

This design example is for end bearing piles that are driven through cohesive soil and tipped out in rock. A resistance factor of 0.7 was used for end bearing in rock based on successful past practice with WEAP analysis and the general direction of Iowa LRFD pile testing and research. This design example presents the procedures to calculate pile resistance from a combination of side friction in soil and end bearing in rock. It also demonstrates how to consider the partial setup effect from the side resistance in cohesive soil.

Track 1 Example 6 (Supplemental Design Example prepared by Iowa DOT)

This design example illustrates design of displacement pipe pile that develops frictional resistance in non-cohesive soil at a pile bent that is exposed to possible scour.

Track 1 Example 7 (Supplemental Design Example prepared by Iowa DOT)

This design example is for prestressed concrete friction pile that is driven in non-cohesive soil at a pile bent that is exposed to possible scour.

Track 2 Example 1

This design example demonstrates how to use the modified Iowa ENR formula to estimate nominal pile driving resistance from observed blow counts during pile driving. The only difference between this design example and Track 1 Example 1 is the construction control. Note that the resistance factors used in this design example are lower than those in Track 1 Example 1, given more uncertainty is involved when using construction control based on the modified Iowa ENR formula rather than a wave equation analysis.

Track 2 Example 2 (Supplemental Design Example prepared by Iowa DOT)

This design example is for timber pile that is driven in non-cohesive soil using the modified Iowa ENR formula for construction control.

Track 3 Example 1

This design example is basically the same as Track 1 Example 1, with additional construction control involving a pile driving analyzer (PDA) and CAPWAP analysis. The purpose of this design example is to demonstrate that when more strict construction control is applied, fewer uncertainties are involved given the pile resistance can be field-verified by PDA/CAPWAP tests. Therefore, higher resistance factors can be used, and this results in shorter pile length.

Track 3 Example 2

This design example is basically the same as Track 1 Example 1, with additional construction control involving pile retaps at three days after end of driving (EOD). Note that the resistance factors with special consideration of pile setup are for seven-day retaps. This design example demonstrates how to estimate the nominal driving resistance at three days after EOD using the setup factor chart. It also demonstrates that higher resistance factors can be used when retap is planned, given the retap is used to verify the increase in geotechnical pile resistance as a result of pile setup.

CHAPTER 3. TRACK 1 EXAMPLES FOR LRFD USING THE WEAP CONSTRUCTION CONTROL METHOD

Track 1 demonstrates the application of the LRFD procedure using WEAP as the construction control method. As briefly described in Chapter 2, seven examples, each having their own special considerations, are presented in this chapter.

Steel H-piles are used in the first five examples, and pipe piles and prestressed concrete piles are used in Examples 6 and 7, respectively. Three different substructure types, integral abutment, pier, and pile bent are considered. Examples 1, 3, and 5 consider the pile LRFD procedures in cohesive soils. Example 2 illustrates the LRFD procedure in mixed soils, while Examples 4, 6, and 7 demonstrate the LRFD applications in non-cohesive soils. The different soil types are described in the Appendix B.

Examples 1 through 5 were prepared based on the outcomes of the three LRFD research projects (Roling et al. 2000, Ng et al. 2011, and AbdelSalam et al. 2012a). Examples 6 and 7 were provided by Iowa DOT as supplemental design examples.

3.1. Track 1 Example 1: Driven H-Pile in Cohesive Soil with Construction Control Based on Wave Equation and No Planned Retap

Table 3.1. Track 1 Example 1: Design and construction steps

Design Step	
1	Develop bridge situation plan (TS&L)*
2	Develop soils package, including soil borings and foundation recommendations*
3	Determine pile arrangement, pile loads, and other design requirements*
4	Estimate the nominal geotechnical resistance per foot of pile embedment
5	Select a resistance factor to estimate pile length based on the soil profile and construction control
6	Calculate the required nominal pile resistance, R_n
7	Estimate contract pile length, L
8	Estimate target nominal pile driving resistance, $R_{ndr\text{-}T}$
9	Prepare CADD notes for bridge plans
10	Check the design depending on bridge project and office practice
Construction Step	
11	Prepare bearing graph
12	Observe construction, record driven resistance, and resolve any construction issues

* These steps determine the basic information for geotechnical pile design and vary depending on bridge project and office practice

Within the Iowa DOT Office of Bridges and Structures, the design steps that determine the basic information necessary for geotechnical design of a steel H-pile generally follow Steps 1 through 3. The steps involve communication among the preliminary design engineer, soils design engineer, and final design engineer.

In other organizations, the basic information may be determined differently, but that process generally should not affect the overall geotechnical design of the pile.

Step 1 – Develop bridge situation plan (or TS&L)

For a typical bridge, the preliminary design engineer plots topographical information, locates the bridge, determines general type of superstructure, location of substructure units, elevations of foundations, hydraulic information (if needed), and other basic information to characterize the bridge. The preliminary design engineer then prepares the TS&L sheet that shows a plan and longitudinal section of the bridge.

For this example, the TS&L gives the following information needed for design of abutment piles:

- 120 ft, single-span, prestressed concrete beam superstructure
- Zero skew
- Integral abutments
- Pile foundations, no prebored holes (because the bridge length is less than 130 ft) (BDM 6.5.1.1.1)
- Bottom of abutment footing elevation 433 ft

Step 2 – Develop soils package, including soil borings and foundation recommendations

Based on location of the abutments, the soils design engineer orders soil borings (typically at least one per substructure unit). Upon receipt of the boring logs, the engineer arranges for them to be plotted on a longitudinal section, checks any special geotechnical conditions on the site, and writes a recommendation for foundation type with any applicable special design considerations.

For this example, the recommendations are as follows:

- Friction piles that tip out in the firm glacial clay layer
- Steel H-piles for the integral abutments
- Structural Resistance Level – 1 (which does not require a driving analysis by the Office of Construction during design (BDM 6.2.6.1))
- Normal driving resistance (This will lead to $\varphi_c = 0.6$ for the structural check, which needs to be performed but is not included in this geotechnical example.)
- No special site considerations for stability, settlement, or lateral movement (Therefore, the Service I load will not be required for design.)
- Standard construction control based on WEAP analysis with no planned retap

The soil profile shown in Figure 3.1 includes the soil boring at the west abutment. Generally, below the bottom of footing elevation, there are three layers: 6 ft of soft silty clay, 9 ft of silty sand, and firm glacial clay to the bottom of the boring at 95 ft.

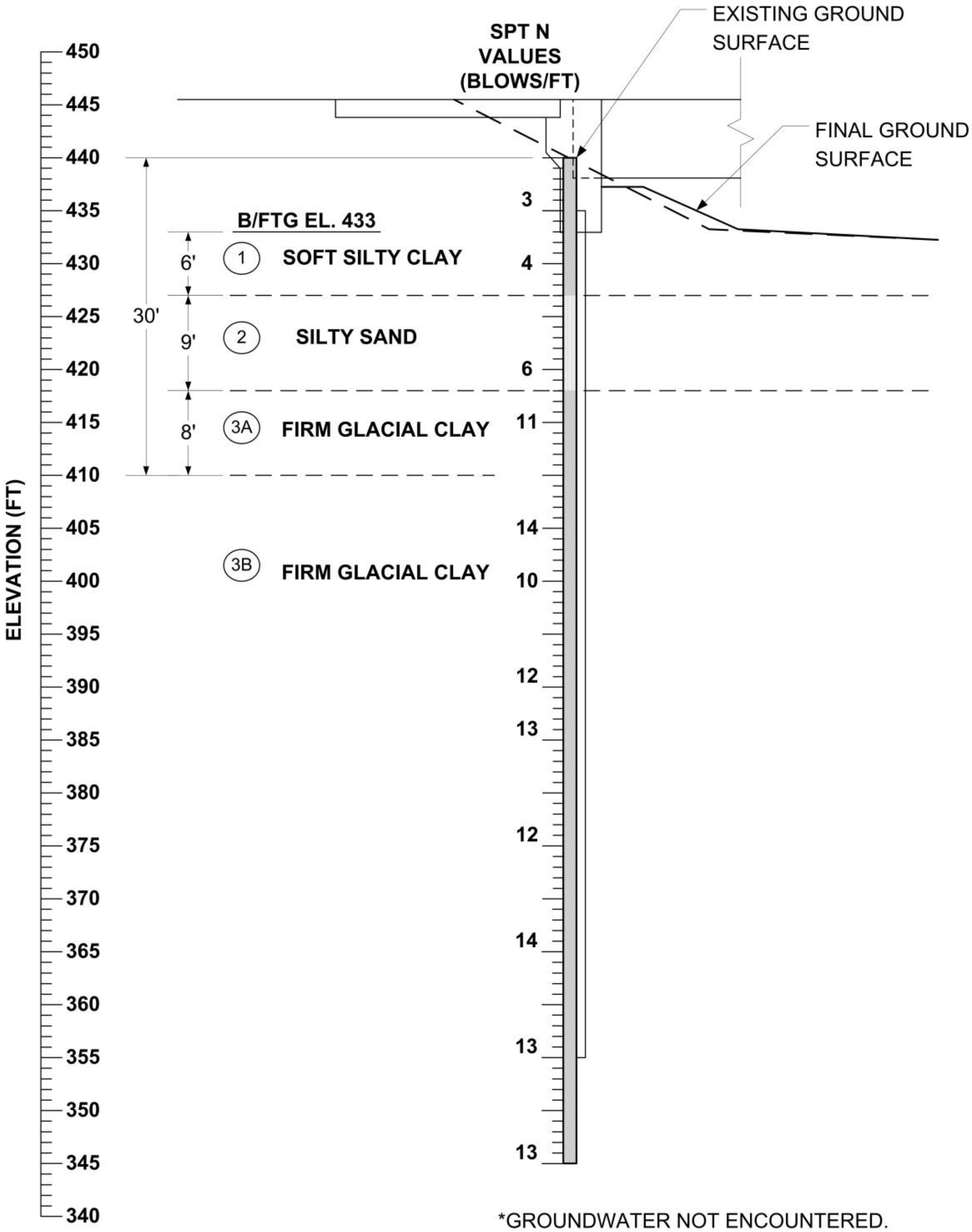


Figure 3.1. Track 1 Example 1: Soil profile

Step 3 – Determine pile arrangement, pile loads, and other design requirements

The final design engineer begins design of the abutment piles with the TS&L and the soils design package. Because the bridge has a prestressed concrete beam superstructure and integral abutments, the engineer selects HP 10×57 piles, following Bridge Design Manual policy (BDM 6.5.1.1.1).

Based on total Strength I abutment load and the Bridge Design Manual policy for pile spacing and number of piles (BDM 6.5.4.1.1), the engineer determines the following:

- Seven HP 10×57 piles plus two wing extension piles, numbers 1 and 9 in Figure 3.2, that support the wings only as shown in the figure
- Strength I load per pile = 128 kips
- No uplift, downdrag, or scour
- Standard Iowa DOT construction control based on WEAP analysis and no planned retap

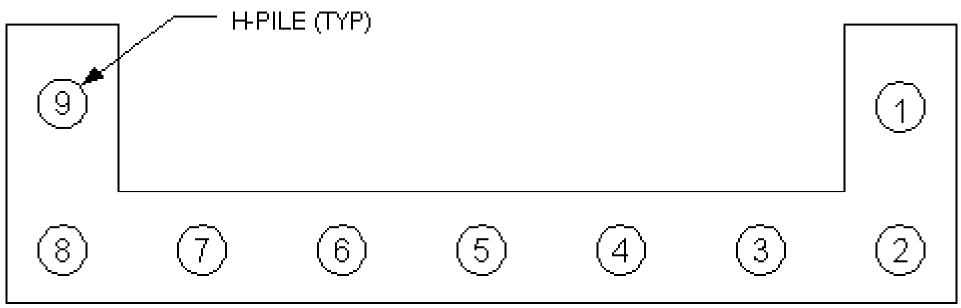


Figure 3.2. Track 1 Example 1: Pile arrangement at an abutment

Because the bridge characteristics fall within integral abutment policy, the site has no unusual characteristics, the soils design engineer did not require further analysis, and construction will not be accelerated or delayed, there will be no need for lateral load or special analysis of the abutment piles. The piles may be simply designed for vertical load.

Step 4 – Estimate the nominal geotechnical resistance per foot of pile embedment

Based on the west abutment soil boring and BDM Table 6.2.7 as shown in Table 3.2, the final design engineer estimates the unit nominal resistances for friction bearing as enumerated in Table 3.3.

Table 3.2. Track 1 Example 1: BDM geotechnical resistance chart

SOIL DESCRIPTION	BLOW COUNT N-VALUE		ESTIMATED NOMINAL RESISTANCE VALUES FOR FRICTION PILE IN KIPS PER FOOT										
	MEAN	RANGE	WOOD PILE	STEEL "H" 10	STEEL "H" 12	STEEL "H" 14	PRESTRESSED 12	PRESTRESSED 14	PRESTRESSED 16	STEEL PIPE 10	STEEL PIPE 12	STEEL PIPE 14	STEEL PIPE 18
Alluvium or Loess													
Very soft silty clay	1	0 - 1	0.8	0.4	0.8	0.8	0.8	0.8	0.8	0.4	0.4	0.4	0.8
Soft silty clay	3	2 - 4	1.2	0.8	1.2	1.2	0.8	0.8	0.8	0.8	0.8	0.8	1.2
Stiff silty clay	6	4 - 8	1.6	1.2	1.6	2.0	1.2	1.6	2.0	1.2	1.2	1.6	2.0
Firm silty clay	11	7 - 15	2.4	2.0	2.4	2.8	2.4	2.8	3.2	1.6	2.0	2.4	2.8
Stiff silt	6	3 - 7	1.6	1.2	1.6	1.6	1.6	1.6	1.6	1.2	1.2	1.6	1.6
Stiff sandy silt	6	4 - 8	1.6	1.2	1.6	1.6	1.6	1.6	1.6	1.2	1.2	1.6	1.6
Stiff sandy clay	6	4 - 8	1.6	1.2	1.6	2.0	2.0	2.0	2.4	1.2	1.6	1.6	2.0
Silty sand	8	3 - 13	1.2	1.2	1.2	1.6	1.6	1.6	1.6	0.8	0.8	1.2	1.6
Clayey sand	13	6 - 20	2.0	1.6	2.0	2.8	2.4	2.4	2.8	1.6	2.0	2.4	2.8
Fine sand	15	8 - 22	2.4	2.0	2.4	2.8	2.4	2.8	3.2	1.6	2.0	2.4	2.8
Coarse sand	20	12 - 28	3.2	2.8	3.2	3.6	3.2	3.6	4.0	2.0	2.4	2.8	3.6
Gravelly sand	21	11 - 31	3.2	2.8	3.2	3.6	3.6	3.6	4.0	2.0	2.4	2.8	3.6
Granular material	> 40	---	(2)	4.0	4.8	5.6	(2)	(2)	(2)	(2)	(2)	(2)	(2)
Glacial Clay													
Firm silty glacial clay	11	7 - 15	2.8	2.4	2.8	3.2	2.8	3.2	3.6	2.0	2.4	2.4	3.2
Firm clay (gumbotil)	12	9 - 15	2.8	2.4	2.8	3.2	2.8	3.2	3.6	2.0	2.4	2.4	3.2
Firm glacial clay (1)	11	7 - 15	2.4 [3.2]	2.8 [3.2]	3.2 [4.0]	3.6 [4.4]	3.2 [4.0]	3.6 [4.4	4.0 [4.8]	2.0 [2.4]	2.4 [2.8]	2.8 [3.2]	3.6 [4.4]
Firm sandy glacial clay (1)	13	9 - 15	2.4 [3.2]	2.8 [3.2]	3.2 [4.0]	3.6 [4.4]	3.2 [4.0]	3.6 [4.4	4.0 [4.8]	2.0 [2.4]	2.4 [2.8]	2.8 [3.2]	3.6 [4.4]
Firm - very firm glacial clay (1)	14	11 - 17	2.8 [3.6]	2.8 [4.0]	3.2 [4.8]	3.6 [5.6]	4.0 [4.8]	4.4 [5.2	4.8 [5.6]	2.4 [3.2]	2.8 [3.6]	3.2 [4.0]	4.0 [5.2]
Very firm glacial clay (1)	24	17 - 30	2.8 [3.6]	2.8 [4.0]	3.2 [4.8]	3.6 [5.6]	3.2 (3) [4.8]	3.6 (3) [5.6]	4.4 (3) [6.4]	2.4 [3.2]	2.8 [3.6]	3.2 [4.0]	4.0 [5.2]
Very firm sandy glacial clay (1)	25	15 - 30	3.2 [4.0]	2.8 [4.0]	3.2 [4.8]	3.6 [5.6]	3.2 (3) [4.8]	3.6 (3) [5.6]	4.4 (3) [6.4]	2.4 [3.2]	2.8 [3.6]	3.2 [4.0]	4.0 [5.2]
Cohesive or glacial material (1)	> 35	---	(2)	2.8 [4.0]	3.2 [4.8]	3.6 [5.6]	(2)	(2)	(2)	2.0 (4) [3.2]	2.4 (4) [4.0]	2.8 (4) [4.4]	3.6 (4) [5.6]

Table notes:

(1) **For double entries the upper value is for an embedded pile within 30 feet of the natural ground elevation, and the lower value [ ] is for pile depths more than 30 feet below the natural ground elevation.**

(2) Do not consider use of this pile type for this soil condition, wood with N > 25, prestressed concrete with N > 35, or steel pipe with N > 40.

(3) Prestressed concrete piles have proven to be difficult to drive in these soils. Prestressed piles should not be driven in glacial clay with consistent N > 30 to 35.

(4) Steel pipe piles should not be driven in soils with consistent N > 40.

Table 3.3. Track 1 Example 1: Estimated nominal geotechnical resistance

<table>
<tr><th>Soil Stratum</th><th colspan="2">Soil Description</th><th>Stratum Thickness (ft)</th><th>Average SPT N Value (blows/ft)</th><th>Estimated Unit Nominal Resistance for Friction Pile (kips/ft)</th></tr>
<tr><td>1</td><td colspan="2">Soft Silty Clay</td><td>6</td><td>4</td><td>0.8</td></tr>
<tr><td>2</td><td colspan="2">Silty Sand</td><td>9</td><td>6</td><td>1.2</td></tr>
<tr><td>3A</td><td rowspan="2">Firm Glacial Clay</td><td>within 30 ft of natural ground elevation</td><td>8</td><td>11</td><td>2.8</td></tr>
<tr><td>3B</td><td>more than 30 ft below natural ground elevation</td><td>65</td><td>12</td><td>3.2</td></tr>
</table>

The firm glacial clay stratum has been divided into two parts to delineate the embedded pile length that is within 30 ft of the natural ground surface as noted in the BDM geotechnical resistance chart. Application of the chart to estimate the nominal resistance values is illustrated on Table 3.2. Note that the SPT N values are too small for use of end bearing in Layer 3B.

Step 5 – Select a resistance factor to estimate pile length based on the soil profile and construction control

In this step, the final design engineer first characterizes the site as cohesive, mixed, or non-cohesive based on Table 3.4 and the soil profile.

Table 3.4. Track 1 Example 1: Soil classification table

<table>
<tr><th rowspan="2">Generalized Soil Category</th><th colspan="4">Soil Classification Method</th></tr>
<tr><th>AASHTO</th><th>USDA Textural</th><th colspan="2">BDM 6.2.7 Geotechnical Resistance Chart</th></tr>
<tr><td rowspan="14">Cohesive</td><td rowspan="14">A-4, A-5, A-6, and A-7</td><td rowspan="14">Clay
Silty clay
Silty clay loam
Silt
Clay loam
Silt loam
Loam
Sandy clay</td><td rowspan="6">Loess</td><td>Very soft silty clay</td></tr>
<tr><td>Soft silty clay</td></tr>
<tr><td>Stiff silty clay</td></tr>
<tr><td>Firm silty clay</td></tr>
<tr><td>Stiff silt</td></tr>
<tr><td>Stiff sandy clay</td></tr>
<tr><td rowspan="8">Glacial Clay</td><td>Firm silty glacial clay</td></tr>
<tr><td>Firm clay (gumbotil)</td></tr>
<tr><td>Firm glacial clay</td></tr>
<tr><td>Firm sandy glacial clay</td></tr>
<tr><td>Firm-very firm glacial clay</td></tr>
<tr><td>Very firm glacial clay</td></tr>
<tr><td>Very firm sandy glacial clay</td></tr>
<tr><td>Cohesive or glacial material</td></tr>
<tr><td rowspan="7">Non-Cohesive</td><td rowspan="7">A-1, A-2, and A-3</td><td rowspan="7">Sandy clay loam
Sandy loam
Loamy sand
Sand</td><td rowspan="7">Alluvium Or Loess</td><td>Stiff sandy silt</td></tr>
<tr><td>Silty sand</td></tr>
<tr><td>Clayey sand</td></tr>
<tr><td>Fine sand</td></tr>
<tr><td>Coarse sand</td></tr>
<tr><td>Gravely sand</td></tr>
<tr><td>Granular material (N>40)</td></tr>
</table>

Only the 9 ft Layer two of silty sand is classified as non-cohesive. The remainder of the profile is classified as cohesive, and most likely will represent more than 70 percent of the pile embedment length. Thus, the soil is expected to fit the cohesive classification, and the resistance factor selection from the three available choices below is 0.65.

$\varphi = 0.65$ for cohesive soil, averaged over the full depth of estimated pile penetration
$\varphi = 0.65$ for mixed soil, averaged over the full depth of estimated pile penetration
$\varphi = 0.55$ for non-cohesive soil, averaged over the full depth of estimated pile penetration

Step 6 – Calculate the required nominal pile resistance, Rn

The required nominal pile resistance is as follows:

$$R_{EOD} = \frac{\sum \eta\gamma Q + \gamma_{DD} DD}{\varphi} = \frac{128 + 0}{0.65} = 197 \text{ kips/pile}$$

where

$\sum \eta\gamma Q = \gamma Q = 128$ kips (Step 3)

$\gamma_{DD} DD = 0$ (no downdrag)

$\varphi = 0.65$ (Step 5)

Step 7 – Estimate contract pile length, L

Based on the nominal resistance values in Step 4, the cumulative nominal geotechnical resistance, $R_{n\text{-}BB}$, per pile is calculated as follows, where D = depth in feet below the bottom of footing:

$D_0 = 0$ ft, $R_{n\text{-}BB0} = 0$

$D_1 = 6$ ft, $R_{n\text{-}BB1} = R_{n\text{-}BB0} + (0.8 \text{ kips/ft})\ (6 \text{ ft}) = 4.8$ kips

$D_2 = 6 + 9 = 15$ ft, $R_{n\text{-}BB2} = R_{n\text{-}BB1} + (1.2 \text{ kips/ft})\ (9 \text{ ft}) = 4.8 + 10.8 = 15.6$ kips

$D_3 = 15 + 8 = 23$ ft, $R_{n\text{-}BB3} = R_{n\text{-}BB2} + (2.8 \text{ kips/ft})\ (8 \text{ ft}) = 15.6 + 22.4 = 38.0$ kips

$D_4 = 23 + 65 = 88$ ft, $R_{n\text{-}BB4} = R_{n\text{-}BB3} + (3.2 \text{ kips/ft})\ (65 \text{ ft}) = 38.0 + 208.0 = 246.0$ kips

A graphic presentation of the estimated nominal geotechnical resistance per pile versus depth is presented in Figure 3.3.

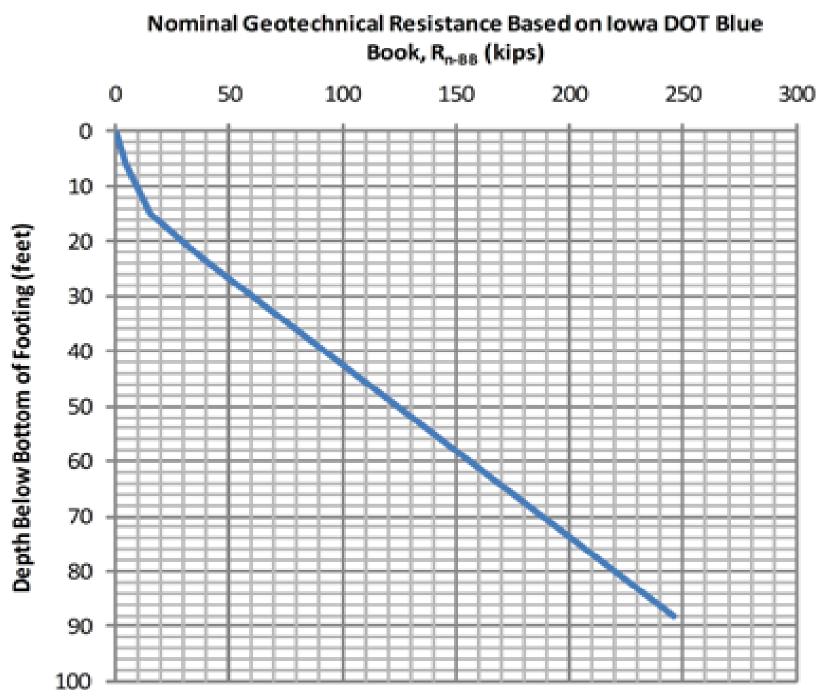


Figure 3.3. Track 1 Example 1: Plot of nominal geotechnical resistance versus depth

From the graph, the depth below the footing necessary to achieve 197 kips is about 73 ft and may be computed as follows:

$D_L = 23 + (197\text{-}38.0)/3.2 = 73$ ft

The contract pile length includes a 2 ft embedment in the footing and a 1 ft allowance for cutoff due to driving damage:

L = 73 + 2 + 1 = 76 ft

The length for steel H-piles is specified in 5 ft increments (BDM 6.2.4.1). Therefore, the contract pile length is 75 ft, with 72 ft embedded.

At this point, the embedded pile length is known and it is necessary to check the resistance factor:

% cohesive soil = [(72-9)/72] (100) = 88% > 70%

Therefore, the resistance factor for cohesive soil is the correct choice.

If the resistance factor were incorrect, the engineer would need to repeat Steps 6 and 7 (although, in this example, the mixed soil classification would not result in numeric changes).

Step 8 – Estimate target nominal pile driving resistance, Rndr-T

For a driven H-pile with no planned retap and use of a WEAP analysis for construction control, the following resistance factors, φ, are recommended to estimate the target nominal pile driving resistance:

φEOD = 0.65 for cohesive soil, averaged over the full depth of estimated pile penetration
φSETUP = 0.2 for cohesive soil, averaged over the full depth of estimated pile penetration
φ = 0.65 for mixed soil, averaged over the full depth of estimated pile penetration
φ = 0.55 for non-cohesive soil, averaged over the full depth of estimated pile penetration

For a normal construction schedule, pile setup at 1 day is the most appropriate choice. Therefore, the nominal pile resistance during construction, R_n, will be determined at EOD by scaling back setup gain, and, then, adjusting retaps to account for setup. Refer to Appendix E for more information on calculating the required nominal resistance at EOD (R_{EOD}).

$\Sigma\eta\gamma Q + \gamma_{DD}DD \leq \varphi R_n$ where η = load modifier = 1.0 from BDM 6.2.3.1

Let $R_n = R_T$ = nominal pile resistance at time T (days) after EOD.

$$R_{EOD} \geq \frac{\sum \eta\gamma Q + \gamma_{DD} DD}{\varphi_{EOD} + \varphi_{SETUP}(F_{SETUP} - 1)}$$

where

$\sum \eta\gamma Q = \gamma Q$ = 128 kips, (Step 2)

$\gamma_{DD} DD = 0$ (no downdrag)

F_{SETUP} = Setup Ratio = R_T/R_{EOD}

To determine the setup ratio, the soil profile was used to calculate the average SPT N-value for the cohesive soil layers penetrated by the driven pile over the contract pile length, as follows:

Calculated average SPT N-value = [(6′)(4) + (8′)(11) + (72′-23′)(12)]/(72′-9′) = 11

The average SPT N-value of 11 yields a Setup Ratio, F_{SETUP}, of 1.47 for 1 day retap, 1.55 for 3 day retap and 1.61 for 7 day retap, as shown in Figure 3.4. Refer to Appendix D for more information on the pile setup design chart.

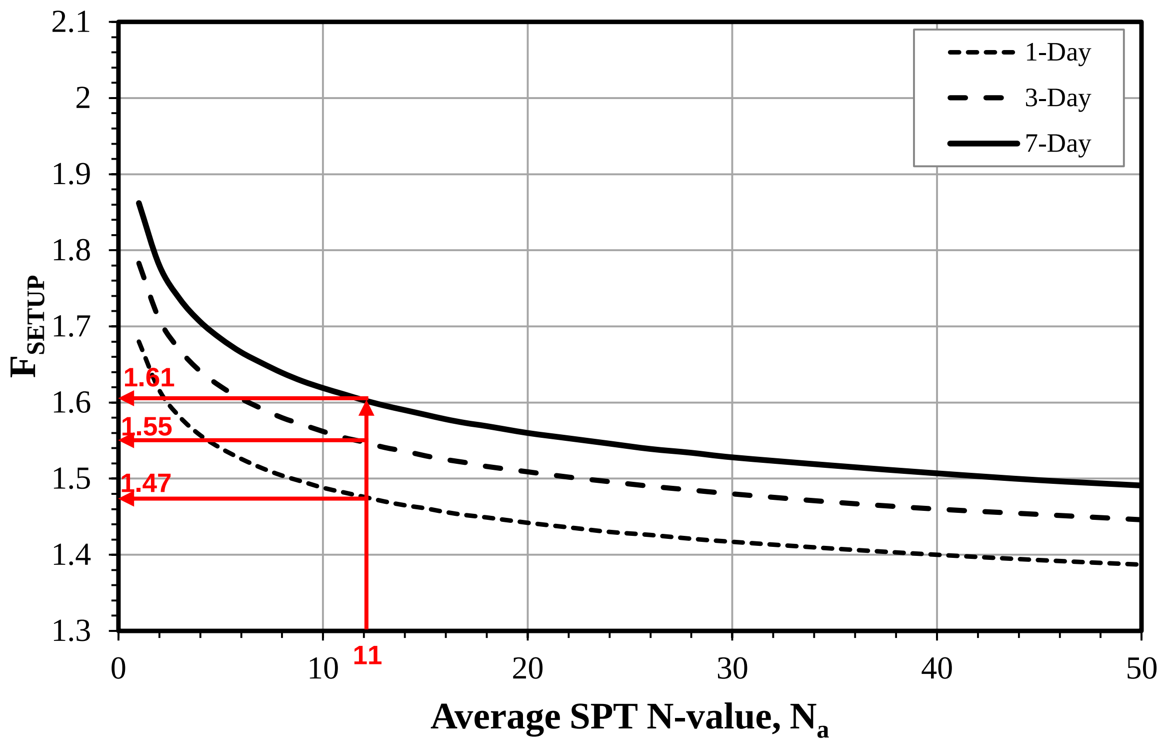


Figure 3.4. Track 1 Example 1: Pile setup factor chart

Let φ_{TAR} = Resistance factor for target nominal resistance ≤ 1.00

$= \varphi_{EOD} + \varphi_{SETUP}(F_{SETUP} - 1)$,

and $R_{ndr\text{-}T} = R_{EOD}$

The target pile driving resistance at EOD is as follows:

$$R_{ndr-T} = R_{EOD}$$

$$\geq \frac{\sum \eta\gamma Q + \gamma_{DD} DD}{\varphi_{TAR}}$$

$$\geq \frac{\sum \eta\gamma Q + \gamma_{DD} DD}{\varphi_{EOD} + \varphi_{SETUP}(F_{SETUP} - 1)}$$

$$\geq \frac{128 + 0}{(0.65) + (0.20)(1.61 - 1)} = \frac{128}{0.77}$$

= 166 kips/pile

The target nominal geotechnical resistance at 1 day retap, then, is as follows:

$R_{1\text{-day}}$ = (166.0)(1.47) = 244 kips = 122 tons

The target nominal geotechnical resistance at 3 day retap, then, is as follows:

$R_{3\text{-day}}$ = (166.0)(1.55) = 257.3 kips = 129 tons

The target nominal geotechnical resistance at 7 day retap, then, is as follows:

$R_{7\text{-day}}$ = (166.0) (1.61) = 267.3 kips = 134 tons

Step 9 – Prepare CADD notes for bridge plans

At this point, the final design engineer selects the appropriate CADD notes and adds the specific pile load values to the notes.

Abutment piles design note

THE CONTRACT LENGTH OF 75 FEET FOR THE WEST ABUTMENT PILES IS BASED ON A COHESIVE SOIL CLASSIFICATION, A TOTAL FACTORED AXIAL LOAD PER PILE (P_U) OF 128 KIPS, AND A GEOTECHNICAL RESISTANCE FACTOR (PHI) OF 0.65.

THE NOMINAL AXIAL BEARING RESISTANCE FOR CONSTRUCTION CONTROL WAS DETERMINED FROM A COHESIVE SOIL CLASSIFICATION AND A GEOTECHNICAL RESISTANCE FACTOR (PHI) OF 0.77.

Abutment piles driving note

THE REQUIRED NOMINAL AXIAL BEARING RESISTANCE FOR WEST ABUTMENT PILES IS 83 TONS AT END OF DRIVE (EOD). IF RETAPS ARE NECESSARY TO ACHIEVE BEARING, THE REQUIRED NOMINAL AXIAL BEARING RESISTANCE IS 122 TONS AT ONE-DAY RETAP, 129 TONS AT THREE-DAY RETAP, OR 134 TONS AT SEVEN-DAY RETAP. THE PILE CONTRACT LENGTH SHALL BE DRIVEN AS PER PLAN UNLESS PILES REACH REFUSAL. CONSTRUCTION CONTROL REQUIRES A WEAP ANALYSIS AND BEARING GRAPH.

Step 10 – Check the design

Within the Iowa DOT Office of Bridges and Structures, a final design engineer other than the bridge designer is assigned to give the bridge design an independent check when final plans are complete. During the checking process, the final design engineer reviews the soils package to ensure all recommendations were followed and also checks structural, geotechnical, and drivability aspects of the design.

For this example, only the structural and geotechnical aspects would be checked because pile driving stresses will be relatively low. (For simplicity, the structural design was not shown in this example.)

Other design organizations may perform checks at various stages of design rather than upon plan completion.

-----------------------END DESIGN AND BEGIN CONSTRUCTION PHASE---------------------

Step 11 – Prepare bearing graph

After the bridge contract is let and prior to start of pile driving, the contractor completes Hammer Data sheets for use of the planned pile driving hammer. The Hammer Data sheets include all pertinent information including the cap (helmet) number and hammer identification information with details, hammer cushion, and pile cushion (where required), as well as pile size, pile length, and estimated pile driving resistance.

The Office of Construction uses the data received to complete a WEAP analysis for construction control during pile driving. Results from the WEAP analysis are then used to prepare an LRFD Driving Graph (without the factor of safety used for allowable stress design). The Driving Graph includes curves of nominal driving resistance versus blows per ft and identifies specific driving conditions where driving stress is a concern. Figure 3.5 is the LRFD Driving Graph for the west abutment.

Special Driving Conditions	Stroke (ft)	**Monitor at 10 Blow Increments**	**Do NOT Exceed**	**Project No:**	Design Example DGT11	**Graph No:**	XX-XXXX-XX-XXX
				Design No:	XXX	**Hammer No:**	XXXXXX
	7	-----	-----	**County:**	XXXXX	**Cap No:**	XXX
	8	-----	-----	**Location:**	West Abutment	**Pile Type:**	HP 10x57
Blows per foot	9	-----	-----	**Hammer:**	Delmag D19-42	**Pile Length:**	75 feet

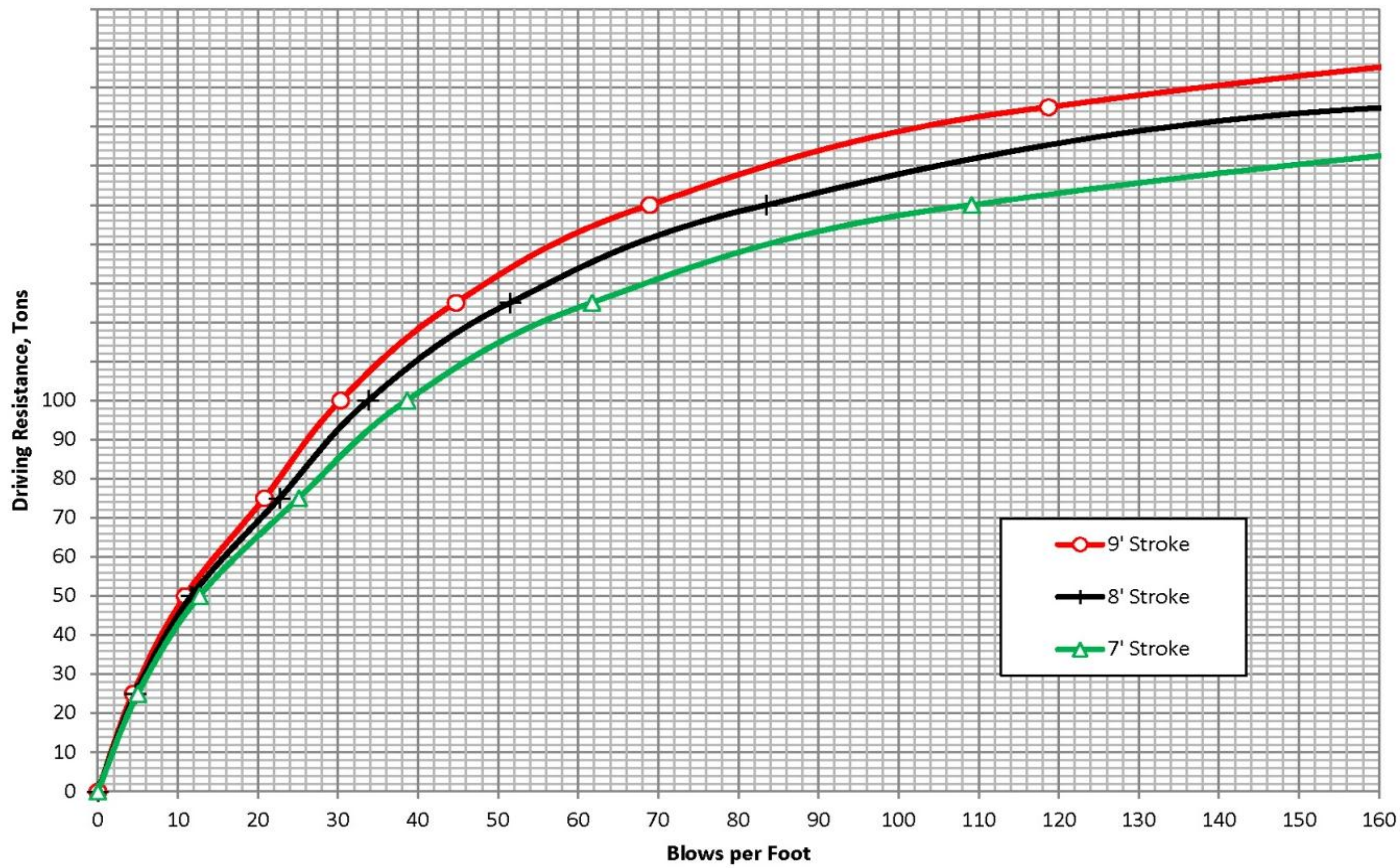


Figure 3.5. Track 1 Example 1: General WEAP bearing graph

Step 12 – Observe construction, record driven resistance, and resolve any construction issues

During pile driving, the construction inspector records the hammer stroke and number of blows to advance the pile an equivalent penetration of 1 ft, and, then, converts the recorded information with the Driving Graph to record the driven resistance per pile at EOD. This information is shown for this example in the driving log in Figure 3.7.

If the recorded pile driving resistance at EOD is less than the target pile nominal driving resistance, the pile is retapped about 24 hours after EOD. (The retap is a remedial measure that makes use of setup for an individual pile. If the 24 hour retap does not indicate sufficient driven resistance, an extension will be added. An extension is expensive, and the designer should not overestimate the benefit of setup.)

For example, at EOD for the planned pile embedment length at Pile 1, the construction inspector recorded a hammer stroke of 7.5 ft and a blow count of 30 blows per ft for the last foot of pile penetration, as shown on the log. Based on the Driving Graph, the construction inspector recorded a driving resistance of 88 tons, which is greater than the target driving resistance of 83 tons, as shown in Figure 3.6.

Pile 4 illustrates the use of pile retaps. At EOD at Pile 4, the construction inspector recorded a driving resistance of 69 tons, which is less than the target nominal pile driving resistance of 83 tons. Twenty-four hours after EOD, Pile 4 was retapped.

The target nominal driving resistance was increased to account for pile setup by 120 percent (per Appendix C), yielding a retap target nominal driving resistance of 122 tons. The pile driving hammer was warmed up with 20 blows on another pile; after two blows on Pile 4 to set the cap, Pile 4 was retapped 10 blows with a measured driven penetration distance of 2-2/5 in. ($10 \times 12/2.4 = 50$ blows per ft) at a stroke of 8.5 ft.

The Pile 4 retap resulted in a retap driving resistance of 127 tons, which is greater than the retap target driving resistance of 122 tons. The driving log shows that all piles reached the target resistance at contract length with relatively little variation.

If the production pile cannot reach the target nominal pile driving resistance of 122 tons at the retap event, the production pile can be spliced with an extension pile, and redriving can be continued to avoid any delay in construction. At this point, the pile setup resistance initially developed is not taken into account. The pile can be extended until the new field measured pile driving resistance reaches the target nominal driving resistance at EOD of 83 tons estimated in Step 8 and described in the CADD note.

Special Driving Conditions	Stroke (ft)	Monitor at 10 Blow Increments	Do NOT Exceed	Project No:	Design Example DGT11	Graph No:	XX-XXXX-XX-XXX
	7	-----	-----	County:	XXXXX	Cap No:	XXX
	8	-----	-----	Location:	West Abutment	Pile Type:	HP 10x57
Blows per foot	9	-----	-----	Hammer:	Delmag D19-42	Pile Length:	75 feet

Design No: XXX | Hammer No: XXXXXX

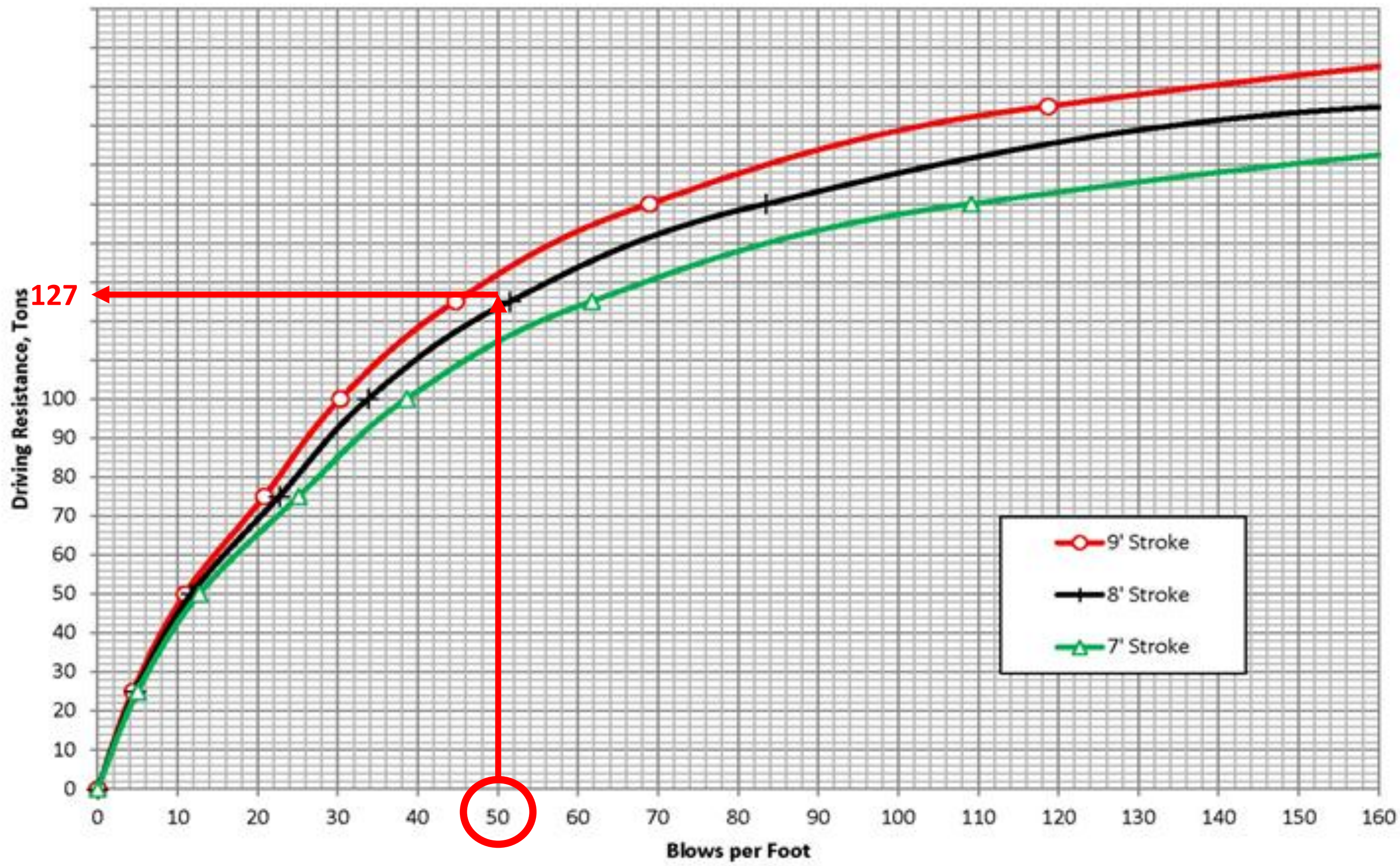


Figure 3.6. Track 1 Example 1: WEAP bearing graph for west abutment piles

Form 830209(E) 9/06

Iowa Department of Transportation

ENGLISH LOG OF PILING DRIVEN WITH WAVE EQUATION

Project No. Someplace in Iowa

County XXX

Design No. 389

Contractor XXXX

Driving Graph No. XX-XXXX-XX-XXX

Nominal Driving Resistance 83 Tons

Pile (Type and Size) HP 10x57
(Wood, Steel or Concrete)

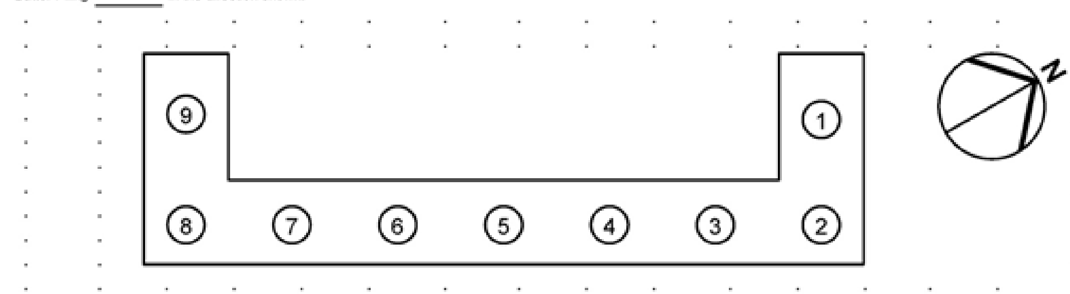
Hammer (Type & Model) Delmag D19-42
(Gravity or Diesel manufacturer and model)

Foundation Description West Abutment
(North abut, Pier 1, etc.)

Station of Foundation C.L. 447+00

Sketch foundation below, number each pile and show steel H-pile orientation as installed. Note battered piles on sketch,and give the amount of batter. Place name and certificate number of welder below if welding was necessary. Forward copies, including driving graph, as outlined in the construction manual. Note on drawing which pile has been logged.

Batter Piling ________ in the direction shown.



Pile No.	Date Driven	(1) Plan Length (ft.)	Length Cutoff (0.0 ft.)	Blows Per Foot	Ram Rise (ft.)	Driven Resistance (Tons)	RETAP (2) Date	RETAP (2) Ram Rise (ft.)	RETAP (2) Blows Per Foot	RETAP (2) Driven Resistance (Tons)	PILE EXTENSIONS (3) Length Added (0.0 ft.)	PILE EXTENSIONS (3) Length Cutoff (0.0 ft.)	PILE EXTENSIONS (3) Ram Rise (ft.)	PILE EXTENSIONS (3) Blows Per Foot	PILE EXTENSIONS (3) Driven Resistance (Tons)	Welds (Count)
1	X-XX-XX	75	1.5	30	7.5	88										
2	X-XX-XX	75	4.5	32	8	96										
3	X-XX-XX	75	2.5	31	7	87										
4	X-XX-XX	75	1.0	20	8	69	X-XX-XX	8.5	34	100						
5	X-XX-XX	75	2.0	28	9	94										
6	X-XX-XX	75	2.0	26	8.5	86										
7	X-XX-XX	75	2.5	30	7.5	89										
8	X-XX-XX	75	4.0	35	7	94										
9	X-XX-XX	75	2.0	28	8.5	90										
---	---	---	---	---	---	---										

Total Welds: ________

(1) Record in the Remarks section below if the pile length is anything other than the plan length at the beginning of drive.

(2) Indicate date of retap in date column (1 day delay min.). List only pile actually checked.

(3) Additional pile length to be authorized by Construction Office.

Plan Length: ________ Feet

Extensions: ________ Feet

Total: ________ Feet

Welders Name: ____________ Lab No.: ________ Exp. Date: ________

Remarks: ______________________________

Inspector ____________ Date ________ Project Engineer ____________

Distribution: Construction (original), District, Project File

Figure 3.7. Track 1 Example 1: Pile driving log

3.2. Track 1 Example 2: Driven H-Pile in Mixed Soil with Scour, Construction Control Based on Wave Equation, and No Planned Retap

Table 3.5. Track 2 Example 2: Design and construction steps

Design Step	
1	Develop bridge situation plan (TS&L)*
2	Develop soils package, including soil borings and foundation recommendations*
3	Determine pile arrangement, pile loads, and other design requirements*
4	Estimate the nominal geotechnical resistance per foot of pile embedment
5	Select a resistance factor to estimate pile length based on the soil profile and construction control
6	Calculate the required nominal pile resistance, R_n
7	Estimate contract pile length, L
8	Estimate target nominal pile driving resistance, $R_{ndr\text{-}T}$
9	Prepare CADD notes for bridge plans
10	Check the design depending on bridge project and office practice
Construction Step	
11	Prepare bearing graph
12	Observe construction, record driven resistance, and resolve any construction issues

* These steps determine the basic information for geotechnical pile design and vary depending on bridge project and office practice

Within the Iowa DOT Office of Bridges and Structures, the design steps that determine the basic information necessary for geotechnical design of a steel H-pile generally follow Steps 1 through 3. The steps involve communication among the preliminary design engineer, soils design engineer, and final design engineer.

In other organizations, the basic information may be determined differently, but that process generally should not affect the overall geotechnical design of the pile.

Step 1 – Develop bridge situation plan (or TS&L)

For a typical bridge, the preliminary design engineer plots topographical information, locates the bridge, determines general type of superstructure, location of substructure units, elevations of foundations, hydraulic information (if needed), and other basic information to characterize the bridge. The preliminary design engineer then prepares the TS&L sheet that shows a plan and longitudinal section of the bridge.

For this example, the TS&L gives the following information needed for design of T-pier piles:

- 208 ft, three-span, prestressed concrete beam superstructure
- Zero skew
- Bottom of pier footing elevation 435 ft

- Pile foundation with design scour elevation of 425 ft (this indicates 10 ft of scour to be considered at the strength limit state). This example includes the geotechnical design for scour but not the structural check for unsupported length, which is required for a complete design (BDM 6.6.4.1.3.1).

Step 2 – Develop soils package, including soil borings and foundation recommendations

Based on location of the piers, the soils design engineer orders soil borings (typically at least one per substructure unit). Upon receipt of the boring logs, the engineer arranges for them to be plotted on a longitudinal section, checks any special geotechnical conditions on the site, and writes a recommendation for foundation type with any applicable special design considerations.

For this example, the recommendations are as follows:

- Friction piles with end bearing that tip out in the very firm glacial clay layer
- Steel H-piles for the T-piers
- Structural Resistance Level – 1 (which does not require a driving analysis by the Office of Construction during design) (BDM 6.2.6.1)
- No downdrag
- Normal driving resistance (This will lead to $\varphi_c = 0.6$ for the structural check, which needs to be performed but is not included in this geotechnical example.)
- No special site considerations for stability, settlement, or lateral movement (Therefore, a Service I load will not be required for design.)
- Standard construction control based on WEAP analysis with no planned retap

Subsurface conditions at the pier shown in Figure 3.8 have been characterized based on a representative test boring, as indicated in the soil profile. Below the bottom of footing elevation, subsurface conditions generally consist of three layers: about 33 ft of silty sand, 13 ft of firm silty clay, and deeper very firm glacial clay. The test boring was terminated at a depth of 95 ft below the existing ground surface, and ground water was encountered at Elevation 439.

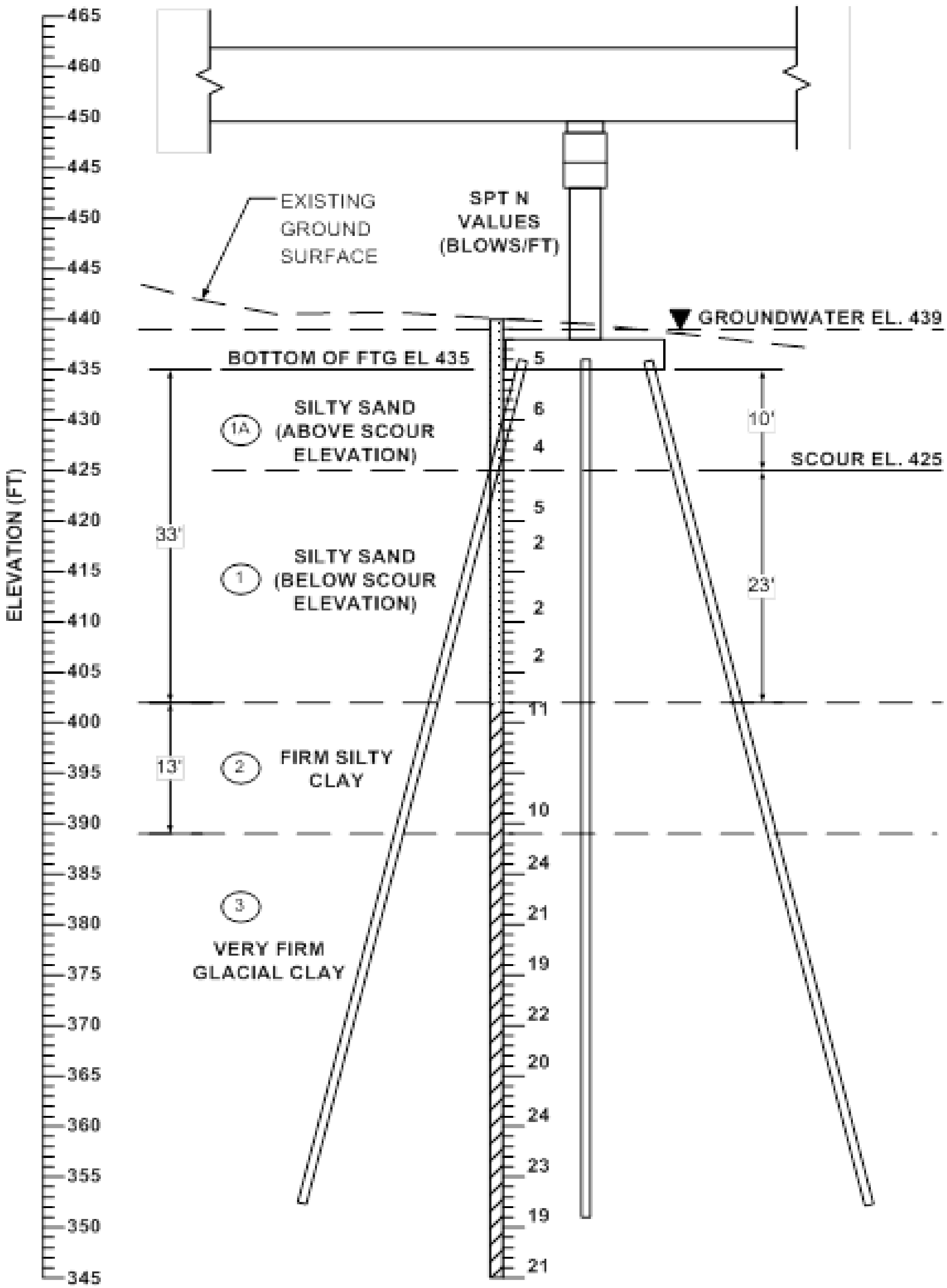


Figure 3.8. Track 1 Example 2: Soil profile

Step 3 – Determine pile arrangement, pile loads, and other design requirements

The final design engineer begins design of the pier piles with the TS&L and the soils design package. Because the bridge has a prestressed concrete beam superstructure and integral abutments, the engineer selects HP 10×57 piles to match abutment piles, following Bridge Design Manual policy (BDM 6.5.1.1.1 and 6.2.1.1).

Based on the reinforced concrete pier (RC-PIER) analysis at the strength limit state and the Bridge Design Manual policy for pile spacing and number of piles (BDM 6.5.4.1.1), the final design engineer determines the following:

- Eighteen HP 10×57 piles at 4′-6 spacing, arranged in three rows of six as shown in Figure 3.9
- Perimeter piles battered at 1:4
- Strength I load per pile = 143 kips
- No uplift
- Standard Iowa DOT construction control based on WEAP analysis and no planned retap

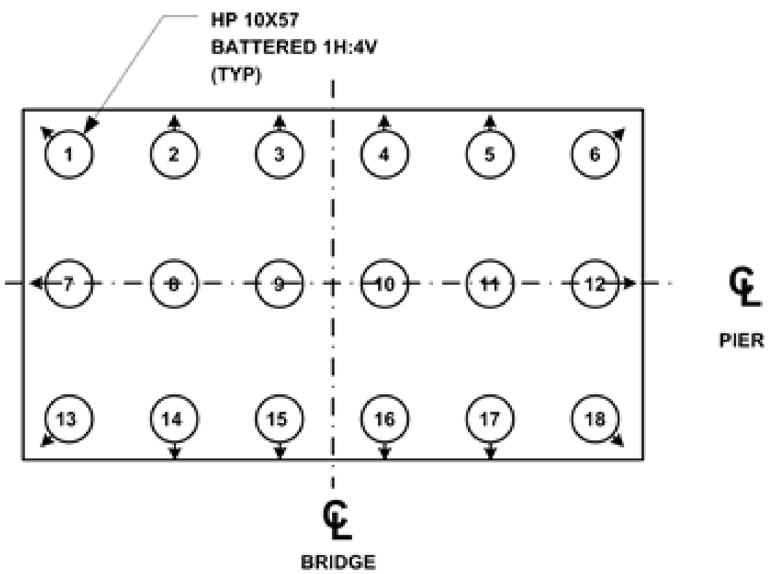


Figure 3.9. Track 1 Example 2: Pile arrangement at a pier

Structural checks of the pile group indicate that the individual pile resistances (BDM 6.2.6.1) combined with battered pile resistances are sufficient for all lateral loads. Thus, the piles may be designed for axial geotechnical resistance without lateral load or other special analysis.

Step 4 – Estimate the nominal friction and end bearing geotechnical resistance

Based on the pier soil boring and BDM Table 6.2.7, the final design engineer estimates the nominal resistances for friction and end bearing shown in Table 3.6.

Table 3.6. Track 1 Example 2: Estimated nominal geotechnical resistance

Soil Stratum	Soil Description	Stratum Thickness (ft)	Average SPT N Value (blows/ft)	Estimated Nominal Resistance for Friction Pile (kips/ft)	Cumulative Nominal Friction Resistance at Bottom of Layer* (kips)	Estimated Nominal Resistance for End Bearing (ksi)
1A	Silty Sand above Scour Elevation	10	5	1.2	12	---
1	Silty Sand below Scour Elevation	23	3	1.2	40	---
2	Firm Silty Clay	13	10	2.0	66	---
3	Very Firm Glacial Clay (more than 30 ft below the natural ground elevation)	44	21	4.0	242	---
3	Very Firm Glacial Clay	---	21**	---	---	1

* This information is used to prepare the calculations in Step 7
** The SPT N value for Layer 3 is near the lower limit for use of end bearing

Step 5 – Select a resistance factor to estimate pile length based on the soil profile and construction control

By inspection, more than 30 percent and less than 70 percent of the embedded pile length will be in non-cohesive soil, so the soil over the pile embedment length is generalized as a mixed soil.

For a driven H-pile with construction control based on a WEAP analysis at EOD and no planned retap, the following resistance factor is recommended to estimate the contract pile length for mixed soil:

φ = 0.65 for mixed soil, averaged over the full depth of estimated pile penetration

Step 6 – Calculate the required nominal pile resistance, R_n

The required nominal pile resistance can be calculated as follows:

$$R_n = \frac{\sum \eta\gamma Q + \gamma_{DD} DD}{\varphi} = \frac{143 + 0}{0.65} = 220 \text{ kips/pile}$$

where

$\sum \eta\gamma Q = \gamma Q$ = 143 kips (Step 3)

$\gamma_{DD}DD$ =0 (no downdrag)

φ = 0.65 (Step 5)

Step 7 – Estimate contract pile length, L

Based on the nominal resistance values in Step 4, the cumulative nominal geotechnical resistance, $R_{n\text{-}BB}$, per pile is calculated as follows, where D = depth in feet below the bottom of footing:

D_0 = 0 ft, $R_{n\text{-}BB0}$ = 0 kips

D_1 = 10 ft, $R_{n\text{-}BB1} = R_{n\text{-}BB0}$ + 0 = 0 kips because scour zone provides no support

D_2 = 10 + 23 = 33 ft, $R_{n\text{-}BB2} = R_{n\text{-}BB1}$ + (1.2 kips/ft) (23 ft) = 0 + 27.6 = 27.6 kips

D_3 = 33 + 13 = 46 ft, $R_{n\text{-}BB3} = R_{n\text{-}BB2}$ + (2.0 kips/ft) (13 ft) = 27.6 + 26.0 = 53.6 kips

End bearing in Layer 3 = (1 ksi)(16.8 in^2) = 16.8 kips, $R_{n\text{-}BB4} = R_{n\text{-}BB3}$ + 16.8 = 70.4 kips

Required additional length in Layer 3 = (220 – 70.4)/4.0 = 37 ft

D_4 = 46 + 37 = 83 ft,

Rn-BB5 = Rn-BB4 + (4.0 kips/ft) (37 ft) = 70.4 + 148.0 = 218.4 kips ≈ 220 kips

The contract pile length includes a 1 ft embedment in the footing and a 1 ft allowance for cutoff due to driving damage:

L = 83 + 1 + 1 = 85 ft

The length for steel H-piles is specified in 5 ft increments (BDM 6.2.4.1). Given the contract pile length is already at an even 5 ft increment, the contract pile length does not need to be rounded to the nearest 5 ft increment.

At this point, the embedded pile length is known and it is necessary to check the site classification for the resistance factor:

% non-cohesive soil below scour elevation = [23/(83-10)](100) = 31.5% > 30% and < 70%

Therefore, the resistance factor for mixed soil is the correct choice.

A minimum pile embedment length also needs to be estimated for construction monitoring. Consider setting the minimum embedment pile length equal to 2/3 the Blue Book nominal capacity plus the 100 percent of the capacity lost over the scour zone.

Two-thirds the nominal capacity = (2/3) (220) = 147 kips/pile.

D_0 = 0 ft, $R_{n\text{-}BB0}$ = 0 kips

D_1 = 10 ft, $R_{n\text{-}BB1} = R_{n\text{-}BB0}$ + 0 = 0 kips because scour zone provides no support

D_2 = 10 + 23 = 33 ft, $R_{n\text{-}BB2} = R_{n\text{-}BB1}$ + (1.2 kips/ft) (23 ft) = 0 + 27.6 = 27.6 kips

D_3 = 33 + 13 = 46 ft, $R_{n\text{-}BB3} = R_{n\text{-}BB2}$ + (2.0 kips/ft) (13 ft) = 27.6 + 26.0 = 53.6 kips

End bearing in Layer 3 = (1 ksi)(16.8 in^2) = 16.8 kips, $R_{n\text{-}BB4} = R_{n\text{-}BB3}$ + 16.8 = 70.4 kips

Required additional length in Layer 3 = (147 – 70.4)/4.0 = 19 ft

D_4 = 46 + 19 = 65 ft, $R_{n\text{-}BB5} = R_{n\text{-}BB4}$ + (4.0 kips/ft) (19 ft) = 70.4 + 76.0

= 146.4 kips ≈ 147 kips

Step 8 – Estimate target nominal pile driving resistance, $R_{ndr\text{-}T}$

The complete embedment length below the bottom of footing will contribute to pile driving resistance. (The soil resistance above scour elevation, which was ignored in Step 4, should be considered in pile driving resistance, $R_{ndr\text{-}T}$).

The complete pile embedment length is 83 ft, which is equal to the 85 ft contract pile length minus the 1 ft of embedment length in the concrete footing and the 1 ft cutoff.

The H-pile will penetrate 33 ft of non-cohesive soil below the bottom of footing.

% non-cohesive soil = [33/83] (100) = 40% > 30%

Therefore, the generalized soil category for pile driving (construction stage) is also “mixed.” Note that it is possible for piles for a substructure to have different soil categories during the design and construction stages.

For a driven H-pile with WEAP analysis construction control and no planned retap, the following resistance factor, φ_{TAR}, is recommended to estimate the target pile driving resistance at EOD for mixed soil:

φ_{TAR} = 0.65 for mixed soil, averaged over the full depth of estimated pile penetration

$$R_{SCOUR} = (1.2\text{ kip/ft})(10\text{ ft}) = 12\text{ kips}$$

$$R_{ndr-T} = \frac{\sum \eta\gamma Q + \gamma_{DD}DD}{\varphi_{TAR}} + R_{SCOUR}$$

$$= \frac{143 + 0}{0.65} + 12$$

= 220 + 12 = 232 kips/pile

Step 9 – Prepare CADD notes for bridge plans

At this point, the final design engineer selects the appropriate CADD notes and adds the specific pile load values to the notes.

Pier piles design note

THE CONTRACT LENGTH OF 85 FEET FOR THE PIER PILES IS BASED ON A MIXED SOIL CLASSIFICATION, A TOTAL FACTORED AXIAL LOAD PER PILE (P_U) OF 143 KIPS, AND A GEOTECHNICAL RESISTANCE FACTOR (PHI) OF 0.65 FOR SOIL.

THE NOMINAL AXIAL BEARING RESISTANCE FOR CONSTRUCTION CONTROL WAS DETERMINED FROM A MIXED SOIL CLASSIFICATION AND A GEOTECHNICAL RESISTANCE FACTOR (PHI) OF 0.65 FOR SOIL. DESIGN SCOUR (100-YEAR) WAS ASSUMED TO AFFECT THE UPPER 10 FEET OF EMBEDDED PILE LENGTH AND CAUSE 12 KIPS OF DRIVING RESISTANCE.

Pier piles driving note

THE REQUIRED NOMINAL AXIAL BEARING RESISTANCE FOR PIER PILES IS 116 TONS AT END OF DRIVE. IF RETAPS ARE NECESSARY THE REQUIRED NOMINAL AXIAL BEARING RESISTANCE IS 116 TONS. THE PILE CONTRACT LENGTH SHALL BE DRIVEN AS PER PLAN UNLESS PILES REACH REFUSAL. IN NO CASE SHALL A PILE BE EMBEDDED LESS THAN 65 FEET BELOW THE STREAMBED. CONSTRUCTION CONTROL REQUIRES A WEAP ANALYSIS AND BEARING GRAPH.

Note that a statement about retaps was included in the driving note, given the piling will be driven in a mixed soil classification. Setup gain is ignored for mixed soil.

Step 10 – Check the design

Within the Iowa DOT Office of Bridges and Structures, a final design engineer other than the bridge designer is assigned to give the bridge design an independent check when final plans are complete. During the checking process, the final design engineer reviews the soils package to ensure all recommendations were followed and also checks structural, geotechnical, and drivability aspects of the design.

For this example, only the structural and geotechnical aspects would be checked because pile driving stresses will be relatively low. (For simplicity, the structural design was not shown in this example.)

Other design organizations may perform checks at various stages of design rather than upon plan completion.

-----------------------END DESIGN AND BEGIN CONSTRUCTION PHASE---------------------

Step 11 – Prepare bearing graph

After the bridge contract is let and prior to start of pile driving, the contractor completes Hammer Data sheets for use of the planned pile driving hammer. The Hammer Data sheets include all pertinent information including the cap (helmet) number and hammer identification information with details, hammer cushion, and pile cushion (where required), as well as pile size, pile length, and estimated pile driving resistance.

The Office of Construction uses the data received to complete a WEAP analysis for construction control during pile driving. Results from the WEAP analysis are then used to prepare an LRFD Driving Graph (without the factor of safety used for allowable stress design). The Driving Graph includes curves of nominal driving resistance versus blows per ft and identifies specific driving conditions where driving stress is a concern.

Step 12 – Observe construction, record driven resistance, and resolve any construction issues

If the recorded pile driving resistance at EOD is less than the target pile nominal driving resistance, the pile is retapped about 24 hours after EOD. (The retap is a remedial measure that makes use of setup for an individual pile. If the 24 hour retap does not indicate sufficient driven resistance, an extension will be added the same day rather than wait to retap another day.)

3.3. Track 1 Example 3: Driven H-Pile in Cohesive Soil with Downdrag, Construction Control Based on Wave Equation, and No Planned Retap

Table 3.7. Track 1 Example 3: Design and construction steps

Design Step	
1	Develop bridge situation plan (TS&L)*
2	Develop soils package, including soil borings and foundation recommendations*
3	Determine pile arrangement, pile loads, and other design requirements*
4	Estimate the nominal geotechnical resistance per foot of pile embedment
5	Select a resistance factor to estimate pile length based on the soil profile and construction control
6	Calculate the required nominal pile resistance, R_n
7	Estimate contract pile length, L
8	Estimate target nominal pile driving resistance, $R_{ndr\text{-}T}$
9	Prepare CADD notes for bridge plans
10	Check the design depending on bridge project and office practice
Construction Step	
11	Prepare bearing graph
12	Observe construction, record driven resistance, and resolve any construction issues

* These steps determine the basic information for geotechnical pile design and vary depending on bridge project and office practice

Within the Iowa DOT Office of Bridges and Structures, the design steps that determine the basic information necessary for geotechnical design of a steel H-pile generally follow Steps 1 through 3. The steps involve communication among the preliminary design engineer, soils design engineer, and final design engineer.

In other organizations, the basic information may be determined differently, but that process generally should not affect the overall geotechnical design of the pile.

Step 1 – Develop bridge situation plan (or TS&L)

For a typical bridge, the preliminary design engineer plots topographical information, locates the bridge, determines general type of superstructure, location of substructure units, elevations of foundations, hydraulic information (if needed), and other basic information to characterize the bridge. The preliminary design engineer then prepares the TS&L sheet that shows a plan and longitudinal section of the bridge.

For this example, the recommendations are as follows:

- 120 ft, single-span, prestressed concrete beam superstructure
- Zero skew
- Integral abutments

- Pile foundations with 15 ft prebored holes (Although the bridge length is less than 130 ft and would not require prebored holes for the integral abutment piles (BDM 6.5.1.1.1), in this case the preliminary design engineer has received permission to use prebored holes to relieve part of the downdrag force. The permission involved consultation with the soils design engineer and the preliminary bridge section leader.)
- Bottom of abutment footing elevation 435 ft

Step 2 – Develop soils package, including soil borings and foundation recommendations

Based on locations of the abutments, the soils design engineer orders soil borings (typically at least one per substructure unit). Upon receipt of the boring logs, the engineer arranges for them to be plotted on a longitudinal section, checks any special geotechnical conditions on the site, and writes a recommendation for foundation type with any applicable special design considerations.

For this example, the engineer recommends the following:

- Downdrag due to the soft silty clay layer, with neutral plane at the top of the firm silty clay layer
- Friction piles with end bearing that tip out in the very firm glacial clay layer
- Steel H-piles for the integral abutments
- Structural Resistance Level – 1 (which does not require a driving analysis by the Office of Construction during design (BDM 6.2.6.1)
- Normal driving resistance (This will lead to $\varphi_c = 0.6$ for the structural check, which needs to be performed but is not included in this geotechnical example.)
- No special site considerations for stability, settlement, or lateral movement (Therefore, a Service I load will not be required for design.)
- Standard construction control based on WEAP analysis with no planned retap

The soil profile shown in Figure 3.10 includes the soil boring at the west abutment. Generally, below the bottom of footing elevation, the three layers are 33 ft of soft silty clay, 13 ft of firm silty sand, and very firm glacial clay to the bottom of the boring at 115 ft.

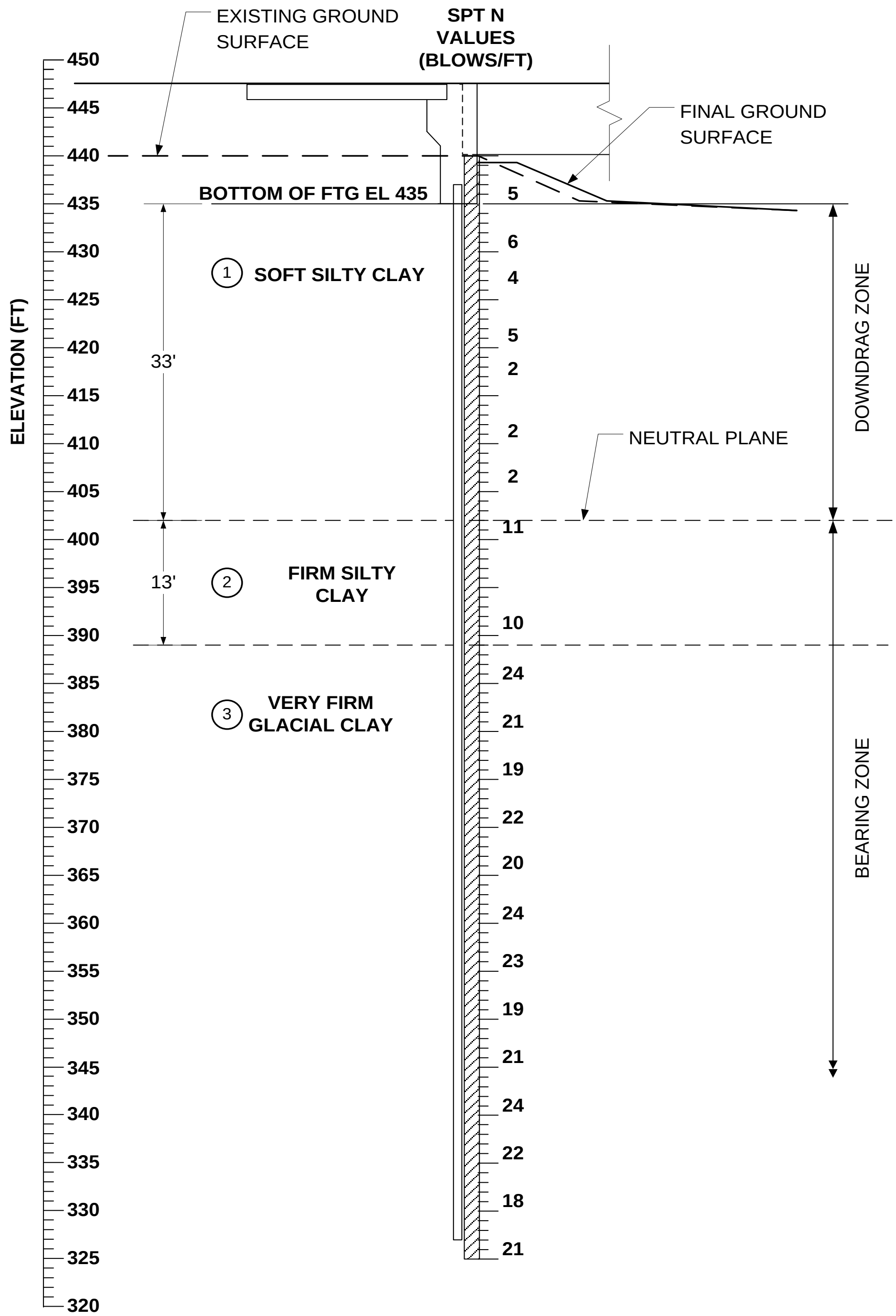


Figure 3.10. Track 1 Example 3: Soil profile

Step 3 – Determine pile arrangement, pile loads, and other design requirements

The final design engineer begins design of the abutment piles with the TS&L and the soils design package. Because the bridge has a prestressed concrete beam superstructure and integral abutments, the engineer selects HP 10×57 piles, following Bridge Design Manual policy (BDM 6.5.1.1.1).

Approximately 8 ft of embankment will be placed behind the abutment after pile installation, and the soft silty clay layer is susceptible to consolidation settlement as noted by the soils design engineer. Therefore, the neutral plane is at the bottom of the soft silty clay. Soil above the neutral plane is in the "Downdrag Zone." Soil below the neutral plane is in the "Bearing Zone." Pile nominal resistance should be based on the resistance from the Bearing Zone only. Soil in the Downdrag Zone induces downdrag load ($\gamma_{DD}DD$) on pile, in addition to the loads from the superstructure ($\sum\eta\gamma Q$).

Based on total Strength I abutment load and the Bridge Design Manual policy for pile spacing and number of piles (BDM 6.5.4.1.1), the final design engineer determines the following:

- Seven HP 10×57 piles plus two wing extension piles, numbers 1 and 9 in Figure 3.11, that support the wings only as shown in the figure
- Strength I load per pile = 132 kips
- Downdrag load in soft silty clay layer (Layer 1) from bottom of prebored hole to bottom of Layer 1, for 33-15 = 18 ft
- Standard construction control based on WEAP analysis with no planned retap

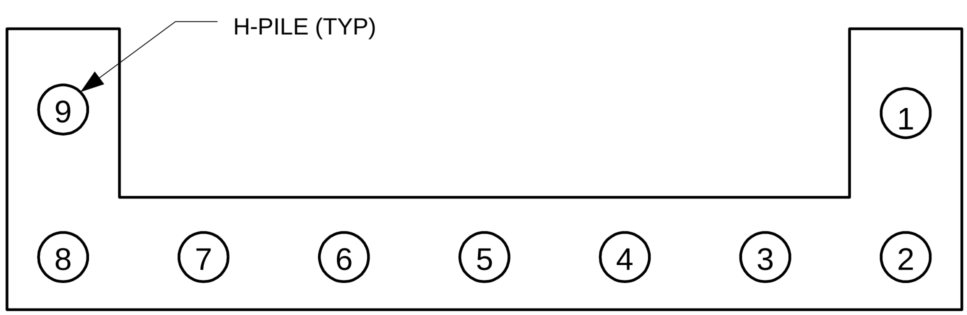


Figure 3.11. Track 1 Example 3: Pile arrangement at an abutment

Because the bridge characteristics fall within integral abutment policy, the site has no unusual characteristics other than downdrag, the soils design engineer did not require further analysis, the project does not require staged construction, and construction will not be accelerated or delayed, there will be no need for lateral load or special analysis of the abutment piles. The piles may be simply designed for applied vertical load plus downdrag.

Step 4 – Estimate the nominal friction and end bearing geotechnical resistance

Based on the west abutment soil boring and BDM Table 6.2.7, the final design engineer estimates the nominal resistances for friction and end bearing shown in Table 3.8.

Table 3.8. Track 1 Example 3: Estimated nominal geotechnical resistance

Soil Stratum	Soil Description	Stratum Thickness (ft)	Average SPT N Value (blows/ft)	Estimated Nominal Resistance for Friction Pile (kips/ft)	Cumulative Nominal Friction Resistance at Bottom of Layer* (kips)	Estimated Nominal Resistance for End Bearing (ksi)
1	Soft Silty Clay	18 below prebore	4	1.2	22	---
2	Firm Silty Clay	13	10	2.0	48	---
3	Very Firm Glacial Clay (30 ft below the natural ground elevation)	64	21	4.0	304	---
3	Very Firm Glacial Clay	---	21**	---	---	1

* This information is used to prepare the calculations in Step 7
** The SPT N value for Layer 3 is near the lower limit for use of end bearing

Step 5 – Select a resistance factor to estimate pile length based on the soil profile and construction control

For a driven H-pile with construction control based on a WEAP analysis at EOD and no planned retap, the following resistance factor is recommended to estimate the contract pile length for cohesive soil (only cohesive soil was present below the west abutment):

φ = 0.65 for cohesive soil, averaged over the full depth of estimated pile penetration

Step 6 – Calculate the required nominal pile resistance, Rn

As mentioned in Step 3, downdrag load should be accounted for in addition to the loads from the superstructure in calculating required nominal pile resistance. The required nominal pile resistance is as follows:

$$R_n = \frac{\sum \eta\gamma Q}{\varphi} + \frac{\gamma_{DD} DD}{\varphi}$$

$$= \frac{132}{0.65} + \frac{(1.0)(22)}{0.65}$$

= 203 + 34

= 237 kips/pile

where

$\sum \eta\gamma Q = \gamma Q$ (Step 2)

with η =1.0 from BDM 6.2.3.1

γQ = 132 kips (Step 3)

γ_{DD} = 1.0 per BDM 6.2.4.3

DD = downdrag load caused by consolidation or deformation of a soft cohesive soil layer over a stiff layer, which is estimated using the Blue Book as shown in Step 4

= DD_{BB} (See Step 4 for DD_{BB})

= 22 kips

φ = 0.65 (Step 5)

Step 7 – Estimate contract pile length, L

Based on the nominal resistance values in Step 4, the cumulative nominal geotechnical resistance, $R_{n\text{-}BB}$, per pile is calculated as follows, where D = depth in feet below the bottom of footing:

D_0 = 0 ft, $R_{n\text{-}BB0}$ = 0 kips

D_1 = 33 ft, $R_{n\text{-}BB1} = R_{n\text{-}BB0}$ + 0 = 0 kips because downdrag zone provides no support

D_2 = 33 + 13 = 46 ft, $R_{n\text{-}BB2} = R_{n\text{-}BB1}$ + (2.0 kips/ft) (13 ft) = 0 + 26.0 = 26.0 kips

End bearing in Layer 3 = (1 ksi)(16.8 in^2) = 16.8 kips, $R_{n\text{-}BB3} = R_{n\text{-}BB2}$ + 16.8 = 42.8 kips

Required additional length in Layer 3 = (237 – 42.8)/4.0 = 49 ft

D_3 = 46 + 49 = 95 ft, $R_{n\text{-}BB4} = R_{n\text{-}BB3}$ + (4.0 kips/ft) (49 ft) = 42.8 + 196.0

= 238.8 kips > 237 kips

The contract pile length includes a 2 ft embedment in the footing and a 1 ft allowance for cutoff due to driving damage:

$L = 95 + 2 + 1 = 98$ ft

The length for steel H-piles is specified in 5 ft increments (BDM 6.2.4.1). Therefore, the contract pile length is rounded to 100 ft.

Because the site has only cohesive soil within the embedded length of the pile, the resistance factor determined in Step 5 need not be checked for site classification.

Step 8 – Estimate target nominal pile driving resistance, Rndr-T

The complete embedment length below the bottom of footing except for the prebored hole will contribute to pile driving resistance (resistance from the soil above the neutral plane needs to be accounted for during pile driving). The pile embedment length is 82 ft, which is equal to the 100 ft contract pile length minus a 1 ft cutoff, 2 ft of embedment length in the concrete footing, and 15 ft of prebored hole.

For driven H-pile with WEAP analysis construction control and no planned retap, the following resistance factors, φ, are recommended to estimate the target nominal pile driving resistance for cohesive soils:

$\varphi_{EOD} = 0.65$ for cohesive soil, averaged over the full depth of estimated pile penetration

$\varphi_{SETUP} = 0.20$ for cohesive soil, averaged over the full depth of estimated pile penetration

Note that the generalized soil category for both design and construction are the same, given only cohesive soils are encountered at this location. For piles penetrating both cohesive soils and non-cohesive soils, a separate generalized soil category is needed because the soil below prebored depth and above the neutral plane should be considered in pile driving resistance for the construction stage, and this may result in a change in the generalized soil category and consequently the resistance factor.

At EOD, the factored target nominal resistance should overcome the factored target nominal resistance from the downdrag zone, in addition to the factored loads (loads from superstructure + downdrag load):

$$\sum \eta\gamma Q + \varphi_{DD}DD = \varphi_{TAR}R_{ndr-T} - \varphi_{TAR}R_{Sdd}$$

where

R_{sdd} = Nominal driving resistance that accounts for the downdrag load estimated in Steps 4 and 6, which is equal to DD_{BB}

φ_{TAR} = Resistance factor for target nominal resistance

$$= \varphi_{EOD} + \varphi_{SETUP}(F_{SETUP} - 1)$$

and F_{SETUP} = Setup Factor

The soil profile was used to calculate the average SPT N-value for cohesive soil penetrated by the driven pile over the contract pile length, as follows:

Calculated average SPT N-value = [(18′)(4) + (13′)(10) + (97′-33′-13′)(21)]/(97′-15′) = 16

The average SPT N-value of 16 yields a Setup Factor, F_{SETUP}, of 1.58 for 7 day retap based on the pile setup factor chart shown in Figure 3.12.

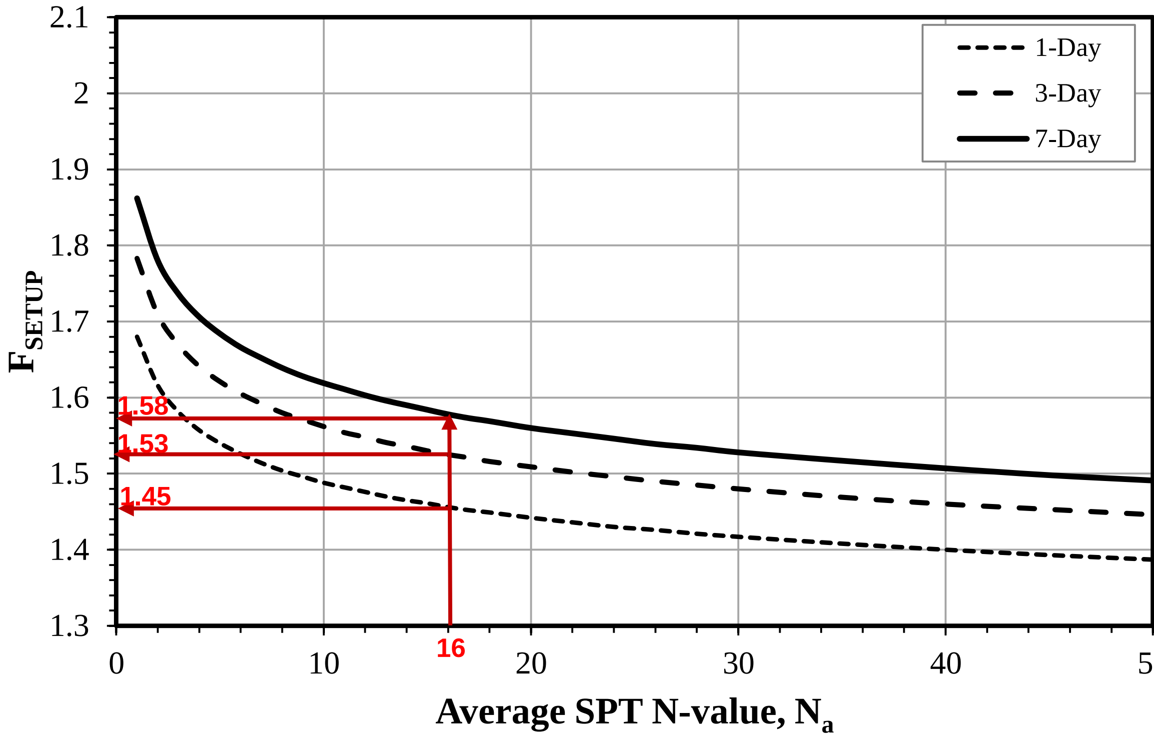


Figure 3.12. Track 1 Example 3: Pile setup factor chart

The target pile driving resistance at EOD is as follows:

$$R_{ndr-T} = \frac{\sum \eta\gamma Q}{\varphi_{TAR}} + \frac{\gamma_{DD} DD}{\varphi_{TAR}} + R_{Sdd,EOD}$$

$$= \frac{\sum \eta\gamma Q}{\varphi_{EOD} + \varphi_{SETUP}(F_{SETUP} - 1)} + \frac{\gamma_{DD} DD}{\varphi_{EOD} + \varphi_{SETUP}(F_{SETUP} - 1)} + R_{Sdd}$$

$$= \frac{132}{(0.65) + (0.20)(1.58 - 1)} + \frac{(1.0)(22)}{(0.65) + (0.20)(1.58 - 1)} + 22$$

$$= \frac{132}{0.77} + \frac{22}{0.77} + 22$$

= 173 + 29 + 22

= 224 kips/pile

The target nominal geotechnical resistance at 1 day retap, then, is as follows:

$R_{1\text{-day}}$ = (173+29)(1.45)+22 = 314.9kips = 157 tons

The target nominal geotechnical resistance at 3 day retap, then, is as follows:

$R_{3\text{-day}}$ = (173+29)(1.53)+22 = 331.1 kips = 166 tons

The target nominal geotechnical resistance at 7 day retap, then, is as follows:

$R_{7\text{-day}}$ = (173+29)(1.58)+22 = 341.2 kips = 171 tons

Step 9 – Prepare CADD notes for bridge plans

At this point, the final design engineer selects the appropriate CADD notes and adds the specific pile load values to the notes.

Abutment piles design note

THE CONTRACT LENGTH OF 100 FEET FOR THE WEST ABUTMENT PILES IS BASED ON A COHESIVE SOIL CLASSIFICATION. A TOTAL FACTORED AXIAL LOAD PER PILE (P_U) OF 132 KIPS PLUS 22 KIPS FOR DOWNDRAG, AND A GEOTECHNICAL RESISTANCE FACTOR (PHI) OF 0.65. TO ACCOUNT FOR SOIL CONSOLIDATION UNDER THE NEW FILL, THE FACTORED AXIAL LOAD INCLUDES A FACTORED DOWNDRAG LOAD OF 22 KIPS.

THE NOMINAL AXIAL BEARING RESISTANCE FOR CONSTRUCTION CONTROL WAS DETERMINED FROM A COHESIVE SOIL CLASSIFICATION AND A GEOTECHNICAL RESISTANCE FACTOR (PHI) OF 0.77.

Abutment piles driving note

THE REQUIRED NOMINAL AXIAL BEARING RESISTANCE FOR WEST ABUTMENT PILES IS 112 TONS AT END OF DRIVE (EOD). IF RETAPS ARE NECESSARY TO ACHIEVE BEARING, THE REQUIRED NOMINAL AXIAL BEARING RESISTANCE IS 157 TONS AT ONE-DAY RETAP, 166 TONS AT THREE-DAY RETAP, OR 171 TONS AT SEVEN-DAY RETAP. THE PILE CONTRACT LENGTH SHALL BE DRIVEN AS PER PLAN UNLESS PILES REACH REFUSAL. CONSTRUCTION CONTROL REQUIRES A WEAP ANALYSIS AND BEARING GRAPH.

Step 10 – Check the design

Within the Iowa DOT Office of Bridges and Structures, a final design engineer other than the bridge designer is assigned to give the bridge design an independent check when final plans are complete. During the checking process, the final design engineer reviews the soils package to ensure all recommendations were followed and also checks structural, geotechnical, and drivability aspects of the design.

For this example, only the structural and geotechnical aspects would be checked because pile driving stresses will be relatively low. (For simplicity, the structural design was not shown in this example.)

Other design organizations may perform checks at various stages of design rather than upon plan completion.

-----------------------END DESIGN AND BEGIN CONSTRUCTION PHASE---------------------

Step 11 – Prepare bearing graph

After the bridge contract is let and prior to start of pile driving, the contractor completes Hammer Data sheets for use of the planned pile driving hammer. The Hammer Data sheets include all pertinent information including the cap (helmet) number and hammer identification information with details, hammer cushion, and pile cushion (where required), as well as pile size, pile length, and estimated pile driving resistance.

The Office of Construction uses the data received to complete a WEAP analysis for construction control during pile driving. Results from the WEAP analysis are then used to prepare an LRFD Driving Graph (without the factor of safety used for allowable stress design). The Driving Graph includes curves of nominal driving resistance versus blows per ft and identifies specific driving conditions where driving stress is a concern.

Step 12 – Observe construction, record driven resistance, and resolve any construction issues

During pile driving, the construction inspector records the hammer stroke and number of blows to advance the pile an equivalent penetration of 1 ft, and, then, converts the recorded information with the Driving Graph to record the driven resistance per pile at EOD.

If the recorded pile driving resistance at EOD is less than the target pile nominal driving resistance, the pile is retapped about 24 hours after EOD. (The retap is a remedial measure that makes use of setup for an individual pile. If the 24 hour retap does not indicate sufficient driven resistance, an extension will be added the same day rather than wait to retap another day.)

3.4. Track 1 Example 4: Driven H-Pile in Sand with Uplift Load, Construction Control Based on Wave Equation, and No Planned Retap

Table 3.9. Track 1 Example 4: Design and construction steps

Design Step	
1	Develop bridge situation plan (TS&L)*
2	Develop soils package, including soil borings and foundation recommendations*
3	Determine pile arrangement, pile loads, and other design requirements*
4	Estimate the nominal geotechnical resistance per foot of pile embedment
5	Select a resistance factor to estimate pile length based on the soil profile and construction control
6	Calculate the required nominal pile resistance, R_n
7	Estimate contract pile length, L
8	Estimate target nominal pile driving resistance, $R_{ndr\text{-}T}$
9	Prepare CADD notes for bridge plans
10	Check the design depending on bridge project and office practice
Construction Step	
11	Prepare bearing graph
12	Observe construction, record driven resistance, and resolve any construction issues

* These steps determine the basic information for geotechnical pile design and vary depending on bridge project and office practice

Within the Iowa DOT Office of Bridges and Structures, the design steps that determine the basic information necessary for geotechnical design of a steel H-pile generally follow Steps 1 through 3. The steps involve communication among the preliminary design engineer, soils design engineer, and final design engineer.

In other organizations, the basic information may be determined differently, but that process generally should not affect the overall geotechnical design of the pile.

Step 1 – Develop bridge situation plan (or TS&L)

For a typical bridge, the preliminary design engineer plots topographical information, locates the bridge, determines general type of superstructure, location of substructure units, elevations of foundations, hydraulic information (if needed), and other basic information to characterize the bridge. The preliminary design engineer then prepares the TS&L sheet that shows a plan and longitudinal section of the bridge.

For this example, the TS&L gives the following information needed for design of the frame pier piles:

- 208 ft, three-span, prestressed concrete beam superstructure
- Zero skew

- Frame piers
- Bottom of pier footing elevation 435 ft
- Pile foundation with no scour

Step 2 – Develop soils package, including soil borings and foundation recommendations

Based on location of the piers, the soils design engineer orders soil borings (typically at least one per substructure unit). Upon receipt of the boring logs, the engineer arranges for them to be plotted on a longitudinal section, checks any special geotechnical conditions on the site, and writes a recommendation for foundation type with any applicable special design considerations.

For this example, the recommendations are as follows:

- Friction piles with end bearing that tip out in the granular material layer
- Steel H-piles for the frame pier footings
- Structural Resistance Level – 1 (which does not require a driving analysis by the Office of Construction during design) (BDM 6.2.6.1)
- Normal driving resistance (This will lead to $\varphi_c = 0.6$ for the structural check, which needs to be performed but is not included in this geotechnical example.)
- No special site considerations for stability, settlement, or lateral movement (Therefore, a Service I load will not be required for design.)
- Standard construction control based on WEAP analysis with no planned retap

Subsurface conditions at the bridge pier shown in Figure 3.13 have been characterized based on a representative test boring, as indicated in the soil profile. Below the bottom of footing elevation, subsurface conditions generally consist of about 8 ft of fine sand, underlain by about 10 ft of coarse sand, 22 ft of gravelly sand, and deeper granular material. The test boring was terminated at a depth of 70 ft below the existing ground surface, and no ground water was reported to have been encountered at the test boring.

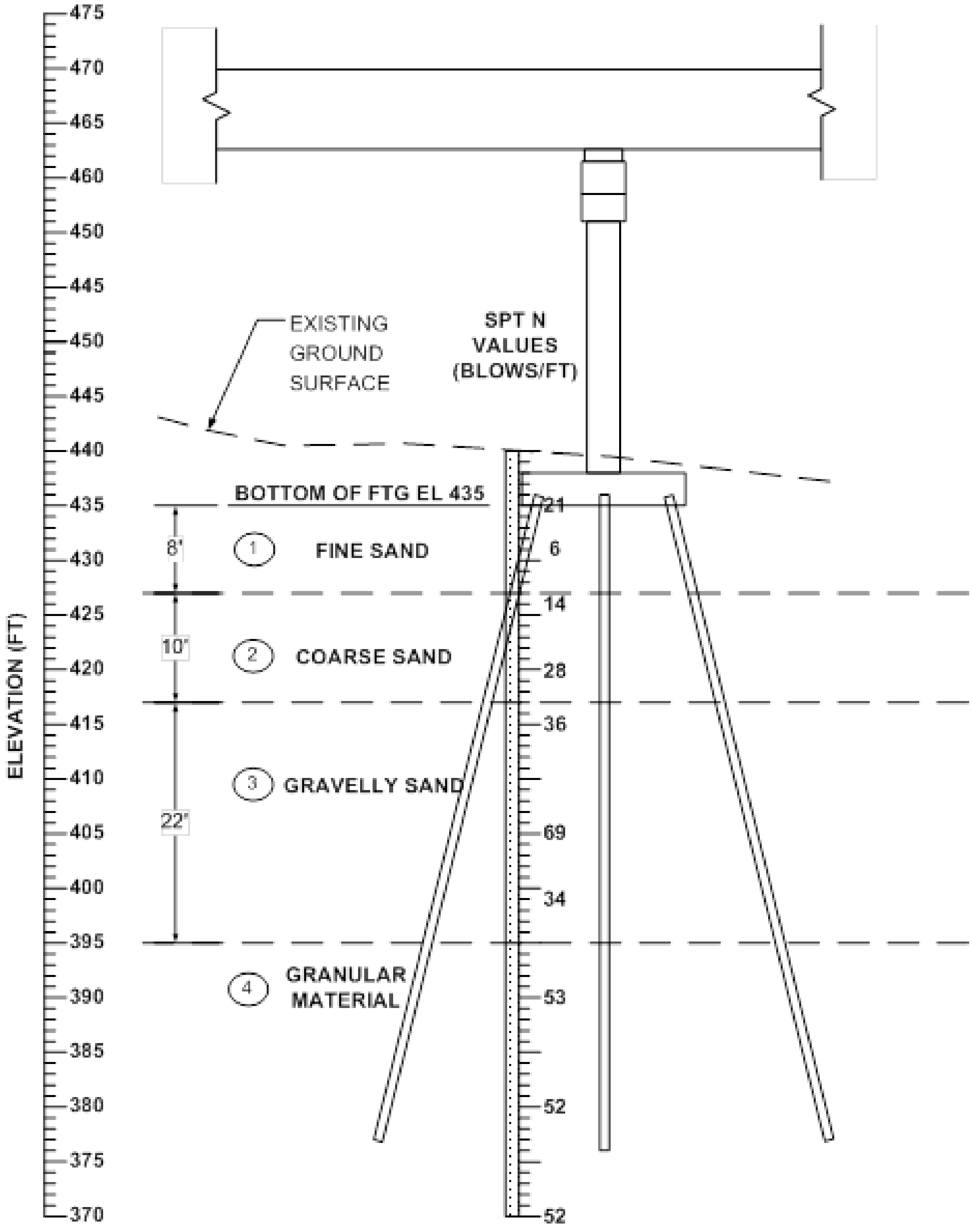


Figure 3.13. Track 1 Example 4: Soil profile

Step 3 – Determine pile arrangement, pile loads, and other design requirements

The final design engineer begins design of the pier piles with the TS&L and the soils design package. Because the bridge has a prestressed concrete beam superstructure and integral abutments, the engineer selects HP 10×57 piles to match abutment piles, following Bridge Design Manual policy (BDM 6.5.1.1.1 and 6.2.1.1).

Based on the reinforced concrete pier (RC-PIER) analysis at the strength limit state and the Bridge Design Manual policy for pile spacing and number of piles (BDM 6.5.4.1.1), the final design engineer determines the following:

- Nine HP 10×57 piles per each of three column footings as shown in Figure 3.14
- Selected perimeter piles battered at 1:4
- Maximum compression load per pile at the strength limit state = 132 kips
- Maximum uplift load per pile at the strength limit state = 50 kips
- Standard construction control based on WEAP analysis with no planned retap

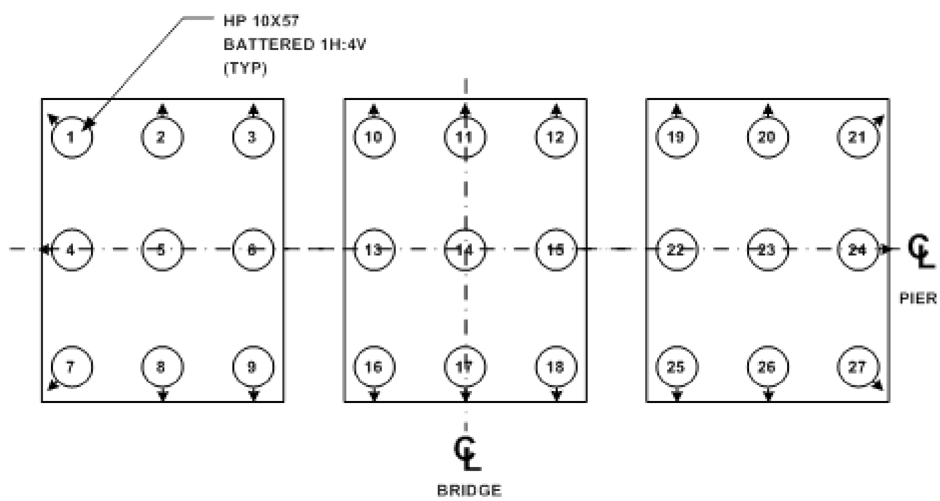


Figure 3.14. Track 1 Example 4: Pile arrangement at pile piers

Structural checks of the pile group indicate that the individual pile resistances (BDM 6.2.6.1) combined with battered pile resistances are sufficient for all lateral loads. Thus, the piles may be designed for axial geotechnical resistance without lateral load or other special analysis.

Step 4 – Estimate the nominal friction and end bearing geotechnical resistance

Based on the pier soil boring and BDM Table 6.2.7, the final design engineer estimates the nominal resistances for friction and end bearing as shown in Table 3.10.

Table 3.10. Track 1 Example 4: Estimated nominal geotechnical resistance

Soil Stratum	Soil Description	Stratum Thickness (ft)	Average SPT-N Value (blows/ft)	Estimated Nominal Resistance Value for Friction Pile (kips/ft)	Estimated Nominal Resistance Value for End Bearing Pile (kips/in^2)
1	Fine Sand	8	13	2.0	--- *
2	Coarse Sand	10	21	2.8	--- *
3	Gravelly Sand	22	35	2.8	3
4	Granular Material	---	52	4.0	4

* End bearing is not considered for fine sand, coarse sand, or gravelly sand with SPT-N values fewer than 25 blows/ft per BDM 6.2.7

Step 5 – Select a resistance factor to estimate pile length based on the soil profile and construction control

For a driven H-pile with construction control based on a WEAP analysis and no planned retap, the following resistance factor, φ, is recommended for use to estimate the contract pile length in non-cohesive soil under axial compressive load:

$\varphi = 0.55$ for non-cohesive soil

For a driven H-pile in axial tension under uplift load, the following resistance factors, φ_{UP}, are recommended for uplift check. (Resistance factors for uplift are the resistance factors for compression with a reduction factor of 0.75 (BDM C6.2.4.4)):

$\varphi_{UP} = 0.40$ for non-cohesive soils at strength limit state
$\varphi_{UP} = 0.45$ for cohesive and mixed soils at strength limit state
$\varphi_{UP} = 0.75$ for non-cohesive, cohesive and mixed soils at extreme event limit state

Step 6 – Calculate the required nominal pile resistance, Rn

For non-cohesive soils, there is no setup effect. Therefore, required nominal pile resistance in compression can be calculated as follows:

$$R_n = \frac{\sum \eta\gamma Q + \gamma_{DD} DD}{\varphi} = \frac{132 + 0}{0.55} = 240 \text{ kips/pile}$$

where

$\sum \eta\gamma Q = 132$ kips (Step 3)

$\gamma_{DD}DD = 0$ (no downdrag)

$\varphi = 0.55$ (Step 5)

Step 7 – Estimate contract pile length, L

Based on the nominal resistance values in Step 4, the cumulative nominal compression geotechnical resistance, $R_{n\text{-}BB}$, per pile is calculated as follows, where D = depth in feet below the bottom of footing:

$D_0 = 0$ ft, $R_{n\text{-}BB0} = 0$ kips

$D_1 = 8$ ft, $R_{n\text{-}BB1} = R_{n\text{-}BB0}$ + (2.0 kips/ft) (8 ft) = 16.0 kips

$D_2 = 8 + 10 = 18$ ft, $R_{n\text{-}BB2} = R_{n\text{-}BB1}$ + (2.8 kips/ft) (10 ft) = 16.0 + 28.0 = 44.0 kips

$D_3 = 18 + 22 = 40$ ft, $R_{n\text{-}BB3} = R_{n\text{-}BB2}$ + (2.8 kips/ft) (22 ft) = 44.0 + 61.6 = 105.6 kips

End bearing in Layer 4 = (4 ksi)(16.8 in^2) = 67.2 kips, $R_{n\text{-}BB4} = R_{n\text{-}BB3}$ + 67.2 = 172.8 kips

Required additional length in Layer 4 = (240 – 172.8)/4.0 = 17 ft

$D_4 = 40 + 17 = 57$ ft, $R_{n\text{-}BB5} = R_{n\text{-}BB4}$ + (4.0 kips/ft) (17 ft) = 172.8 + 68.0

= 240.8 kips > 240 kips needed

The contract pile length includes a 1 ft embedment in the footing and a 1 ft allowance for cutoff due to driving damage:

L = 57 + 1 + 1 = 59 ft

The length for steel H-piles is specified in 5 ft increments (BDM 6.2.4.1). Therefore, the contract pile length is rounded to 60 ft.

Uplift may be checked using the previous computations for pile length. Neglecting end bearing (which cannot provide uplift resistance) and including the additional 1 ft of pile due to round-up, the nominal resistance is as follows:

240.8 kips – 67.2 kips + (4.0 kips/ft) (1 ft) = 177.6 kips

With a resistance factor of $\varphi_{UP} = 0.40$ for non-cohesive soil (Step 5), the factored uplift resistance is as follows:

$R_{UP} = \varphi_{UP} R_{n\_UP}$ = (0.40)(177.6 tons) = 71 kips > Uplift Load = 50 kips, OK

Minimum required pile driven length for uplift resistance is as follows:

40 ft + [50 kips - (0.40)(105.6 kips)] / [(0.40)(4.0 kips/ft)] = 40 ft + 5 ft = 45 ft

The final design engineer also checks group uplift resistance. For this volume, it is assumed that the pile spacing is sufficient so that group uplift resistance does not govern in design.

The check above indicates the pile will not pull out of the ground, but will it pull out of the footing?

The section perimeter of HP10×57, is 60 in., and the embedment length in the concrete footing is 12 in. (1 ft). With a nominal bond resistance of 0.060 ksi and a resistance factor of φ = 0.45, the factored uplift resistance for pile embedment in the concrete footing is as follows:

(0.060 ksi)(60 in.)(12 in.)(0.45) = 19 kips < 25 kips, NOT Good

Therefore, 1 ft of embedment into the concrete footing is not sufficient to provide the required uplift resistance. By inspection, a relatively simple change would be to increase the embedment in the footing to 1 ft 6 in., which can be accommodated in the typical footing thickness. A second option would be to use shear studs to increase the uplift resistance in concrete so the 1 ft embedment length can be maintained.

Therefore, the contract pile length remains at L = 60 ft.

The soil below the footing is non-cohesive, so there is no need to check the site classification.

Step 8 – Estimate target nominal pile driving resistance, Rndr-T

The complete embedment length below the bottom of footing will contribute to pile driving resistance. Given there was no need to make allowance for pre-boring, downdrag load, or scour, the pile embedment length below bottom of footing will be the same as that considered to estimate R_n.

For a driven H-pile with WEAP analysis construction control and no planned retap, the following resistance factor, φ, is recommended to estimate the target nominal pile driving resistance in non-cohesive soil:

φ_{TAR} = 0.55 for non-cohesive soil

Therefore, the target nominal pile driving resistance is as follows:

$$\mathrm{R_{ndr-T}} = \frac{\sum \eta\gamma Q + \gamma_{DD} DD}{\varphi_{TAR}} = \frac{132 + 0}{0.55} = 240 \text{ kips/pile}$$

Step 9 – Prepare CADD notes for bridge plans

At this point, the final design engineer selects the appropriate CADD notes and adds the specific pile load values to the notes.

Pier piles design note

> THE CONTRACT LENGTH OF 60 FEET FOR THE PIER PILES IS BASED ON A NON-COHESIVE SOIL CLASSIFICATION, A TOTAL FACTORED AXIAL LOAD PER PILE (P_U) OF 132 KIPS, AND A GEOTECHNICAL RESISTANCE FACTOR (PHI) OF 0.55. PIER PILES ALSO WERE DESIGNED FOR A FACTORED TENSION FORCE OF 50 KIPS.
>
> THE NOMINAL AXIAL BEARING RESISTANCE FOR CONSTRUCTION CONTROL WAS DETERMINED FROM A NON-COHESIVE SOIL CLASSIFICATION AND A GEOTECHNICAL RESISTANCE FACTOR (PHI) OF 0.55.

Pier piles driving note

> THE REQUIRED NOMINAL AXIAL BEARING RESISTANCE FOR PIER PILES IS 120 TONS AT END OF DRIVE. THE PILE CONTRACT LENGTH SHALL BE DRIVEN AS PER PLAN UNLESS PILES REACH REFUSAL. IN NO CASE SHALL A PILE BE EMBEDDED LESS THAN 45 FEET. CONSTRUCTION CONTROL REQUIRES A WEAP ANALYSIS AND BEARING GRAPH.

Step 10 – Check the design

Within the Iowa DOT Office of Bridges and Structures, a final design engineer other than the bridge designer is assigned to give the bridge design an independent check when final plans are complete. During the checking process, the final design engineer reviews the soils package to ensure all recommendations were followed and also checks structural, geotechnical, and drivability aspects of the design.

For this example, only the structural and geotechnical aspects would be checked because pile driving stresses will be relatively low. (For simplicity, the structural design was not shown in this example.)

Other design organizations may perform checks at various stages of design rather than upon plan completion.

----------------------END DESIGN AND BEGIN CONSTRUCTION PHASE--------------------

Step 11 – Prepare bearing graph

After the bridge contract is let and prior to start of pile driving, the contractor completes Hammer Data sheets for use of the planned pile driving hammer. The Hammer Data sheets include all pertinent information including the cap (helmet) number and hammer identification information with details, hammer cushion, and pile cushion (where required), as well as pile size, pile length, and estimated pile driving resistance.

The Office of Construction uses the data received to complete a WEAP analysis for construction control during pile driving. Results from the WEAP analysis are then used to prepare an LRFD Driving Graph (without the factor of safety used for allowable stress design). The Driving Graph includes curves of nominal driving resistance versus blows per ft and identifies specific driving conditions where driving stress is a concern.

Step 12 – Observe construction, record driven resistance, and resolve any construction issues

If the recorded pile driving resistance at EOD is less than the target pile nominal driving resistance, the pile may be retapped about 24 hours after EOD. (The retap is a remedial measure that makes use of setup for an individual pile. If the 24 hour retap does not indicate sufficient driven resistance, an extension will be added the same day rather than wait to retap another day.) For the site in this example, retaps are unlikely to be helpful because of the cohesionless soil.

3.5. Track 1 Example 5: Driven H-Pile in Cohesive Soil to Bedrock, Construction Control Based on Wave Equation, and No Planned Retap

Table 3.11. Track 1 Example 5: Design and construction steps

Design Step	
1	Develop bridge situation plan (TS&L)*
2	Develop soils package, including soil borings and foundation recommendations*
3	Determine pile arrangement, pile loads, and other design requirements*
4	Estimate the nominal geotechnical resistance per foot of pile embedment**
5	Estimate the nominal friction and end bearing geotechnical resistances**
6	Select resistance factors to estimate pile length based on the soil profile and construction control**
7	Check the required factored pile geotechnical resistance, φR_n**
8	Estimate contract pile length, L**
9	Prepare CADD notes for bridge plans
10	Check the design depending on bridge project and office practice
Construction Step	
11	Prepare bearing graph
12	Observe construction, record driven resistance, and resolve any construction issues

* These steps determine the basic information for geotechnical pile design and vary depending on bridge project and office practice
** These steps follow a different pattern than other examples

Within the Iowa DOT Office of Bridges and Structures, the design steps that determine the basic information necessary for geotechnical design of a steel H-pile generally follow Steps 1 through 3. The steps involve communication among the preliminary design engineer, soils design engineer, and final design engineer.

In other organizations, the basic information may be determined differently, but that process generally should not affect the overall geotechnical design of the pile in Steps 4 through 9.

Step 1 – Develop bridge situation plan (or TS&L)

For a typical bridge, the preliminary design engineer plots topographical information, locates the bridge, determines general type of superstructure, location of substructure units, elevations of foundations, hydraulic information (if needed), and other basic information to characterize the bridge. The preliminary design engineer then prepares the TS&L sheet that shows a plan and longitudinal section of the bridge.

For this example, the TS&L gives the following information needed for design of abutment piles:

- 312 ft, three-span, prestressed concrete beam superstructure

- Seven BTC beam cross section
- Zero skew
- Integral abutments
- Pile foundations with 10 ft prebored holes
- Bottom of west abutment footing elevation 5 ft below natural ground elevation

Step 2 – Develop soils package, including soil borings and foundation recommendations

Based on locations of the abutments, the soils design engineer orders soil borings (typically at least one per substructure unit). Upon receipt of the boring logs, the engineer arranges for them to be plotted on a longitudinal section, checks any special geotechnical conditions on the site, and writes a recommendation for foundation type with any applicable special design considerations.

For this example, the recommendations are as follows:

- Piles driven to hard shale bedrock at 40 ft below natural ground elevation at west abutment
- Steel H-piles for the integral abutments
- Structural Resistance Level – 2 (which does not require a driving analysis by the Office of Construction during design (BDM 6.2.6.1). SRL-2 in this case allows the designer to consider both friction and end bearing.)
- Normal driving resistance (This will lead to $\varphi_c = 0.6$ for the structural check.)
- No special site considerations for stability, settlement, or lateral movement (Therefore, a Service I load will not be required for design.)

Standard construction control was based on WEAP analysis with no planned retap.

The soil profile is as follows. Stratum 3 is divided into 3A for soil above the elevation 30 ft below natural ground and 3B below 3A. The distinction is for different friction values.

- Stratum 1 – Topsoil 4 ft
- Stratum 2 – Firm glacial clay 14 ft, average N-value = 12
- Stratum 3A – Very firm glacial clay 12 ft, average N-value = 21
- Stratum 3B – Very firm glacial clay 10 ft, average N-value 21
- Stratum 4 – Hard shale, average N-value = 162

Step 3 – Determine pile arrangement, pile loads, and other design requirements

The final design engineer begins design of the abutment piles with the TS&L and the soils design package. Because the bridge has a prestressed concrete beam superstructure and integral abutments, the engineer selects HP 10×57 piles, following Bridge Design Manual policy (BDM 6.5.1.1.1).

Based on total Strength I abutment load and the Bridge Design Manual policy for pile spacing and number of piles (BDM 6.5.4.1.1), the final design engineer determines the following:

- Strength I factored load for abutment (not including wing extension) piles = 1330 kips
- HP 10×57 piles
- Nominal structural resistance per pile at SRL-2 = 365 kips (BDM Table 6.2.6.1-1)
- Nominal maximum structural resistance for an integral abutment pile with 10 ft prebore = 365 kips (BDM Table 6.5.1.1.1-1)
- Minimum number of piles based on structural resistance = 1330/(0.6)(365) = 6.1
- Minimum number of piles based on superstructure cross section: 7 beams, Therefore, 7 piles (BDM 6.2.4.1)
- Seven piles with two wing extension piles as shown in Figure 3.15, if geotechnical resistance is sufficient
- Required factored geotechnical resistance per pile = 1330/7 = 190 kips

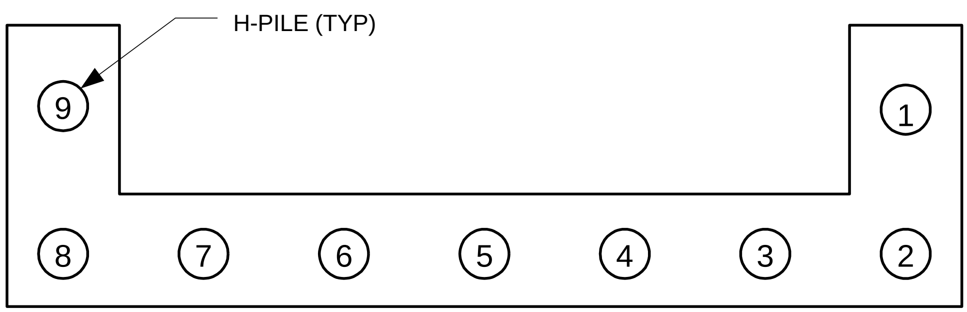


Figure 3.15. Track 1 Example 5: Pile arrangement at an abutment

Because the bridge characteristics fall within integral abutment policy, the site has no unusual characteristics, the soils design engineer did not require further analysis, the project does not require staged construction, and construction will not be accelerated or delayed, there will be no need for lateral load or special analysis of the abutment piles. The piles may be simply designed for applied vertical load.

Step 4 – Estimate the nominal friction and end bearing geotechnical resistances

Based on the west abutment soil profile and BDM Table 6.2.7, the final design engineer estimates the nominal resistances for friction and end bearing shown in Table 3.12.

Table 3.12. Track 1 Example 5: Estimated nominal geotechnical resistance

Soil Stratum	Soil Description	Stratum Thickness (ft)	Average SPT N Value (blows/ft)	Estimated Nominal Resistance for Friction Pile (kips/ft)	Cumulative Nominal Friction Resistance at Bottom of Layer (kips)	Estimated Nominal Resistance for End Bearing (ksi)
1	Topsoil	4 below natural ground	---	---	---	---
2	Firm Glacial Clay	14 total, 3 below prebore	12	2.8	8.4	---
3A	Very Firm Glacial Clay	12	21	2.8	33.6 + 8.4 = 42.0	---
3B	Very Firm Glacial Clay (30 ft below the natural ground elevation)	10	21	4.0	40.0 + 42.0 = 82.0	---
4	Hard Shale	---	162	---	---	(16.8)(12) = 201.6

Step 5 – Select resistance factors to estimate pile length based on the soil profile and construction control

For a driven H-pile with construction control based on a WEAP analysis at EOD and no planned retap, the following resistance factor is recommended to estimate the contract pile length for friction bearing in cohesive soil. Only cohesive soil was present below the west abutment.

$\varphi = 0.65$ for cohesive soil, averaged over the full depth of estimated pile penetration

Based on successful past practice with WEAP analysis and referring to Appendix H, the following resistance factor will be used for end bearing on bedrock.

$\varphi = 0.70$ for bedrock

Step 6 – Check the required factored pile geotechnical resistance, φRn

Using the results from Steps 4 and 5 and adding friction and end bearing factored resistances:

$\varphi R_n = (0.65)(82.0) + (0.70)(201.6) = 194.4$ kips

$[\varphi R_n = 194.4 \text{ kips}] > [\gamma Q = 190 \text{ kips}]$ OK

In this case, because piles are driven to bedrock, if the factored geotechnical resistance were insufficient, the final design engineer would need to increase the number or possibly the size of piles for the abutment.

Step 7 – Estimate contract pile length, L

With piles driven to bedrock, the contract length can be determined from known elevations and an estimate of the length driven into bedrock. The Blue Book recommends that piles be driven 4 to 8 ft into hard shale (N = 50 to 200). Interpolating first for N = 162:

$L_{br} = 4 + (8\text{-}4)(162\text{-}50)/(200\text{-}50) = 7$ ft

L = cutoff + embedment in abutment + prebore + soil layers below prebore + embedment in bedrock = 1+2+10+25+7 = 45 ft

The length for steel H-piles is specified in 5 ft increments (BDM 6.2.4.1). Therefore, there is no need to round the 45 ft length, but the final design engineer could add 5 ft just to ensure that pile extensions would not be required if the elevation of bedrock varies over the length of the abutment.

Because the site has only cohesive soil within the length of the pile embedded in soil, the resistance factor determined in Step 5 need not be checked for site classification.

Step 8 – Estimate target nominal pile driving resistance, Rndr-T

The driving resistance will depend on both the friction and end bearing resistances. Because the friction resistance will be achieved before the end bearing resistance, assume that the full friction resistance will be achieved and the remainder of the resistance will be end bearing. The fraction of friction resistance is computed as follows:

$F_{fr} = (0.65)(82.0)/190 = 0.28$

The fraction for end bearing, then, is as follows:

$F_{eb} = 1 – 0.28 = 0.72$

For driven H-piles with WEAP analysis construction control and no planned retap, the following resistance factors, φ, are recommended to estimate the target nominal pile driving resistance for friction in cohesive soils:

φ_{EOD} = 0.65 for cohesive soil, averaged over the full depth of estimated pile penetration

φ_{SETUP} = 0.20 for cohesive soil, averaged over the full depth of estimated pile penetration

Next, determine the resistance factor for friction in the soil, including setup:

N_a = [(3)(12) + (22)(21)]/25 = 20

From the graph for 7 day setup (Figure 3.16), F_{SETUP} = 1.55.

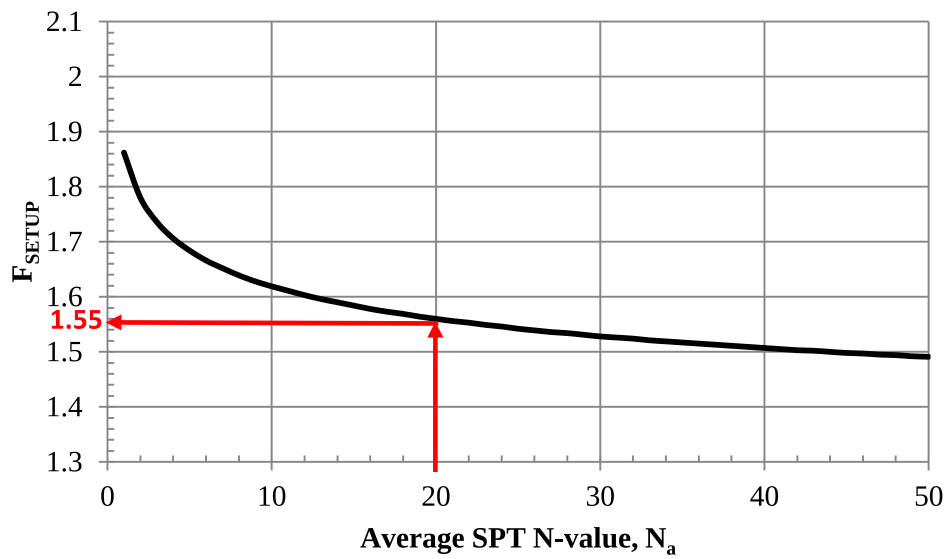


Figure 3.16. Track 1 Example 5: Pile setup factor chart

Then, determine the target resistance factor for friction in the soil:

φ_{TAR} = Resistance factor for target nominal resistance

$= \varphi_{EOD} + \varphi_{SETUP}(F_{SETUP} - 1)$

= 0.65 + 0.20*(1.55-1) = 0.76

With the estimated fractions of friction and end bearing, target resistance factor for friction, and the resistance factor of 0.70 for end bearing, compute the target pile driving resistance at EOD:

$R_{ndr\text{-}T}$ = 190/[(0.28)(0.76) + (0.72)(0.70)] = 265 kips/pile

Step 9 – Prepare CADD notes for bridge plans

At this point, the final design engineer selects the appropriate CADD notes and adds the specific pile load values to the notes.

Abutment piles design note

> THE CONTRACT LENGTH OF 45 FEET FOR THE WEST ABUTMENT PILES IS BASED ON A COHESIVE SOIL CLASSIFICATION, A TOTAL FACTORED AXIAL LOAD PER PILE (P_U) OF 190 KIPS, AND A GEOTECHNICAL RESISTANCE FACTOR (PHI) OF 0.65 FOR SOIL AND 0.70 FOR ROCK END BEARING.
>
> THE NOMINAL AXIAL BEARING RESISTANCE FOR CONSTRUCTION CONTROL WAS DETERMINED FROM A COHESIVE SOIL CLASSIFICATION AND A GEOTECHNICAL RESISTANCE FACTOR (PHI) OF 0.76 FOR SOIL AND 0.70 FOR ROCK END BEARING.

Abutment piles driving note

> THE REQUIRED NOMINAL AXIAL BEARING RESISTANCE FOR WEST ABUTMENT PILES IS 133 TONS AT END OF DRIVE (EOD). THE PILE CONTRACT LENGTH SHALL BE DRIVEN AS PER PLAN UNLESS PILES REACH REFUSAL. CONSTRUCTION CONTROL REQUIRES A WEAP ANALYSIS AND BEARING GRAPH.

Step 10 – Check the design

Within the Iowa DOT Office of Bridges and Structures, a final design engineer other than the bridge designer is assigned to give the bridge design an independent check when final plans are complete. During the checking process, the final design engineer reviews the soils package to ensure all recommendations were followed and also checks structural, geotechnical, and drivability aspects of the design.

For this example, only the structural and geotechnical aspects would be checked because pile driving stresses will be relatively low.

Other design organizations may perform checks at various stages of design rather than upon plan completion.

-----------------------END DESIGN AND BEGIN CONSTRUCTION PHASE---------------------

Step 11 – Prepare bearing graph

After the bridge contract is let and prior to start of pile driving, the contractor completes Hammer Data sheets for use of the planned pile driving hammer. The Hammer Data sheets include all pertinent information including the cap (helmet) number and hammer identification information with details, hammer cushion, and pile cushion (where required), as well as pile size, pile length, and required (or target) nominal axial pile driving resistance.

For state projects, the Office of Construction uses the data received to complete a WEAP analysis for construction control during pile driving. Results from the WEAP analysis are then used to prepare an LRFD Driving Graph (without the factor of safety used for allowable stress design). The Driving Graph includes hammer stroke height curves that relate blows per ft to nominal driving resistance, and identifies specific driving conditions where driving stress is a concern.

Step 12 – Observe construction, record driven resistance, and resolve any construction issues

During pile driving, the construction inspector records the hammer stroke and number of blows to advance the pile an equivalent penetration of 1 ft, and, then, converts the recorded information with the Driving Graph to record the driven resistance per pile at EOD.

If the recorded pile driving resistance at EOD is less than the required (or target) nominal axial pile driving resistance, the pile is typically retapped about 24 hours after EOD. However, when driving to rock, as in this case, it is unlikely that retaps would be successful because the amount of friction resistance is only about one-quarter of the total resistance. (In this case, if EOD does not indicate sufficient driven resistance, an extension will be added.)

3.6. Track 1 Example 6: Driven Pipe Pile in Non-Cohesive Soil with Scour, Construction Control Based on Wave Equation, and No Planned Retap (prepared by Iowa DOT)

Table 3.13. Track 1 Example 6: Design and construction steps

Design Step	
1	Develop bridge situation plan (TS&L)*
2	Develop soils package, including soil borings and foundation recommendations*
3	Determine pile arrangement, pile loads, and other design requirements*
4	Estimate the nominal geotechnical resistance per foot of pile embedment
5	Select a resistance factor to estimate pile length based on the soil profile and construction control
6	Calculate the required nominal pile resistance, R_n
7	Estimate contract pile length, L
8	Estimate target nominal pile driving resistance, R_{ndr-T}
9	Prepare CADD notes for bridge plans
10	Check the design depending on bridge project and office practice
Construction Step	
11	Prepare bearing graph
12	Observe construction, record driven resistance, and resolve any construction issues

* These steps determine the basic information for geotechnical pile design and vary depending on bridge project and office practice

Use of pipe piles in Iowa is unusual at the present time. However, within the Iowa DOT Office of Bridges and Structures, the design steps that determine the basic information necessary for geotechnical design of a steel pipe pile generally would follow as indicated in Steps 1 through 3. The steps involve communication among the preliminary design engineer, soils design engineer, and final design engineer.

In other organizations, the basic information may be determined differently, but that process generally should not affect the overall geotechnical design of the pile.

Step 1 – Develop bridge situation plan (or TS&L)

For a typical bridge, the preliminary design engineer plots topographical information, locates the bridge, determines general type of superstructure, location of substructure units, elevations of foundations, hydraulic information (if needed), and other basic information to characterize the bridge. The preliminary design engineer then prepares the TS&L sheet that shows a plan and longitudinal section of the bridge.

For this example, the TS&L gives the following information needed for design of pier piles:

- 120 ft, three-span continuous concrete slab superstructure
- 25-degree skew

- P10L pile bents
- Bottom of pier cap elevation 905 ft
- Streambed elevation 895 ft
- Design scour elevation 888 ft (This indicates 7 ft of scour to be considered at the strength limit state. This example includes the geotechnical design for scour but not the structural check for unsupported length, which is required for a complete design (BDM 6.6.4.1.3.1).)

Step 2 – Develop soils package, including soil borings and foundation recommendations

Based on location of the pile bents, the soils design engineer orders soil borings (typically at least one per substructure unit). Upon receipt of the boring logs, the engineer arranges for them to be plotted on a longitudinal section, checks any special geotechnical conditions on the site, and writes a recommendation for foundation type with any applicable special design considerations.

Subsurface conditions at the pile bents have been characterized based on representative test borings. The streambed is underlain by 5 ft of soft to stiff silty clay (N_a = 4), 15 ft of fine sand (N_a = 16), 40 ft of medium sand (N_a = 20), and bouldery gravel and hard shale.

For this example, the recommendations are as follows:

- Displacement piles, either steel pipe or prestressed concrete, that tip out in the medium sand layer
- P10L nominal resistance (which does not require a driving analysis by the Office of Construction during design)
- No downdrag
- Normal driving resistance (This will lead to $\varphi_c = 0.7$ for the structural check, which needs to be performed but is not included in this geotechnical example.)
- No special site considerations for stability, settlement, or lateral movement (Therefore, a Service I load will not be required for design.)
- Standard construction control based on WEAP analysis with no planned retap

Step 3 – Determine pile arrangement, pile loads, and other design requirements

The final design engineer begins design of the pile bent piles with the TS&L and the soils design package and determines the following:

- P10L Type 1, steel pipe piles, 16 inches in diameter (Track 1 Example 7 covers the alternate choice of Type 2, prestressed concrete piles.)
- End piles battered at 1:12 in keeping with office policy (BDM 6.6.1.1.3)
- 12 piles per bent
- Strength I factored load per pile = 94 kips

- No uplift
- Standard Iowa DOT construction control based on WEAP analysis and no planned retap

Development of the P10L standard included analysis for various typical conditions involving movement and the nominal resistance per the standard was limited accordingly. Thus, for typical bridges, such as the one in this example, the piles may be designed for axial geotechnical resistance without additional consideration of eccentric and lateral loads.

Step 4 – Estimate the nominal friction and end bearing geotechnical resistance

Based on the subsurface information at the pile bents and BDM Table 6.2.7, the final design engineer estimates the nominal resistances for friction and end bearing shown in Table 3.14.

Table 3.14. Track 1 Example 6: Estimated nominal geotechnical resistance

Soil Stratum	Soil Description	Stratum Thickness (ft)	Average SPT N Value (blows/ft)	Estimated Nominal Resistance for Friction Pile* (kips/ft)**	Cumulative Nominal Friction Resistance at Bottom of Layer (kips)**	Estimated Nominal Resistance for End Bearing (kips)**
1	Soft to Stiff Silty Clay above Scour Elevation	5	4	1.4	7.0	---
2A	Fine Sand above Scour Elevation	2	16	2.6	12.2	---
2	Fine Sand below Scour Elevation	13	16	2.6	46.0	---
3	Medium Sand	40	20	2.9	162.0	---
3	Medium Sand	---	20	---	---	86

* These values are the average for 14 in. and 18 in. pipe piles. Because the soil categories and N-values do not fit the geotechnical resistance charts exactly, there also is some judgment involved.
** This information is used to prepare the calculations in Step 7.

Step 5 – Select a resistance factor to estimate pile length based on the soil profile and construction control

By inspection, more than 70 percent of the embedded pile length will be in non-cohesive soil.

For driven pipe piles with construction control based on a WEAP analysis at EOD and no planned retap, the following resistance factor is recommended to estimate the contract pile length (Appendix C, Table C.1):

$\varphi = 0.55$ for non-cohesive soil, averaged over the full depth of estimated pile penetration

Step 6 – Calculate the required nominal pile resistance, R_n

For non-cohesive soil, there is no significant setup effect. Therefore, the required nominal pile resistance can be calculated as follows:

$$R_n = \frac{\sum \eta\gamma Q + \gamma_{DD} DD}{\varphi} = \frac{94 + 0}{0.55} = 170.9 \text{ kips/pile}$$

where

$\sum\eta\gamma Q = \gamma Q = 94$ kips (Step 3)

$\gamma_{DD}DD = 0$ (no downdrag)

$\varphi = 0.55$ (Step 5)

Step 7 – Estimate contract pile length, L

Based on the nominal and cumulative resistance values in Step 4, the nominal geotechnical resistance, $R_{n\text{-}BB}$, per pile is calculated as follows, where D = depth in feet below the streambed:

$D_0 = 0$ ft, $R_{n\text{-}BB0} = 0$ kips

$D_1 = 5$ ft, $R_{n\text{-}BB1} = R_{n\text{-}BB0} + 0 = 0$ kips because scour zone provides no support

$D_2 = 5 + 2 = 7$ ft, $R_{n\text{-}BB2} = R_{n\text{-}BB1} + 0 = 0$ kips because scour zone provides no support

$D_3 = 7 + 13 = 20$ ft, $R_{n\text{-}BB3} = R_{n\text{-}BB2} + (2.6 \text{ kips/ft})(13 \text{ ft}) = 0 + 33.8 = 33.8$ kips

End bearing in Layer 3 = 86 kips, $R_{n\text{-}BB4} = R_{n\text{-}BB3} + 86 = 119.8$ kips

Required additional length in Layer 3 = (170.9 – 119.8)/2.9 = 17.6, rounded to 18 ft

$D_4 = 20 + 18 = 38$ ft, $R_{n\text{-}BB5} = R_{n\text{-}BB4} + (2.9 \text{ kips/ft})(18 \text{ ft}) = 119.8 + 52.2$

$= 172.0 \text{ kips} > 170.9$ kips

The contract pile length includes 10 ft above streambed, a 1 ft embedment in the cap, and a 1 ft cutoff for driving damage.

L = 38 + 10 + 1 + 1 = 50 ft

The length for steel pipe piles should be specified to the nearest 1 ft increment. (Pipe pile lengths should account for cutoff but not be rounded to the nearest 5 ft increment.)

At this point, the embedded pile length is known and it is necessary to check the site classification for the resistance factor:

% non-cohesive soil below scour elevation = [31/(38-7)](100) = 100% > 70%

Therefore, the resistance factor for non-cohesive soil is the correct choice.

A minimum pile embedment length also needs to be estimated for construction monitoring. Consider setting the minimum embedment pile length equal to 2/3 the Blue Book nominal capacity plus the 100 percent of the capacity lost over the scour zone.

Two-thirds the nominal capacity = (2/3) (170.9) = 114 kips/pile.

D_0 = 0 ft, $R_{n\text{-}BB0}$ = 0 kips

D_1 = 5 ft, $R_{n\text{-}BB1} = R_{n\text{-}BB0}$ + 0 = 0 kips because scour zone provides no support

D_2 = 5 + 2 = 7 ft, $R_{n\text{-}BB2} = R_{n\text{-}BB1}$ + 0 = 0 kips because scour zone provides no support

D_3 = 7 + 13 = 20 ft, $R_{n\text{-}BB3} = R_{n\text{-}BB2}$ + (2.6 kips/ft) (13 ft) = 0 + 33.8 = 33.8 kips

End bearing in Layer 3 = 86 kips, $R_{n\text{-}BB4} = R_{n\text{-}BB3}$ + 86 = 119.8 kips > 114, OK

Add an additional 5 pile diameters, 7 ft, penetration into Layer 3 to develop end bearing

D_4 = 20 + 7 = 27 ft, $R_{n\text{-}BB5} = R_{n\text{-}BB4}$ + (2.9 kips/ft) (7 ft) = 119.8 + 20.3

= 140.1 kips > 114 kips

Step 8 – Estimate target nominal pile driving resistance, $R_{ndr\text{-}T}$

The complete embedment length below the streambed will contribute to pile driving resistance. (The soil resistance above scour elevation, which was ignored in Step 4, should be considered in pile driving resistance, $R_{ndr\text{-}T}$.)

The complete pile embedment length is 38 ft, which is equal to the 50 ft contract pile length minus the pile height above streambed, embedment length in the concrete cap, and cutoff estimate.

The pipe pile will penetrate 33 ft of non-cohesive soil below the streambed:

% non-cohesive soil = [33/38] (100) = 87% > 70%

Therefore, the generalized soil category for pile driving (construction stage) is also "non-cohesive." Note that it is possible for piles for a substructure to have different soil categories during the design and construction stages.

For driven pipe pile with WEAP analysis construction control and no planned retap, the following resistance factor, φ_{TAR}, is recommended to estimate the target nominal pile driving resistance for non-cohesive soil (Appendix C, Table C.3):

φ_{TAR} = 0.55 for non-cohesive soil, averaged over the full depth of estimated pile penetration

$$R_{ndr-T} = \frac{\sum \eta\gamma Q + \gamma_{DD} DD}{\varphi_{TAR}} + R_{SCOUR}$$

$$= \frac{94 + 0}{0.55} + 12.2$$

$$= 170.0 + 12.2 = 183.1 \text{ kips/pile}$$

where

R_{SCOUR} = 12.2 kips (Step 4)

Step 9 – Prepare CADD notes for bridge plans

At this point, the final design engineer selects the appropriate CADD notes and adds the specific pile values to the notes.

Pier piles design note

THE CONTRACT LENGTH OF 50 FEET FOR THE PIER PILES IS BASED ON A NON-COHESIVE SOIL CLASSIFICATION, A TOTAL FACTORED AXIAL LOAD PER PILE (P_U) OF 94 KIPS, AND A GEOTECHNICAL RESISTANCE FACTOR (PHI) OF 0.55 FOR SOIL.

THE NOMINAL AXIAL BEARING RESISTANCE FOR CONSTRUCTION CONTROL WAS DETERMINED FROM A NON-COHESIVE SOIL CLASSIFICATION AND A GEOTECHNICAL RESISTANCE FACTOR (PHI) OF 0.55 FOR SOIL.

Pier piles driving note

THE REQUIRED NOMINAL AXIAL BEARING RESISTANCE FOR PIER PILES IS 92 TONS AT END OF DRIVE (EOD). THE PILE CONTRACT LENGTH SHALL BE DRIVEN AS PER PLAN UNLESS PILES REACH REFUSAL. IN NO CASE SHALL A PILE BE EMBEDDED LESS THAN 27 FEET BELOW THE STREAMBED. CONSTRUCTION CONTROL REQUIRES A WEAP ANALYSIS AND BEARING GRAPH.

Step 10 – Check the design

Within the Iowa DOT Office of Bridges and Structures, a final design engineer other than the bridge designer is assigned to give the bridge design an independent check when final plans are complete. During the checking process, the final design engineer reviews the soils package to ensure all recommendations were followed and also checks structural, geotechnical, and drivability aspects of the design.

In this example, only the structural and geotechnical aspects would be checked because pile driving stresses will be relatively low. (For simplicity, the structural design was not shown in this example.)

Other design organizations may perform checks at various stages of design rather than upon plan completion.

-----------------------END DESIGN AND BEGIN CONSTRUCTION PHASE---------------------

Step 11 – Prepare bearing graph

After the bridge contract is let and prior to start of pile driving, the contractor completes Hammer Data sheets for use of the planned pile driving hammer. The Hammer Data sheets include all pertinent information including the cap (helmet) number and hammer identification information with details, hammer cushion, and pile cushion (where required), as well as pile size, pile length, and estimated pile driving resistance.

The Office of Construction uses the data received to complete a WEAP analysis for construction control during pile driving. Results from the WEAP analysis are then used to prepare an LRFD Driving Graph (without the factor of safety used for allowable stress design). The Driving Graph includes curves of nominal driving resistance versus blows per ft and identifies specific driving conditions where driving stress is a concern.

Step 12 – Observe construction, record driven resistance, and resolve any construction issues

Usually, if the recorded pile driving resistance at EOD is less than the target pile nominal driving resistance, the pile is retapped about 24 hours after EOD. (The retap is a remedial measure that makes use of setup for an individual pile. If the 24 hour retap does not indicate sufficient driven resistance, an extension will be added the same day rather than wait to retap another day.)

In this example it is unlikely that there would be a significant amount of setup because of the non-cohesive soil, and extensions would be required if the driving resistance did not meet the target driving resistance.

3.7. Track 1 Example 7: Driven Prestressed Concrete Pile in Non-Cohesive Soil with Scour, Construction Control Based on Wave Equation, and No Planned Retap (prepared by Iowa DOT)

Table 3.15. Track 1 Example 7: Design and construction steps

Design Step	
1	Develop bridge situation plan (TS&L)*
2	Develop soils package, including soil borings and foundation recommendations*
3	Determine pile arrangement, pile loads, and other design requirements*
4	Estimate the nominal geotechnical resistance per foot of pile embedment
5	Select a resistance factor to estimate pile length based on the soil profile and construction control
6	Calculate the required nominal pile resistance, R_n
7	Estimate contract pile length, L
8	Estimate target nominal pile driving resistance, R_{ndr-T}
9	Prepare CADD notes for bridge plans
10	Check the design depending on bridge project and office practice
Construction Step	
11	Prepare bearing graph
12	Observe construction, record driven resistance, and resolve any construction issues

* These steps determine the basic information for geotechnical pile design and vary depending on bridge project and office practice

Use of prestressed concrete piles in Iowa is unusual at the present time. However, within the Iowa DOT Office of Bridges and Structures, the design steps that determine the basic information necessary for geotechnical design of a prestressed concrete pile generally would follow Steps 1 through 3. The steps involve communication among the preliminary design engineer, soils design engineer, and final design engineer.

In other organizations, the basic information may be determined differently, but that process generally should not affect the overall geotechnical design of the pile.

Step 1 – Develop bridge situation plan (or TS&L)

For a typical bridge, the preliminary design engineer plots topographical information, locates the bridge, determines general type of superstructure, location of substructure units, elevations of foundations, hydraulic information (if needed), and other basic information to characterize the bridge. The preliminary design engineer then prepares the TS&L sheet that shows a plan and longitudinal section of the bridge.

For this example, the TS&L gives the following information needed for design of pier piles:

- 120 ft, three-span continuous concrete slab superstructure

- 25 degree skew
- P10L pile bents
- Bottom of pier cap elevation 905 ft
- Streambed elevation 895 ft
- Design scour elevation 888 ft (This indicates 7 ft of scour to be considered at the strength limit state. This example includes the geotechnical design for scour, but not the structural check for unsupported length, which is required for a complete design (BDM 6.6.4.1.3.1).)

Step 2 – Develop soils package, including soil borings and foundation recommendations

Based on location of the pile bents, the soils design engineer orders soil borings (typically at least one per substructure unit). Upon receipt of the boring logs, the engineer arranges for them to be plotted on a longitudinal section, checks any special geotechnical conditions on the site, and writes a recommendation for foundation type with any applicable special design considerations.

Subsurface conditions at the pile bents have been characterized based on representative test borings. The streambed is underlain by 5 ft of soft to stiff silty clay (N_a = 4), 15 ft of fine sand (N_a = 16), 40 ft of medium sand (N_a = 20), and bouldery gravel and hard shale.

For this example, the recommendations are as follows:

- Displacement piles, either prestressed concrete or steel pipe, that tip out in the medium sand layer
- P10L nominal resistance (which does not require a driving analysis by the Office of Construction during design)
- No downdrag
- Normal driving resistance (In general this will lead to φ_c = 0.75 for the structural check of prestressed concrete piles, which needs to be performed, but is not included in this geotechnical example. For steel pipe piles the resistance factors are 0.70 for normal driving or 0.60 for hard driving, but that distinction is not made for prestressed concrete piles.)
- No special site considerations for stability, settlement, or lateral movement (Therefore, a Service I load will not be required for design.)
- Standard construction control based on WEAP analysis with no planned retap

Step 3 – Determine pile arrangement, pile loads, and other design requirements

The final design engineer begins design of the pile bent piles with the TS&L and the soils design package and determines the following:

- P10L Type 2, prestressed concrete piles, 16 in. square (Track 1 Example 6 covers the alternate choice of Type 1, steel pipe piles.)

- End piles battered at 1:12 in keeping with office policy (BDM 6.6.1.1.3)
- 11 piles per bent
- Strength I factored load per pile = 102 kips
- No uplift
- Standard Iowa DOT construction control based on WEAP analysis and no planned retap.

Development of the P10L standard included analysis for various typical conditions involving movement and the nominal resistance per the standard was limited accordingly. Thus, for typical bridges, such as the one in this example, the piles may be designed for axial geotechnical resistance without additional consideration of eccentric and lateral loads.

Step 4 – Estimate the nominal friction and end bearing geotechnical resistance

Based on the subsurface information at the pile bents and BDM Table 6.2.7, the final design engineer estimates the nominal resistances for friction and end bearing shown in Table 3.16.

Table 3.16. Track 1 Example 7: Estimated nominal geotechnical resistance

Soil Stratum	Soil Description	Stratum Thickness (ft)	Average SPT N Value (blows/ft)	Estimated Nominal Resistance for Friction Pile* (kips/ft)**	Cumulative Nominal Friction Resistance at Bottom of Layer (kips)**	Estimated Nominal Resistance for End Bearing (kips)**
1	Soft to Stiff Silty Clay above Scour Elevation	5	4	1.4	7.0	---
2A	Fine Sand above Scour Elevation	2	16	3.2	13.4	---
2	Fine Sand below Scour Elevation	13	16	3.2	55.0	---
3	Medium Sand	40	20	3.6	199.0	---
3	Medium Sand	---	20	---	---	108

* Because the soil categories and N-values do not fit the geotechnical resistance charts exactly, there is some judgment involved in selecting and interpolating for these values
** This information is used to prepare the calculations in Step 7

Step 5 – Select a resistance factor to estimate pile length based on the soil profile and construction control

By inspection, more than 70 percent of the embedded pile length will be in non-cohesive soil.

For driven prestressed concrete piles with construction control based on a WEAP analysis at EOD and no planned retap, the following resistance factor is recommended to estimate the contract pile length (Appendix C, Table C.1):

$\varphi = 0.55$ for non-cohesive soil, averaged over the full depth of estimated pile penetration

Step 6 – Calculate the required nominal pile resistance, R_n

For non-cohesive soil, there is no significant setup effect. Therefore, the required nominal pile resistance can be calculated as follows:

$$\mathrm{R_n} = \frac{\sum \eta\gamma \mathrm{Q} + \gamma_{\mathrm{DD}}\mathrm{DD}}{\varphi} = \frac{102 + 0}{0.55} = 185.5 \text{ kips/pile}$$

where

$\sum\eta\gamma Q = \gamma Q = 102$ kips (Step 3)

$\gamma_{DD}DD = 0$ (no downdrag)

$\varphi = 0.55$ (Step 5)

Step 7 – Estimate contract pile length, L

Based on the nominal and cumulative resistance values in Step 4, the nominal geotechnical resistance, $R_{n\text{-}BB}$, per pile is calculated as follows, where D = depth in feet below the streambed:

$D_0 = 0$ ft, $R_{n\text{-}BB0} = 0$ kips

$D_1 = 5$ ft, $R_{n\text{-}BB1} = R_{n\text{-}BB0} + 0 = 0$ kips because scour zone provides no support

$D_2 = 5 + 2 = 7$ ft, $R_{n\text{-}BB2} = R_{n\text{-}BB1} + 0 = 0$ kips because scour zone provides no support

$D_3 = 7 + 13 = 20$ ft, $R_{n\text{-}BB3} = R_{n\text{-}BB2} + (3.2 \text{ kips/ft})(13 \text{ ft}) = 0 + 41.6 = 41.6$ kips

End bearing in Layer 3 = 108 kips, $R_{n\text{-}BB4} = R_{n\text{-}BB3} + 108 = 149.6$ kips

Required additional length in Layer 3 = (185.5 – 149.6)/3.6 = 10.0 ft

$D_4 = 20 + 10 = 30$ ft, $R_{n\text{-}BB5} = R_{n\text{-}BB4} + (3.6 \text{ kips/ft})(10 \text{ ft}) = 149.6 + 36.0$

$= 185.6 \text{ kips} > 185.5 \text{ kips}$

The contract pile length includes 10 ft above streambed and a 1 ft embedment in the cap:

$$L = 30 + 10 + 1 = 41 \text{ ft}$$

The length for prestressed concrete piles is specified in 1 ft increments (BDM 6.2.4.1), but extensions should be specified to the nearest 5 ft.

In this example, the pile is short enough that no extension is required, and the 41 ft length is the contract length. (Prestressed concrete pile lengths need not account for cutoff.)

At this point, the embedded pile length is known and it is necessary to check the site classification for the resistance factor:

% non-cohesive soil below scour elevation = [23/(30-7)](100) = 100% > 70%

Therefore, the resistance factor for non-cohesive soil is the correct choice.

A minimum pile embedment length also needs to be estimated for construction monitoring. Consider setting the minimum embedment pile length equal to 2/3 the Blue Book nominal capacity plus the 100 percent of the capacity lost over the scour zone.

Two-thirds the nominal capacity = (2/3) (185.5) = 124 kips/pile.

D_0 = 0 ft, $R_{n\text{-}BB0}$ = 0 kips

D_1 = 5 ft, $R_{n\text{-}BB1} = R_{n\text{-}BB0}$ + 0 = 0 kips because scour zone provides no support

D_2 = 5 + 2 = 7 ft, $R_{n\text{-}BB2} = R_{n\text{-}BB1}$ + 0 = 0 kips because scour zone provides no support

D_3 = 7 + 13 = 20 ft, $R_{n\text{-}BB3} = R_{n\text{-}BB2}$ + (3.2 kips/ft) (13 ft) = 0 + 41.6 = 41.6 kips

End bearing in Layer 3 = 108 kips, $R_{n\text{-}BB4} = R_{n\text{-}BB3}$ + 108 = 149.6 kips > 124

Add an additional 5 pile diameters, 7 ft, penetration into Layer 3 to develop end bearing

D_4 = 20 + 7 = 27 ft, $R_{n\text{-}BB5} = R_{n\text{-}BB4}$ + (3.6 kips/ft) (7 ft) = 149.6 + 25.2

= 174.8 kips > 124 kips

Step 8 – Estimate target nominal pile driving resistance, $R_{ndr\text{-}T}$

The complete embedment length below the streambed will contribute to pile driving resistance, i.e., the soil resistance above scour elevation, which was ignored in Step 4, should be considered in pile driving resistance, $R_{ndr\text{-}T}$.

The complete pile embedment length is 30 ft, which is equal to the 41 ft contract pile length minus the pile height above streambed and embedment length in the concrete cap.

The prestressed concrete pile will penetrate 23 ft of non-cohesive soil below the streambed:

% non-cohesive soil = [23/30] (100) = 77% > 70%

Therefore, the generalized soil category for pile driving (construction stage) is also "non-cohesive." Note it is possible for piles for a substructure to have different soil categories during the design and construction stages.

For driven prestressed concrete pile with WEAP analysis construction control and no planned retap, the following resistance factor, φ_{TAR}, is recommended to estimate the target pile nominal driving resistance for non-cohesive soil (Appendix C, Table C.3).

φ_{TAR} = 0.55 for non-cohesive soil, averaged over the full depth of estimated pile penetration

$$R_{ndr-T} = \frac{\sum \eta\gamma Q + \gamma_{DD} DD}{\varphi_{TAR}} + R_{SCOUR}$$

$$= \frac{102 + 0}{0.55} + 13.4$$

$$= 185.5 + 13.4 = 198.9 \text{ kips/pile}$$

where

R_{SCOUR} = 13.4 kips (Step 4)

Step 9 – Prepare CADD notes for bridge plans

At this point, the final design engineer selects the appropriate CADD notes and adds the specific pile values to the notes.

Pier piles design note

THE CONTRACT LENGTH OF 41 FEET FOR THE PIER PILES IS BASED ON A NON-COHESIVE SOIL CLASSIFICATION, A TOTAL FACTORED AXIAL LOAD PER PILE (P_U) OF 102 KIPS, AND A GEOTECHNICAL RESISTANCE FACTOR (PHI) OF 0.55 FOR SOIL.

THE NOMINAL AXIAL BEARING RESISTANCE FOR CONSTRUCTION CONTROL WAS DETERMINED FROM A NON-COHESIVE SOIL CLASSIFICATION AND A GEOTECHNICAL RESISTANCE FACTOR (PHI) OF 0.55 FOR SOIL.

Pier piles driving note

> THE REQUIRED NOMINAL AXIAL BEARING RESISTANCE FOR PIER PILES IS 100 TONS AT END OF DRIVE (EOD). THE PILE CONTRACT LENGTH SHALL BE DRIVEN AS PER PLAN UNLESS PILES REACH REFUSAL. IN NO CASE SHALL A PILE BE EMBEDDED LESS THAN 27 FEET BELOW THE STREAMBED. CONSTRUCTION CONTROL REQUIRES A WEAP ANALYSIS AND BEARING GRAPH.

Step 10 – Check the design

Within the Iowa DOT Office of Bridges and Structures, a final design engineer other than the bridge designer is assigned to give the bridge design an independent check when final plans are complete. During the checking process, the final design engineer reviews the soils package to ensure all recommendations were followed and also checks structural, geotechnical, and drivability aspects of the design.

For this example, only the structural and geotechnical aspects would be checked because pile driving stresses will be relatively low. (For simplicity, the structural design was not shown in this example.)

Other design organizations may perform checks at various stages of design rather than upon plan completion.

-----------------------END DESIGN AND BEGIN CONSTRUCTION PHASE---------------------

Step 11 – Prepare bearing graph

After the bridge contract is let and prior to start of pile driving, the contractor completes Hammer Data sheets for use of the planned pile driving hammer. The Hammer Data sheets include all pertinent information including the cap (helmet) number and hammer identification information with details, hammer cushion, and pile cushion (where required), as well as pile size, pile length, and estimated pile driving resistance.

The Office of Construction uses the data received to complete a WEAP analysis for construction control during pile driving. Results from the WEAP analysis are then used to prepare an LRFD Driving Graph (without the factor of safety used for allowable stress design). The Driving Graph includes curves of nominal driving resistance versus blows per ft and identifies specific driving conditions where driving stress is a concern.

Step 12 – Observe construction, record driven resistance, and resolve any construction issues

Usually, if the recorded pile driving resistance at EOD is less than the target pile nominal driving resistance, the pile is retapped about 24 hours after EOD. (The retap is a remedial measure that makes use of setup for an individual pile. If the 24 hour retap does not indicate sufficient driven resistance, an extension will be added the same day rather than wait to retap another day.)

In this example it is unlikely that there would be a significant amount of setup because of the non-cohesive soil, and extensions would be required if the driving resistance did not meet the target driving resistance.

CHAPTER 4. TRACK 2 EXAMPLES FOR LRFD USING THE MODIFIED IOWA ENR FORMULA

Track 2 demonstrates the application of the LRFD approach using the modified Iowa ENR formula as the construction control method. As briefly described in Chapter 2, two examples are presented in this chapter.

The design of steel H-piles installed in cohesive soil is illustrated in Example 1, while the design of timber piles is illustrated in Example 2. Only pile designs at integral abutment are presented.

Example 1 was prepared based on the outcomes of the three previous LRFD research projects (Roling et al. 2000, Ng et al. 2011, AbdelSalam et al. 2012a). Example 2 was provided by the Iowa DOT as a supplemental design example.

4.1. Track 2 Example 1: Driven H-Pile in Cohesive Soil with Construction Control Based on Modified Iowa ENR Formula and No Planned Retap

Table 4.1. Track 2 Example 1: Design and construction steps

Design Step	
1	Develop bridge situation plan (TS&L)*
2	Develop soils package, including soil borings and foundation recommendations*
3	Determine pile arrangement, pile loads, and other design requirements*
4	Estimate the nominal geotechnical resistance per foot of pile embedment
5	Select a resistance factor to estimate pile length based on the soil profile and construction control
6	Calculate the required nominal pile resistance, R_n
7	Estimate contract pile length, L
8	Estimate target nominal pile driving resistance, $R_{ndr\text{-}T}$
9	Prepare CADD notes for bridge plans
10	Check the design depending on bridge project and office practice
Construction Step	
11	Request and check contractor’s hammer data
12	Observe construction, record driven resistance, and resolve any construction issues

* These steps determine the basic information for geotechnical pile design and vary depending on bridge project and office practice

Within the Iowa DOT Office of Bridges and Structures, the design steps that determine the basic information necessary for geotechnical design of a steel H-pile generally follow Steps 1 through 3 as indicated in Track 1 Example 1.

Because Track 2 will not be used by the Iowa DOT, this example simply gives the basic information for the geotechnical design. This information would be determined in various ways depending on the bridge owner (county or city) and any involved engineering consultants.

The process generally should not affect the overall geotechnical design of the pile. Because counties and cities typically follow state standards, this example contains references to the Bridge Design Manual (BDM).

Step 1 – Develop bridge situation plan (or TS&L)

An engineer involved in the bridge project plots topographical information, locates the bridge, determines general type of superstructure, location of substructure units, elevations of foundations, hydraulic information (if needed), and other basic information to characterize the bridge. The engineer then prepares the TS&L sheet that shows a plan and longitudinal section of the bridge.

For this example, the TS&L gives the following information needed for design of abutment piles:

- 120 ft single span, prestressed concrete beam superstructure
- Zero skew
- Integral abutments
- Pile foundations, no prebored holes (because the bridge length is less than 130 ft) (BDM 6.5.1.1.1)
- Bottom of abutment footing elevation 433 ft

Step 2 – Develop soils information, including soil borings and foundation recommendations

Based on location of the abutments, an engineer involved in the bridge project orders soil borings (typically at least one per substructure unit). Upon receipt of the boring logs, the engineer arranges for them to be plotted on a longitudinal section, checks any special geotechnical conditions on the site, and develops recommendations for foundation type with any applicable special design considerations.

For this example, the recommendations are as follows:

- Friction piles that tip out in the firm glacial clay layer
- Steel H-piles for the integral abutments
- Structural Resistance Level – 1 (which does not require a driving analysis during design (BDM 6.2.6.1))
- Normal driving resistance (This will lead to $\varphi_c = 0.6$ for the structural check, which needs to be performed, but is not included in this geotechnical example.)
- No special site considerations for stability, settlement, or lateral movement (Therefore, the Service I load will not be required for design.)
- Construction control based on the modified Iowa ENR formula (modified to remove factor of safety) with no planned retap

The soil profile shown in Figure 4.1 includes the soil boring at the west abutment. Generally, below the bottom of footing elevation there are three layers: 6 ft of soft silty clay, 9 ft of silty sand, and firm glacial clay to the bottom of the boring at 95 ft. Layer 3 is subdivided at a depth of 30 ft because nominal friction resistance step-increases at that elevation. No groundwater was encountered in the boring.

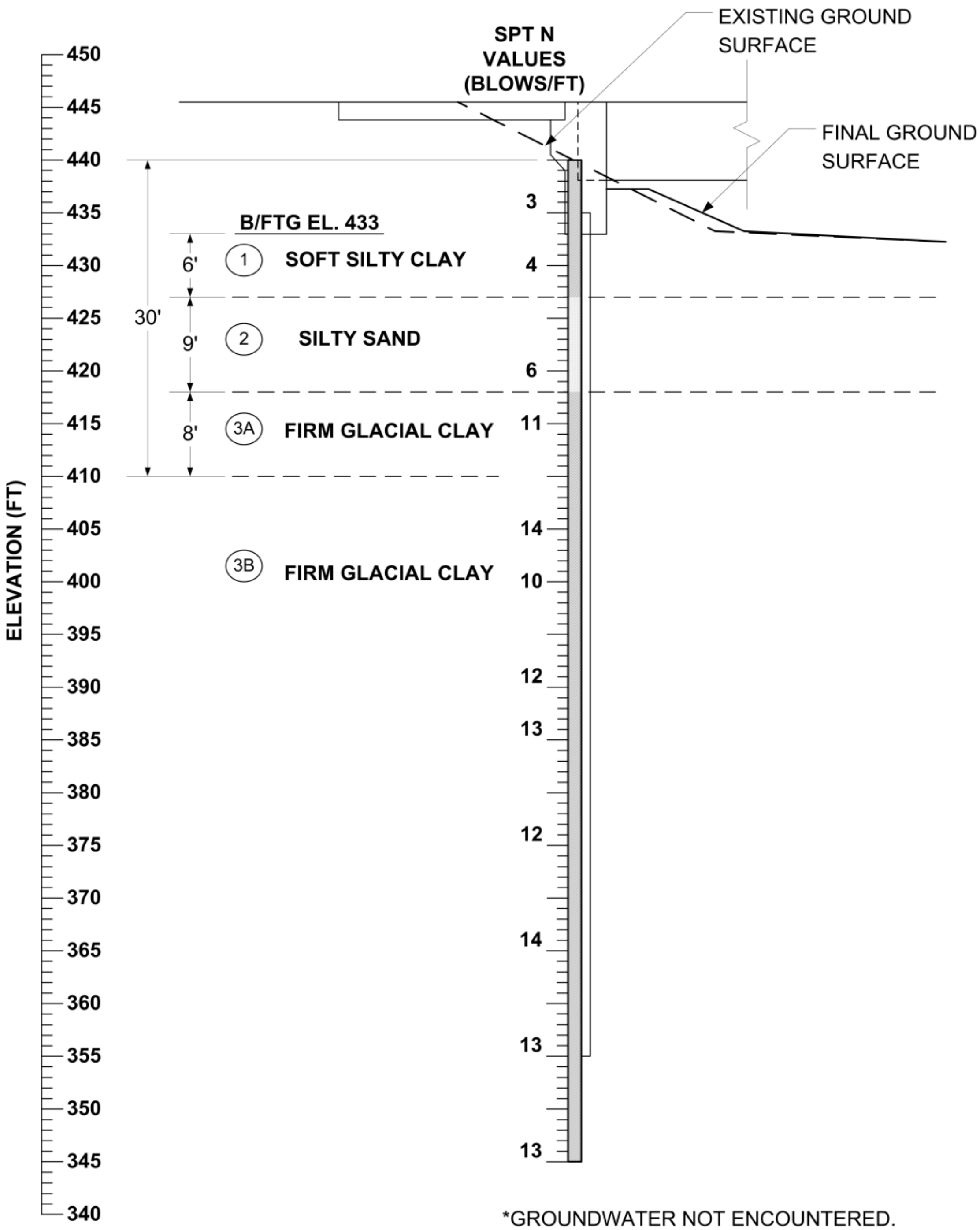


Figure 4.1. Track 2 Example 1: Soil profile

Step 3 – Determine pile arrangement, pile loads, and other design requirements

An engineer involved in the bridge project begins design of the abutment piles with the TS&L, boring logs, and foundation recommendations. Because the bridge has a prestressed concrete beam superstructure and integral abutments, the engineer selects HP 10×57 piles, following Bridge Design Manual policy (BDM 6.5.1.1.1).

Based on total Strength I abutment load and the Bridge Design Manual policy for pile spacing and number of piles (BDM 6.5.4.1.1), the engineer determines the following:

- Seven HP 10×57 piles plus two wing extension piles, Nos. 1 and 9, as shown in Figure 4.2, that support the wings only
- Strength I load per pile = 128 kips
- No uplift, downdrag, or scour
- Construction control based on the modified Iowa ENR formula (modified to remove factor of safety) with no planned retap

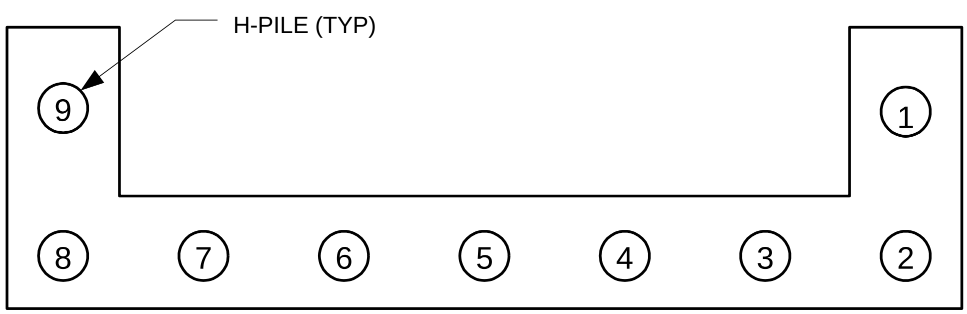


Figure 4.2. Track 2 Example 1: Pile arrangement at an abutment

Because the bridge characteristics fall within integral abutment policy, the site has no unusual characteristics, construction will not be accelerated or delayed, and there will be no need for lateral load or special analysis of the abutment piles. The piles may be simply designed for vertical load.

Step 4 – Estimate the nominal geotechnical resistance per foot of pile embedment

Based on the west abutment soil boring and BDM Table 6.2.7, the engineer estimates the unit nominal resistances for friction bearing as shown in Table 4.2.

Table 4.2. Track 2 Example 1: Estimated nominal geotechnical resistance

<table>
<tr><th>Soil Stratum</th><th colspan="2">Soil Description</th><th>Stratum Thickness (ft)</th><th>Average SPT N Value (blows/ft)</th><th>Estimated Unit Nominal Resistance for Friction Pile (kips/ft)</th></tr>
<tr><td>1</td><td colspan="2">Soft Silty Clay</td><td>6</td><td>4</td><td>0.8</td></tr>
<tr><td>2</td><td colspan="2">Silty Sand</td><td>9</td><td>6</td><td>1.2</td></tr>
<tr><td>3A</td><td rowspan="2">Firm Glacial Clay</td><td>within 30 ft of natural ground elevation</td><td>8</td><td>11</td><td>2.8</td></tr>
<tr><td>3B</td><td>more than 30 ft below natural ground elevation</td><td>65</td><td>12</td><td>3.2</td></tr>
</table>

The firm glacial clay stratum has been divided into two parts to delineate the embedded pile length that is within 30 ft of the natural ground surface as noted in the BDM geotechnical resistance chart as shown in Table 4.3. Application of the chart to estimate the nominal resistance values is illustrated in the table. Note that the SPT N values are too small for use of end bearing in Layer 3B.

Table 4.3. Track 2 Example 2: BDM geotechnical resistance chart

SOIL DESCRIPTION	BLOW COUNT N-VALUE		ESTIMATED NOMINAL RESISTANCE VALUES FOR FRICTION PILE IN KIPS PER FOOT										
			WOOD	STEEL "H"			PRESTRESSED			STEEL PIPE			
	MEAN	RANGE	PILE	10	12	14	12	14	16	10	12	14	18
Alluvium or Loess													
Very soft silty clay	1	0 - 1	0.8	0.4	0.8	0.8	0.8	0.8	0.8	0.4	0.4	0.4	0.8
Soft silty clay	3	2 - 4	1.2	0.8	1.2	1.2	0.8	0.8	0.8	0.8	0.8	0.8	1.2
Stiff silty clay	6	4 - 8	1.6	1.2	1.6	2.0	1.2	1.6	2.0	1.2	1.2	1.6	2.0
Firm silty clay	11	7 - 15	2.4	2.0	2.4	2.8	2.4	2.8	3.2	1.6	2.0	2.4	2.8
Stiff silt	6	3 - 7	1.6	1.2	1.6	1.6	1.6	1.6	1.6	1.2	1.2	1.6	1.6
Stiff sandy silt	6	4 - 8	1.6	1.2	1.6	1.6	1.6	1.6	1.6	1.2	1.2	1.6	1.6
Stiff sandy clay	6	4 - 8	1.6	1.2	1.6	2.0	2.0	2.0	2.4	1.2	1.6	1.6	2.0
Silty sand	8	3 - 13	1.2	1.2	1.2	1.6	1.6	1.6	1.6	0.8	0.8	1.2	1.6
Clayey sand	13	6 - 20	2.0	1.6	2.0	2.8	2.4	2.4	2.8	1.6	2.0	2.4	2.8
Fine sand	15	8 - 22	2.4	2.0	2.4	2.8	2.4	2.8	3.2	1.6	2.0	2.4	2.8
Coarse sand	20	12 - 28	3.2	2.8	3.2	3.6	3.2	3.6	4.0	2.0	2.4	2.8	3.6
Gravelly sand	21	11 - 31	3.2	2.8	3.2	3.6	3.6	3.6	4.0	2.0	2.4	2.8	3.6
Granular material	> 40	---	(2)	4.0	4.8	5.6	(2)	(2)	(2)	(2)	(2)	(2)	(2)
Glacial Clay													
Firm silty glacial clay	11	7 - 15	2.8	2.4	2.8	3.2	2.8	3.2	3.6	2.0	2.4	2.4	3.2
Firm clay (gumbotil)	12	9 - 15	2.8	2.4	2.8	3.2	2.8	3.2	3.6	2.0	2.4	2.4	3.2
Firm glacial clay (1)	11	7 - 15	2.4 [3.2]	2.8 [3.2]	3.2 [4.0]	3.6 [4.4]	3.2 [4.0]	3.6 [4.4	4.0 [4.8]	2.0 [2.4]	2.4 [2.8]	2.8 [3.2]	3.6 [4.4]
Firm sandy glacial clay (1)	13	9 - 15	2.4 [3.2]	2.8 [3.2]	3.2 [4.0]	3.6 [4.4]	3.2 [4.0]	3.6 [4.4	4.0 [4.8]	2.0 [2.4]	2.4 [2.8]	2.8 [3.2]	3.6 [4.4]
Firm - very firm glacial clay (1)	14	11 - 17	2.8 [3.6]	2.8 [4.0]	3.2 [4.8]	3.6 [5.6]	4.0 [4.8]	4.4 [5.2	4.8 [5.6]	2.4 [3.2]	2.8 [3.6]	3.2 [4.0]	4.0 [5.2]
Very firm glacial clay (1)	24	17 - 30	2.8 [3.6]	2.8 [4.0]	3.2 [4.8]	3.6 [5.6]	3.2 (3) [4.8]	3.6 (3) [5.6]	4.4 (3) [6.4]	2.4 [3.2]	2.8 [3.6]	3.2 [4.0]	4.0 [5.2]
Very firm sandy glacial clay (1)	25	15 - 30	3.2 [4.0]	2.8 [4.0]	3.2 [4.8]	3.6 [5.6]	3.2 (3) [4.8]	3.6 (3) [5.6]	4.4 (3) [6.4]	2.4 [3.2]	2.8 [3.6]	3.2 [4.0]	4.0 [5.2]
Cohesive or glacial material (1)	> 35	---	(2)	2.8 [4.0]	3.2 [4.8]	3.6 [5.6]	(2)	(2)	(2)	2.0 (4) [3.2]	2.4 (4) [4.0]	2.8 (4) [4.4]	3.6 (4) [5.6]

Table notes:

(1) **For double entries the upper value is for an embedded pile within 30 feet of the natural ground elevation, and the lower value [ ] is for pile depths more than 30 feet below the natural ground elevation.**

(2) Do not consider use of this pile type for this soil condition, wood with N > 25, prestressed concrete with N > 35, or steel pipe with N > 40.

(3) Prestressed concrete piles have proven to be difficult to drive in these soils. Prestressed piles should not be driven in glacial clay with consistent N > 30 to 35.

(4) Steel pipe piles should not be driven in soils with consistent N > 40.

Step 5 – Select a resistance factor to estimate pile length based on the soil profile and construction control

In this step, the engineer first characterizes the site as cohesive, mixed, or non-cohesive based on Table 4.4 and the soil profile.

Table 4.4. Track 2 Example 1: Soil classification table

Generalized Soil Category	**Soil Classification Method**			
	AASHTO	**USDA Textural**	**BDM 6.2.7 Geotechnical Resistance Chart**	
Cohesive	A-4, A-5, A-6, and A-7	Clay Silty clay Silty clay loam Silt Clay loam Silt loam Loam Sandy clay	Loess	Very soft silty clay
				Soft silty clay
				Stiff silty clay
				Firm silty clay
				Stiff silt
				Stiff sandy clay
			Glacial Clay	Firm silty glacial clay
				Firm clay (gumbotil)
				Firm glacial clay
				Firm sandy glacial clay
				Firm-very firm glacial clay
				Very firm glacial clay
				Very firm sandy glacial clay
				Cohesive or glacial material
Non-Cohesive	A-1, A-2, and A-3	Sandy clay loam Sandy loam Loamy sand Sand	Alluvium Or Loess	Stiff sandy silt
				Silty sand
				Clayey sand
				Fine sand
				Coarse sand
				Gravely sand
				Granular material (N>40)

Only the 9 ft Layer two of silty sand is classified as non-cohesive. The remainder of the profile is classified as cohesive, and most likely will represent more than 70 percent of the pile embedment length. Thus, the soil is expected to fit the cohesive classification, and the resistance factor is selected from the choices below as 0.60.

φ = 0.60 for cohesive soil, averaged over the full depth of estimated pile penetration
φ = 0.60 for mixed soil, averaged over the full depth of estimated pile penetration
φ = 0.50 for non-cohesive soil, averaged over the full depth of estimated pile penetration

Step 6 – Calculate the required nominal pile resistance, R_n

The required nominal pile resistance is as follows:

$$R_n = \frac{\sum \eta\gamma Q + \gamma_{DD} DD}{\varphi} = \frac{128 + 0}{0.60} = 213 \text{ kips/pile}$$

where

$\sum\eta\gamma Q = \gamma Q = 128$ kips (Step 3)

$\gamma_{DD}DD = 0$ (no downdrag)

$\varphi = 0.60$ (Step 5)

Step 7 – Estimate contract pile length, L

Based on the nominal resistance values in Step 4, the cumulative nominal geotechnical resistance, $R_{n\text{-}BB}$, per pile is calculated as follows, where D = depth in feet below the bottom of footing:

$D_0 = 0$ ft, $R_{n\text{-}BB0} = 0$

$D_1 = 6$ ft, $R_{n\text{-}BB1} = R_{n\text{-}BB0} + (0.8 \text{ kips/ft})(6 \text{ ft}) = 4.8$ kips

$D_2 = 6 + 9 = 15$ ft, $R_{n\text{-}BB2} = R_{n\text{-}BB1} + (1.2 \text{ kips/ft})(9 \text{ ft}) = 4.8 + 10.8 = 15.6$ kips

$D_3 = 15 + 8 = 23$ ft, $R_{n\text{-}BB3} = R_{n\text{-}BB2} + (2.8 \text{ kips/ft})(8 \text{ ft}) = 15.6 + 22.4 = 38.0$ kips

Additional depth required = (213 – 38.0)/3.2 = 55 ft

$D_4 = 23 + 55 = 78$ ft, $R_{n\text{-}BB4} = R_{n\text{-}BB3} + (3.2 \text{ kips/ft})(55 \text{ ft}) = 38.0 + 176.0$

$= 214.0$ kips > 213 kips

The contract pile length includes a 2 ft embedment in the footing and a 1 ft allowance for cutoff due to driving damage:

L = 78 + 2 + 1 = 81 ft

The length for steel H-piles is specified in 5 ft increments (BDM 6.2.4.1). Therefore, the contract pile length is 80 ft.

At this point, the embedded pile length is known and it is necessary to check the site classification for the resistance factor:

% cohesive soil = [(77-9)/77] (100) = 88% > 70%

Therefore, $\varphi = 0.60$ is confirmed for estimating the contract pile length. If the resistance factor were incorrect, the engineer would need to repeat Steps 6 and 7 (although, in this example, the mixed soil classification would not result in numeric changes).

Step 8 – Estimate target nominal pile driving resistance, $R_{ndr\text{-}T}$

The complete embedment length below the bottom of footing will contribute to pile driving resistance. In addition to the required embedment length to achieve the nominal pile resistance, driving resistance would need to be added if part of the embedment length had been ignored to account for downdrag load or scour.

Given there was no need to make allowance for downdrag load or scour in this example, the pile embedment length below bottom of footing will be the same as that considered to estimate the required nominal pile resistance, $R_{n\text{-}D}$.

The soil embedment length is 77 ft, which is equal to the 80 ft contract pile length minus the 2 ft of embedment length in the concrete footing and 1 ft cutoff.

For a driven H-pile with construction control based on the modified Iowa ENR formula at EOD and no planned retap, the following resistance factor, φ, is recommended to estimate the target nominal pile driving resistance for cohesive soil:

$\varphi_{TAR} = 0.55$ for cohesive soil, averaged over the full depth of estimated pile penetration

The target pile driving resistance at EOD can be calculated as follows:

$$R_{ndr-T} = \frac{\sum \gamma Q + \gamma_{DD} DD}{\varphi_{TAR}} = \frac{128 + 0}{0.55} = 233 \text{ kips/pile} = 117 \text{ tons/pile}$$

The average SPT N-value of 11 yields a Setup Ratio, F_{SETUP}, of 1.47 for 1 day retap, 1.55 for 3 day retap, and 1.61 for 7 day retap from the graph in Figure 4.3.

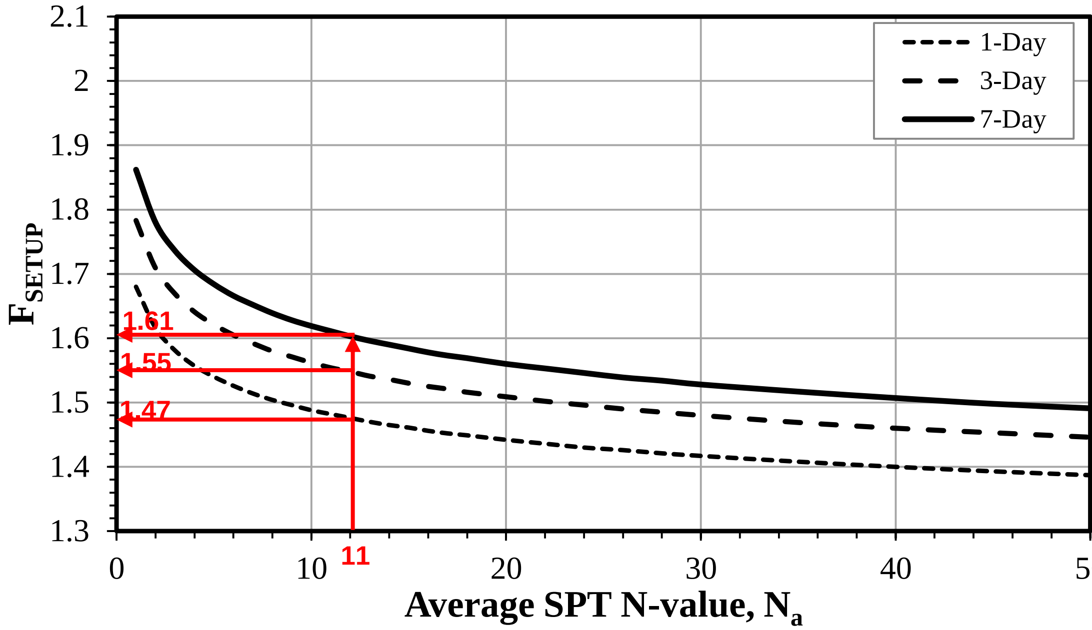


Figure 4.3. Track 2 Example 1: Pile setup factor chart

The target nominal geotechnical resistance at 1 day retap, then, is as follows:

$R_{1\text{-day}}$ = (233.0)(1.47) = 342.5 kips = 171 tons

The target nominal geotechnical resistance at 3 day retap, then, is as follows:

$R_{3\text{-day}}$ = (233.0)(1.55) = 361.2 kips = 181 tons

The target nominal geotechnical resistance at 7 day retap, then, is as follows:

$R_{7\text{-day}}$ = (233.0)(1.61) = 375.1 kips = 188 tons

Note that construction control involving the modified Iowa ENR formula will require an increase in the target nominal driving resistance, $R_{ndr\text{-}T}$, over that required when a WEAP analysis is used for construction control.

The target pile driving resistance at EOD here needed to be increased from 166 kips/pile for WEAP analysis (Track 1 Example 1) to 233 kips/pile due to a reduction in the statistical reliability of the construction control.

Step 9 – Prepare CADD notes for bridge plans

At this point, the final design engineer selects the appropriate CADD notes and adds the specific pile load values to the notes.

Abutment piles design note

THE CONTRACT LENGTH OF 80 FEET FOR THE WEST ABUTMENT PILES IS BASED ON A COHESIVE SOIL CLASSIFICATION, A TOTAL FACTORED AXIAL LOAD PER PILE (P_U) OF 128 KIPS, AND A GEOTECHNICAL RESISTANCE FACTOR (PHI) OF 0.60.

THE NOMINAL AXIAL BEARING RESISTANCE FOR CONSTRUCTION CONTROL WAS DETERMINED FROM A COHESIVE SOIL CLASSIFICATION AND A GEOTECHNICAL RESISTANCE FACTOR (PHI) OF 0.55.

Abutment piles driving note

THE REQUIRED NOMINAL AXIAL BEARING RESISTANCE FOR WEST ABUTMENT PILES IS 117 TONS AT END OF DRIVE (EOD). IF RETAPS ARE NECESSARY TO ACHIEVE BEARING, THE REQUIRED NOMINAL AXIAL BEARING RESISTANCE IS 171 TONS AT ONE-DAY RETAP, 181 TONS AT THREE-DAY RETAP, OR 188 TONS AT SEVEN-DAY RETAP. THE PILE CONTRACT LENGTH SHALL BE DRIVEN AS PER PLAN UNLESS PILES REACH REFUSAL. CONSTRUCTION CONTROL REQUIRES A MODIFIED IOWA DOT FORMULA.

Step 10 – Check the design

Policies for performing checks during design and after completion of design will vary among counties, cities, and engineering consultants.

-----------------------END DESIGN AND BEGIN CONSTRUCTION PHASE---------------------

Step 11 – Request and check contractor's hammer data

The contractor requested the engineer's approval for a DELMAG D19-42 single-acting diesel hammer to install the HP10×57 friction piles and supplied the following manufacturer's information.

DELMAG D19-42

Minimum rated energy = 22,721 ft-lbs (setting 1)
Maximum rated energy = 31,715 ft-lbs (setting 2)
Maximum rated energy = 37,868 ft-lbs (setting 3)
Maximum rated energy = 47,335 ft-lbs (setting 4)
Maximum obtainable stroke = 12.5 feet
Ram weight = 4,189 lbs = 2.095 tons
Drive anvil (cap) weight = 749 lbs = 0.375 tons
Hammer weight (including trip device) = 8,400 lbs
Hammer operating efficiency = 80 percent

Based on the Iowa DOT *Standard Specifications for Highway and Bridge Construction, Series 2009,* Appendix Table 2501.03-1, the minimum energy required for diesel hammers with 66 to 90 ft long HP10×57 piling is 29,000 ft-lbs; the maximum energy allowed for diesel hammers is 40,000 ft-lbs for up to 65 ft long piles. Based on this information, the DELMAG D19-42 hammer was accepted, provided that the hammer was operated at fuel settings 2 or 3 (not 1 or 4).

Step 12 – Observe construction, record driven resistance, and resolve any construction issues

At EOD at the contract plan length, the construction inspector records the hammer stroke and number of blows per ft of pile penetration. This information is used with the following modified Iowa ENR formula to estimate driving resistance. The formula in *Standard Specifications for Highway and Bridge Construction, Series 2009,* Article 2501.03, M, 2, a, has been modified below to remove the factor of safety so that the formula indicates nominal resistance.

$$R_{ndr} = \frac{12E}{S + 0.1} \times \frac{W}{W + M}$$

where

R_{ndr} = nominal pile driving resistance, in tons

W = weight of ram, in tons (unless the hammer has free fall, hammer efficiency should be considered in the value of "W")

M = weight of pile, drive cap (helmet, cushion, striker plate, and pile inserts if used), drive anvil, and follower (if applicable), in tons

E = W x H = energy per blow, in ft-tons

H = Hammer stroke, in ft

S = average pile penetration in inches per blow for the last 10 blows

12 = conversion factor for ft to in.

For example, at EOD for the planned pile embedment length at Pile 1 in the Log of Piling Driven shown in Figure 4.4, the construction inspector recorded a hammer stroke of 7.5 ft and a blow count of 31 blows/ft for the last foot of pile penetration.

Form 830210 9/06

Iowa Department of Transportation

LOG OF PILING DRIVEN BY FORMULA

Project No. Anybody's Guess

County Someplace in Iowa

Design No. 389

Contractor Somebody Construction Co.

Iowa DOT Hammer No. XXXX

Gross Weight of Hammer ________ **Effective Wt.** ________

Weight of Driving Parts 4189 pounds

Weight of Anvil 749 pounds

Weight of Cap 1,190 pounds **Cap No.** XXX

Weight of Pile 4,560 pounds

Plan Pile Length 80 feet

Pile (Type and Size) HP 10x57
(Wood, Steel or Concrete)

Hammer (Type & Model) Delmag D19-42
(Gravity or Diesel manufacturer and model)

Foundation Description West Abutment
(North abut, Pier 1, etc.)

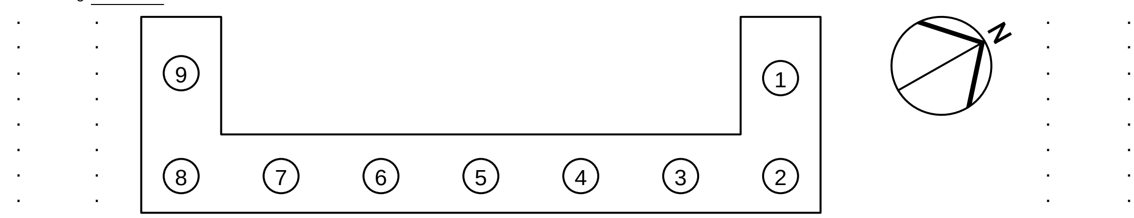
Station of Foundation C.L. 447+00

Formula Used Iowa Modified ENR Formula

Nominal Driving Resistance 117 Tons at EOD, 140 tons at 1-day retap

Sketch foundation below, number each pile and show steel H-pile orientation as installed. Note battered piles on sketch,and give the amount of batter. Place name and certificate number of welder below if welding was necessary. Forward 2 copies to the Iowa DOT District Office upon completion of each foundation. Note on drawing which pile has been logged.

Batter Piling ________ in the direction shown.



Pile No.	Date Driven	(1) Plan Length (ft.)	Length Cutoff (0.0 ft.)	(2) Average Penetration Last Blows (inches)	Ram Rise (ft.)	Driven Resistance (Tons)	RETAP (3) Date	RETAP (3) Ram Rise (ft.)	RETAP (3) (2) Ave. Penetration Last Blows (inches)	RETAP (3) Driven Resistance (Tons)	PILE EXTENSIONS (4) Length Added (0.0 ft.)	PILE EXTENSIONS (4) Length Cutoff (0.0 ft.)	PILE EXTENSIONS (4) Ram Rise (ft.)	PILE EXTENSIONS (4) (2) Ave. Penetration Last Blows (inches)	PILE EXTENSIONS (4) Driven Resistance (Tons)	Welds (Count)
1	X-XX-XX	80	0.0	0.34	7.5	121										
2	X-XX-XX	80	5.0	0.35	8.0	126										
3	X-XX-XX	80	1.5	0.40	8.5	120										
4	X-XX-XX	80	3.5	0.34	7.5	121										
5	X-XX-XX	80	2.5	0.34	7.5	121										
6	X-XX-XX	80	0.0	0.36	8.0	123										
7	X-XX-XX	80	4.5	0.40	8.5	120										
8	X-XX-XX	80	0.0	0.39	7.5	108	X-XX-XX	8	0.20	188						
9	X-XX-XX	80	0.0	0.41	9.0	125										
---	---	---	---	---	---	---										

(1) Record in the Remarks section below if the pile length is anything other than the plan length at the beginning of drive.
(2) For gravity hammers, enter the penetration in the last 5 blows divided by 5. For steam or diesel hammers, enter the penetration in the last 10 blows divided by 10.
(3) Indicate date of retap in date column (1 day delay min.). List only pile actually checked.
(4) Additional pile length to be authorized by the Engineer.

Total Welds: ________

Plan Length: 720.0 Feet
Extensions: 0.0 Feet
Total: 720.0 Feet

Welders Name: ________ Lab No.: ________ Exp. Date: ________

Remarks: ________

Inspector ________ Date ________ Project Engineer ________

Figure 4.4. Track 2 Example 1: Pile driving log

The construction inspector used the formula to calculate a driving resistance of 119 tons as indicated below, which is greater than the target driving resistance of 117 tons.

$W = 4189 \times 0.8 / 2000 = 1.68$ tons (for 80% hammer efficiency)

For a D19-42 to drive HP10× piles:

Drive anvil weight = 749 lbs

Striker plate weight = 440 lbs

Helmet weight = 750 lbs

$M = [(75 \times 57) + 749 + 440 + 750] = 6{,}214$ lbs $= 3.11$ tons

$S = (1/31)$ (12 in/ft) $= 0.39$ in./blow

$$R_{ndr} = \frac{12WH}{S+0.1} \times \frac{W}{W+M} = \frac{(12)(1.68)(7.5)}{(0.39+0.1)} \times \frac{(1.68)}{(1.68+3.11)} = \frac{151.2}{0.49}(0.35)$$

$R_{ndr} = 108$ tons

Pile 8 in the pile log illustrates the use of pile retaps. At EOD at Pile 8, a driving resistance of 108 tons was recorded, which is less than the target nominal driving resistance of 117 tons. A 24 hour retap was scheduled and, due to setup in cohesive soil, a 20 percent setup gain was considered to compute target 1 day retap resistance at 171 tons.

Twenty-four hours after EOD, Pile 8 was retapped. The pile driving hammer was warmed up with 20 blows on another pile and, after two blows on Pile 8 to set the cap, Pile 8 was driven 10 blows with a pile penetration of 2 in. and a stroke of 8 ft. The pile retap resulted in a retap driving resistance of 188 tons, which exceeds the one-day target retap resistance of 171 tons.

$S = (3/10) = 0.3$ in./blow

$$R_{ndr} = \frac{12WH}{S+0.1} \times \frac{W}{W+M} = \frac{(12)(1.68)(8.0)}{(0.2+0.1)} \times \frac{(1.68)}{(1.68+3.11)} = \frac{161.3}{0.30}(0.35)$$

$R_{ndr} = 188$ tons

4.2. Track 2 Example 2: Driven Timber Pile in Non-Cohesive Soil with Construction Control Based on Modified Iowa ENR Formula and No Planned Retap (prepared by Iowa DOT)

Table 4.5. Track 2 Example 2: Design and construction steps

Design Step	
1	Develop bridge situation plan (TS&L)*
2	Develop soils package, including soil borings and foundation recommendations*
3	Determine pile arrangement, pile loads, and other design requirements*
4	Estimate the nominal geotechnical resistance per foot of pile embedment
5	Select a resistance factor to estimate pile length based on the soil profile and construction control
6	Calculate the required nominal pile resistance, R_n
7	Estimate contract pile length, L
8	Estimate target nominal pile driving resistance, $R_{ndr\text{-}T}$
9	Prepare CADD notes for bridge plans
10	Check the design depending on bridge project and office practice
Construction Step	
11	Request and check contractor's hammer data
12	Observe construction, record driven resistance, and resolve any construction issues

* These steps determine the basic information for geotechnical pile design and vary depending on bridge project and office practice

Because Track 2 will not be used by the Iowa DOT (due to construction control by WEAP rather than the Modified Iowa DOT ENR formula), this example simply gives the basic information for the geotechnical design. The information would be determined in various ways depending on the bridge owner (county or city) and any involved engineering consultants. The process generally should not affect the overall geotechnical design of the pile. Because counties and cities typically follow state standards, this example contains references to the Bridge Design Manual (BDM).

Step 1 – Develop bridge situation plan (or TS&L)

An engineer involved in the bridge project plots topographical information, locates the bridge, determines general type of superstructure, location of substructure units, elevations of foundations, hydraulic information (if needed), and other basic information to characterize the bridge. The engineer then prepares the TS&L sheet that shows a plan and longitudinal section of the bridge.

For this example, the TS&L gives the following information needed for design of the west abutment piles:

- 120 ft, three-span continuous concrete slab superstructure
- 25-degree skew

- Integral abutments
- Pile foundation, no prebored holes (because the bridge length is less than 130 ft and there is no significant downdrag) (BDM 6.5.1.1.1)
- Bottom of abutment footing elevation 922 ft

Step 2 – Develop soils information, including soil borings and foundation recommendations

Based on location of the abutments, an engineer involved in the bridge project orders soil borings (typically at least one per substructure unit). Upon receipt of the boring logs, the engineer arranges for them to be plotted on a longitudinal section, checks any special geotechnical conditions on the site, and develops recommendations for foundation type with any applicable special design considerations.

Subsurface conditions at the abutment have been characterized based on a representative test boring. From the 922 ft elevation, the abutment is underlain by 5 ft of soft to stiff silty clay (N_a = 4), 20 ft of fine sand (N_a = 16), 40 ft of medium sand (N_a = 20), and bouldery gravel and hard shale.

For this example, the recommendations are as follows:

- Timber piles that tip out in the medium sand layer
- No significant downdrag
- Normal driving resistance
- No special site considerations for stability, settlement, or lateral movement (Therefore, a Service I load will not be required for design.)
- Construction control based on the modified Iowa ENR formula (modified to remove factor of safety) with no planned retap

Step 3 – Determine pile arrangement, pile loads, and other design requirements

An engineer involved in the bridge project begins design of the west abutment piles with the TS&L, boring logs, and foundation recommendations.

Based on total Strength I abutment load and the Bridge Design Manual policy for pile spacing and number of piles (BDM 6.5.4.1.1), the engineer determines the following:

- 12 timber piles
- Strength I factored load per pile = 54 kips (The office has a nominal axial structural resistance limit of 64 kips for timber integral abutment piles (BDM 6.2.6.3). The AASHTO LRFD resistance factor for compression parallel to grain is 0.90 (AASHTO LRFD 8.5.2.2). Thus, the maximum Strength I factored load per pile is φP_n = (0.9)(64) = 57.6 kips. Therefore, the 54-kip Strength I load is acceptable structurally because it is less than the maximum permissible factored timber pile resistance.)

- No uplift, downdrag, or scour
- Construction control based on the modified Iowa ENR formula (modified to remove factor of safety) with no planned retap

Because the bridge characteristics fall within integral abutment policy, the site has no unusual characteristics, construction will not be accelerated or delayed, and there will be no need for lateral load or special analysis of the abutment piles. The piles may be simply designed for vertical load.

Step 4 – Estimate the nominal geotechnical resistance per foot of pile embedment

Based on the west abutment soil boring and BDM Table 6.2.7, the engineer estimates the unit nominal resistances for friction bearing as shown in Table 4.6.

Table 4.6. Track 2 Example 2: Estimated nominal geotechnical resistance

Soil Stratum	Soil Description	Stratum Thickness (ft)	Average SPT N Value (blows/ft)	Estimated Unit Nominal Resistance for Friction Pile* (kips/ft)**	Cumulative Nominal Friction Resistance at Bottom of Stratum (kips)**	Estimated Nominal Resistance for End Bearing* (kips)**
1	Soft to Stiff Silty Clay	5	4	1.4	7.0	---
2	Fine Sand	20	16	2.4	55.0	---
3	Medium Sand	40	20	2.8	167.0	32

* Because the soil categories and N-values do not fit the geotechnical resistance charts exactly there is some judgment involved in selecting and interpolating for these values
** This information is used to prepare the calculations in Step 7

Step 5 – Select a resistance factor to estimate pile length based on the soil profile and construction control

Only the 5 ft Layer (1) of soft to stiff silty clay is classified as cohesive. The remainder of the profile is classified as non-cohesive and most likely will represent more than 70 percent of the pile embedment length. Thus, the soil is expected to fit the non-cohesive classification, and the resistance factor is selected from the choices below as 0.50 (Appendix C, Table C.1).

φ = 0.60 for cohesive soil, averaged over the full depth of estimated pile penetration
φ = 0.60 for mixed soil, averaged over the full depth of estimated pile penetration
φ =0.50 for non-cohesive soil, averaged over the full depth of estimated pile penetration

Step 6 – Calculate the required nominal pile resistance, R_n

The required nominal pile resistance is as follows:

$$R_n = \frac{\sum \eta\gamma Q + \gamma_{DD} DD}{\varphi} = \frac{54 + 0}{0.50} = 108 \text{ kips/pile}$$

where

$\sum \eta\gamma Q = \gamma Q = 54$ kips (Step 3)

$\gamma_{DD} DD = 0$ (no downdrag)

$\varphi = 0.50$ (Step 5)

The Blue Book notes that in the majority of (Iowa static) load tests of timber piles, the piles yielded (began to settle more than the allowed amount) at no more than 75 tons (150 kips). The Blue Book also suggests that the "ultimate load" (nominal resistance) should not exceed 60 tons (120 kips) for short to medium piles. The required nominal resistance of 108 kips in this example is within that limit.

Step 7 – Estimate contract pile length, L

Based on the nominal resistance values in Step 4, the cumulative nominal geotechnical resistance, $R_{n\text{-}BB}$, per pile is calculated as follows, where D = depth in feet below the bottom of footing:

$D_0 = 0$ ft, $R_{n\text{-}BB0} = 0$

$D_1 = 5$ ft, $R_{n\text{-}BB1} = R_{n\text{-}BB0} + (1.4 \text{ kips/ft})(5 \text{ ft}) = 7.0$ kips

$D_2 = 5 + 20 = 25$ ft, $R_{n\text{-}BB2} = R_{n\text{-}BB1} + (2.4 \text{ kips/ft})(20 \text{ ft}) = 7.0 + 48.0 = 55.0$ kips

End bearing in Layer 3 = 32 kips, $R_{n\text{-}BB3} = R_{n\text{-}BB2} + 32 = 87.0$ kips

Required additional length in Layer 3 = (108.0 – 87.0)/2.8 = 7.5 ft, round to 8 ft

$D_4 = 25 + 8 = 33$ ft, $R_{n\text{-}BB4} = R_{n\text{-}BB3} + (2.8 \text{ kips/ft})(8 \text{ ft}) = 87.0 + 22.4$

$= 109.4 \text{ kips} > 108.0$ kips

The contract pile length includes a 2 ft embedment in the footing and a 1 ft allowance for cutoff due to driving damage:

$L = 33 + 2 + 1 = 36$ ft

The length for timber piles is specified in 5 ft increments (BDM 6.2.4.1). Therefore, the contract pile length is rounded to 35 ft.

At this point, the embedded pile length is known and it is necessary to check the site classification for the resistance factor:

% non-cohesive soil = [(32-5)/32] (100) = 84% > 70%

Therefore, $\varphi = 0.50$ is confirmed for estimating the contract pile length. If the resistance factor were incorrect, the engineer would need to repeat Steps 6 and 7 (and, in this example, the change to mixed soil classification would increase the resistance factor and result in a shorter pile).

Step 8 – Estimate target nominal pile driving resistance, R_{ndr-T}

The complete embedment length below the bottom of footing will contribute to pile driving resistance. In addition to the required embedment length to achieve the nominal pile resistance, driving resistance would need to be added if part of the embedment length had been ignored to account for downdrag load or scour.

Given there was no need to make allowance for downdrag load or scour in this example, the pile embedment length below bottom of footing will be the same as that considered to estimate the required nominal pile resistance, R_{n-D}.

The soil embedment length is 32 ft, which is equal to the 35 ft contract pile length minus the 2 ft of embedment length in the concrete footing and 1 ft cutoff.

For driven timber pile with construction control based on the modified Iowa ENR formula at EOD and no planned retap, the following resistance factor, φ, is recommended to estimate the target nominal pile driving resistance for cohesive soil (Appendix H):

$\varphi_{TAR} = 0.35$ for all soil types

Therefore, the target nominal pile driving resistance can be calculated as follows:

$$R_{ndr-T} = \frac{\sum \gamma Q + \gamma_{DD} DD}{\varphi_{TAR}} = \frac{54 + 0}{0.35} = 154 \text{ kips/pile} = 77 \text{ tons/pile}$$

Note that construction control involving the modified Iowa ENR formula will require an increase in the target nominal driving resistance, R_{ndr-T}, over that required when a WEAP analysis is used for construction control. WEAP analysis would give (54 + 0) / 0.40 = 135 kips/pile or 68 tons/pile.

Also of note is the fact that the Iowa DOT has had a structural service load limit for a timber pile of 20 tons and a driving limit of 40 tons to avoid overdriving (IDOT SS 2501.03, O, 2, c). For one western Iowa bridge with soil conditions similar to this example, timber piles were driven to 40 tons or more, which was considered hard driving and, from the pile logs, seemed to be causing pile damage.

At 40 tons formula-driven capacity, the penetration was about 0.22 in. per blow (55 blows/ft) for the last 10 blows. The modified Iowa ENR formula used in this example gives a result four times that of the Iowa ENR formula used in the past and, therefore, the driving limit should be set at four times 40 tons divided by an average load factor of 1.45, which equals 110 tons. That limit will be included in the CADD note.

Step 9 – Prepare CADD notes for bridge plans

At this point, the final design engineer selects the appropriate CADD notes and adds the specific pile values to the notes.

Abutment piles design note

> THE CONTRACT LENGTH OF 35 FEET FOR THE WEST ABUTMENT PILES IS BASED ON A NON-COHESIVE SOIL CLASSIFICATION, A TOTAL FACTORED AXIAL LOAD PER PILE (P_U) OF 54 KIPS, AND A GEOTECHNICAL RESISTANCE FACTOR (PHI) OF 0.50 FOR SOIL.
>
> THE NOMINAL AXIAL BEARING RESISTANCE FOR CONSTRUCTION CONTROL WAS DETERMINED FROM A NON-COHESIVE SOIL CLASSIFICATION AND A GEOTECHNICAL RESISTANCE FACTOR (PHI) OF 0.35 FOR SOIL.

Abutment piles driving note

> THE REQUIRED NOMINAL AXIAL BEARING RESISTANCE FOR WEST ABUTMENT PILES IS 77 TONS AT END OF DRIVE (EOD). THE PILE CONTRACT LENGTH SHALL BE DRIVEN AS PER PLAN UNLESS PILES REACH A DRIVING LIMIT OF 110 TONS. CONSTRUCTION CONTROL REQUIRES A MODIFIED IOWA DOT FORMULA.

Step 10 – Check the design

Policies for performing checks during design and after completion of design will vary among counties, cities, and engineering consultants.

----------------------END DESIGN AND BEGIN CONSTRUCTION PHASE--------------------

Step 11 – Request and check contractor's hammer data

The contractor requested the engineer's approval for a DELMAG D19 single-acting diesel hammer to install the timber piles and supplied the following manufacturer's information:

DELMAG D19-42

Minimum rated energy = 22,721 ft-lbs (setting 1)
Maximum rated energy = 31,715 ft-lbs (setting 2)
Maximum rated energy = 37,868 ft-lbs (setting 3)
Maximum rated energy = 47,335 ft-lbs (setting 4)
Maximum obtainable stroke = 12.13 ft
Ram weight = 4,015 lbs = 2.007 tons
Drive anvil (cap) weight = 753 lbs = 0.377 tons
Driving cap weight = 1,200 lbs = 0.60 tons
Hammer weight (including trip device) = 8,715 lbs
Hammer operating efficiency = 80 percent

Based on the Iowa DOT *Standard Specifications for Highway and Bridge Construction, Series 2009*, Appendix Table 2501.03-1, the minimum energy required for diesel hammers with 35 ft long timber piling is 17,000 ft-lbs, and the maximum energy allowed for diesel hammers is 24,000 ft-lbs. Based on this information, the DELMAG D19 hammer was accepted at setting 1 (but not 2, 3, or 4).

Note that gravity hammers can be used to install the timber piles. However, the minimum energy required for gravity hammers with 35 ft long timber piling is 15,000 ft-lbs; and the maximum energy allowed for gravity hammers is 25,000 ft-lbs.

Step 12 – Observe construction, record driven resistance, and resolve any construction issues

At EOD at the contract plan length, the construction inspector records the hammer stroke and number of blows per ft of pile penetration. This information is used with the following modified Iowa ENR formula to estimate driving resistance. The formula in *Standard Specifications for Highway and Bridge Construction, Series 2009,* Article 2501.03, M, 2, a, has been modified below to remove the factor of safety so that the formula indicates nominal resistance:

$$R_{ndr} = \frac{12E}{S + 0.1} \times \frac{W}{W + M}$$

where

R_{ndr} = nominal pile driving resistance, in tons

W = weight of ram, in tons (Unless the hammer has free fall, hammer efficiency should be considered in the value of "W." The Iowa DOT Standard Specifications apparently are silent regarding efficiency, and agencies that use the formula for construction control do not always reduce the weight. See the note below.)

M = weight of pile, drive cap (helmet, cushion, striker plate, and pile inserts if used), drive anvil and follower (if applicable), in tons
E = W × H = energy per blow, in ft-tons
H = Hammer stroke, in ft
S = average pile penetration in inches per blow for the last 10 blows
12 = conversion factor for ft to in.

For example, at EOD for the planned pile embedment length at Pile 1 in the Log of Piling Driven (not copied for this example), the construction inspector recorded a hammer stroke of 7.5 ft and a blow count of 20 blows/ft for the last foot of pile penetration. The construction inspector used the formula to calculate a driving resistance of 103 tons as indicated below, which is greater than the target driving resistance of 77 tons.

W = 4015 × 0.8 / 2000 = 1.606 tons (for 80% hammer efficiency)

M = pile + cap + anvil = (1246 + 1200 + 753) /2000 = 1.60 tons

S = (1/20) (12 in./ft) = 0.60 in./blow

$$R_{ndr} = \frac{12WH}{S + 0.1} \times \frac{W}{W + M} = \frac{(12)(1.606)(7.5)}{(0.60 + 0.1)} \times \frac{1.606}{(1.606 + 1.60)}$$

= 103 tons > 77 tons, OK

The R_{ndr} of 103 tons also is less than the driving limit of 110 tons, so the pile was not overdriven.

Note that, if efficiency is not considered in this example, R_{ndr} is larger than 103 tons, which suggests that bearing can be achieved at fewer blows per ft. Formula users need to consider efficiency carefully to achieve the required pile resistance.

W = 4015 / 2000 = 2.007 tons

$$R_{ndr} = \frac{12WH}{S + 0.1} \times \frac{W}{W + M} = \frac{(12)(2.007)(7.5)}{(0.60 + 0.1)} \times \frac{2.007}{(2.007 + 1.60)}$$

= 144 tons > 77 tons, OK

CHAPTER 5. TRACK 3 EXAMPLES FOR SPECIAL PROJECTS

The Track 3 examples in this chapter demonstrate the application of the LRFD procedure on special projects using WEAP as the construction control method.

As briefly described in Chapter 2, Example 1 in this track is the same as Track 1 Example 1 described in Chapter 3, except an additional construction control involving a Pile Driving Analyzer (PDA) with subsequent CAPWAP analysis is considered in Track 3 Example 1. Similar to Track 1 Example 1, Example 2 in this track demonstrates pile designs involving pile retaps at three days after EOD.

5.1. Track 3 Example 1: Driven H-Pile in Cohesive Soil with Construction Control Based on PDA/CAPWAP and Wave Equation with No Planned Retap

Table 5.1. Track 3 Example 1: Design and construction steps

Design Step	
1	Develop bridge situation plan (TS&L)*
2	Develop soils package, including soil borings and foundation recommendations*
3	Determine pile arrangement, pile loads, and other design requirements*
4	Estimate the nominal geotechnical resistance per foot of pile embedment
5	Select a resistance factor to estimate pile length based on the soil profile and construction control
6	Calculate the required nominal pile resistance, R_n
7	Estimate contract pile length, L
8	Estimate target nominal pile driving resistance, $R_{ndr\text{-}T}$
9	Prepare CADD notes for bridge plans
10	Check the design depending on bridge project and office practice
Construction Step	
11	Prepare bearing graph
12	Observe construction, record driven resistance, and resolve any construction issues

* These steps determine the basic information for geotechnical pile design and vary depending on bridge project and office practice

Within the Iowa DOT Office of Bridges and Structures, the design steps that determine the basic information necessary for geotechnical design of a steel H-pile generally follow Steps 1 through 3. The steps involve communication among the preliminary design engineer, soils design engineer, and final design engineer.

In other organizations, the basic information may be determined differently, but that process generally should not affect the overall geotechnical design of the pile in Steps 4 through 9.

Step 1 – Develop bridge situation plan (or TS&L)

For a typical bridge, the preliminary design engineer plots topographical information, locates the bridge, determines general type of superstructure, location of substructure units, elevations of foundations, hydraulic information (if needed), and other basic information to characterize the bridge. The preliminary design engineer then prepares the TS&L sheet that shows a plan and longitudinal section of the bridge.

For this example, the TS&L gives the following information needed for design of abutment piles:

- 120 ft, single-span, prestressed concrete beam superstructure
- Zero skew
- Integral abutments
- Pile foundations, no prebored holes (because the bridge length is less than 130 ft) (BDM 6.5.1.1.1)
- Bottom of abutment footing elevation 433 ft
- Construction Control Based on PDA/CAPWAP and Wave Equation with No Planned Retap

Step 2 – Develop soils package, including soil borings and foundation recommendations

Based on location of the abutments, the soils design engineer orders soil borings (typically at least one per substructure unit). Upon receipt of the boring logs, the engineer arranges for them to be plotted on a longitudinal section, checks any special geotechnical conditions on the site, and writes a recommendation for foundation type with any applicable special design considerations.

For this example, the engineer recommends the following:

- Friction piles that tip out in the firm glacial clay layer
- Steel H-piles for the integral abutments
- Structural Resistance Level – 1 (which does not require a driving analysis by the Office of Construction during design (BDM 6.2.6.1))
- Normal driving resistance (This will lead to $\varphi_c = 0.6$ for the structural check, which needs to be performed but is not included in this geotechnical example.)
- No special site considerations for stability, settlement, or lateral movement (Therefore, the Service I load will not be required for design.)
- Construction control based on PDA/CAPWAP and wave equation with no planned retap

The soil profile shown in Figure 5.1 includes the soil boring at the west abutment. Generally below the bottom of footing elevation there are three layers: 6 ft of soft silty clay, 9 ft of silty sand, and firm glacial clay to the bottom of the boring at 95 ft. Layer 3 is subdivided at a depth of 30 ft because of a step-increase in nominal friction resistance at that elevation. No groundwater was encountered in the boring.

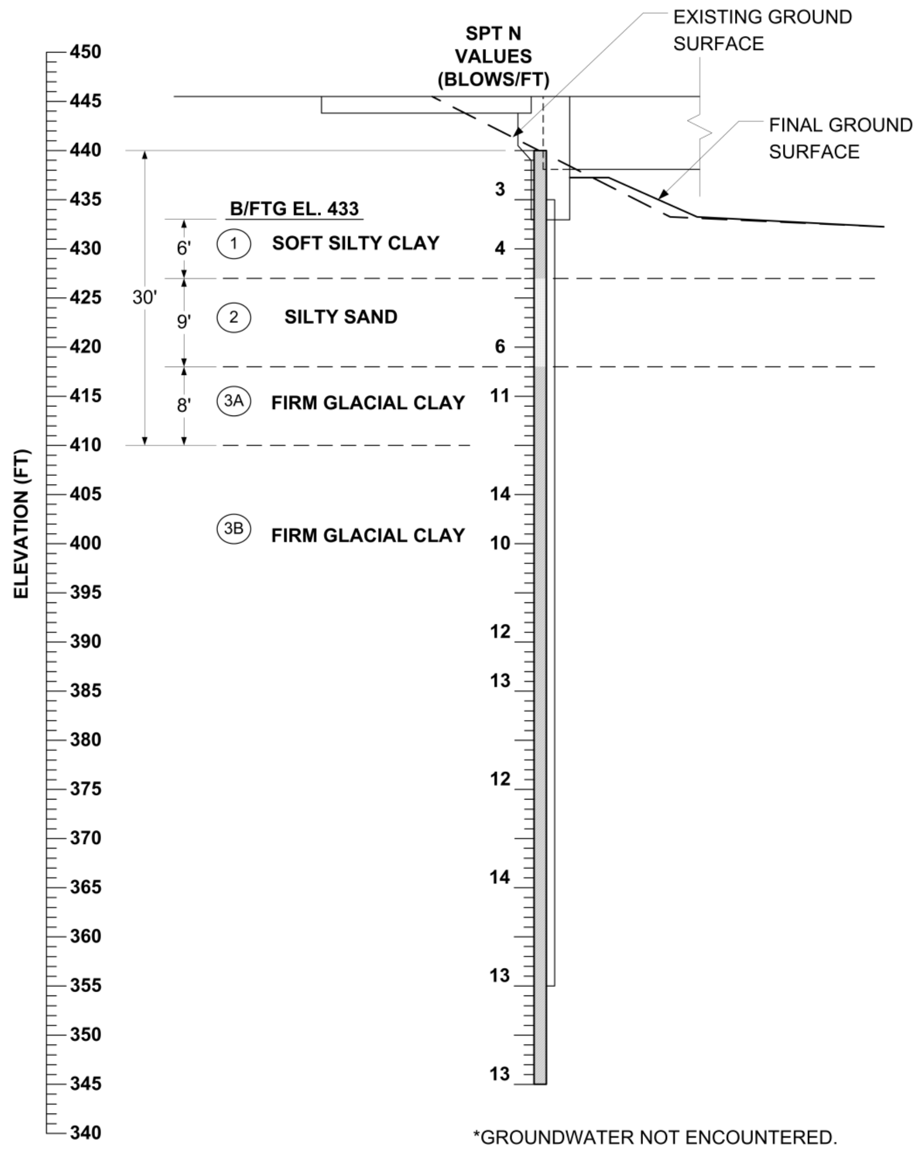


Figure 5.1. Track 3 Example 1: Soil profile

Step 3 – Determine pile arrangement, pile loads, and other design requirements

The final design engineer begins design of the abutment piles with the TS&L and the soils design package. Because the bridge has a prestressed concrete beam superstructure and integral abutments, the engineer selects HP 10×57 piles, following Bridge Design Manual policy (BDM 6.5.1.1.1).

Based on total Strength I abutment load and the Bridge Design Manual policy for pile spacing and number of piles (BDM 6.5.4.1.1), the engineer determines the following:

- Seven HP 10×57 piles plus two wing extension piles, numbers 1 and 9 in Figure 5.2, that support the wings only as shown in the figure
- Strength I load per pile = 128 kips
- No uplift, downdrag, or scour
- Construction Control Based on PDA/CAPWAP and Wave Equation with No Planned Retap

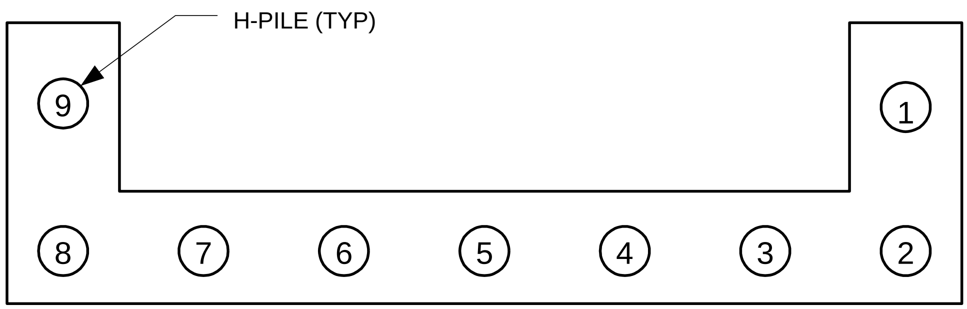


Figure 5.2. Track 3 Example 1: Pile arrangement at an abutment

Because the bridge characteristics fall within integral abutment policy, the site has no unusual characteristics, the soils design engineer did not require further analysis, and construction will not be accelerated or delayed, there will be no need for lateral load or special analysis of the abutment piles. The piles may be simply designed for vertical load.

Step 4 – Estimate the nominal geotechnical resistance per foot of pile embedment

Based on the west abutment soil boring and BDM Table 6.2.7, the final design engineer estimates the unit nominal resistances for friction bearing as shown in Table 5.2.

The firm glacial clay stratum has been divided into two parts to delineate the embedded pile length that is within 30 ft of the natural ground surface as noted in the BDM geotechnical friction resistance chart as shown in Table 5.3. Application of the chart to estimate the nominal resistance values is shown in Table 5.2 . Note that the SPT N values are too small for use of end bearing in Layer 3B.

Table 5.2. Track 3 Example 1: Estimated nominal geotechnical resistance

<table>
<tr><th>Soil Stratum</th><th colspan="2">Soil Description</th><th>Stratum Thickness (ft)</th><th>Average SPT N Value (blows/ft)</th><th>Estimated Unit Nominal Resistance for Friction Pile (kips/ft)</th></tr>
<tr><td>1</td><td colspan="2">Soft Silty Clay</td><td>6</td><td>4</td><td>0.8</td></tr>
<tr><td>2</td><td colspan="2">Silty Sand</td><td>9</td><td>6</td><td>1.2</td></tr>
<tr><td>3A</td><td rowspan="2">Firm Glacial Clay</td><td>within 30 ft of natural ground elevation</td><td>8</td><td>11</td><td>2.8</td></tr>
<tr><td>3B</td><td>more than 30 ft below natural ground elevation</td><td>65</td><td>12</td><td>3.2</td></tr>
</table>

Table 5.3. Track 3 Example 1: BDM geotechnical resistance chart

SOIL DESCRIPTION	BLOW COUNT N-VALUE		ESTIMATED NOMINAL RESISTANCE VALUES FOR FRICTION PILE IN KIPS PER FOOT										
			WOOD PILE	STEEL "H"			PRESTRESSED			STEEL PIPE			
	MEAN	RANGE		10	12	14	12	14	16	10	12	14	18
Alluvium or Loess													
Very soft silty clay	1	0 - 1	0.8	0.4	0.8	0.8	0.8	0.8	0.8	0.4	0.4	0.4	0.8
Soft silty clay	3	2 - 4	1.2	0.8	1.2	1.2	0.8	0.8	0.8	0.8	0.8	0.8	1.2
Stiff silty clay	6	4 - 8	1.6	1.2	1.6	2.0	1.2	1.6	2.0	1.2	1.2	1.6	2.0
Firm silty clay	11	7 - 15	2.4	2.0	2.4	2.8	2.4	2.8	3.2	1.6	2.0	2.4	2.8
Stiff silt	6	3 - 7	1.6	1.2	1.6	1.6	1.6	1.6	1.6	1.2	1.2	1.6	1.6
Stiff sandy silt	6	4 - 8	1.6	1.2	1.6	1.6	1.6	1.6	1.6	1.2	1.2	1.6	1.6
Stiff sandy clay	6	4 - 8	1.6	1.2	1.6	2.0	2.0	2.0	2.4	1.2	1.6	1.6	2.0
Silty sand	8	3 - 13	1.2	1.2	1.2	1.6	1.6	1.6	1.6	0.8	0.8	1.2	1.6
Clayey sand	13	6 - 20	2.0	1.6	2.0	2.8	2.4	2.4	2.8	1.6	2.0	2.4	2.8
Fine sand	15	8 - 22	2.4	2.0	2.4	2.8	2.4	2.8	3.2	1.6	2.0	2.4	2.8
Coarse sand	20	12 - 28	3.2	2.8	3.2	3.6	3.2	3.6	4.0	2.0	2.4	2.8	3.6
Gravelly sand	21	11 - 31	3.2	2.8	3.2	3.6	3.6	3.6	4.0	2.0	2.4	2.8	3.6
Granular material	> 40	---	(2)	4.0	4.8	5.6	(2)	(2)	(2)	(2)	(2)	(2)	(2)
Glacial Clay													
Firm silty glacial clay	11	7 - 15	2.8	2.4	2.8	3.2	2.8	3.2	3.6	2.0	2.4	2.4	3.2
Firm clay (gumbotil)	12	9 - 15	2.8	2.4	2.8	3.2	2.8	3.2	3.6	2.0	2.4	2.4	3.2
Firm glacial clay(1)	11	7 - 15	2.4 [3.2]	2.8 [3.2]	3.2 [4.0]	3.6 [4.4]	3.2 [4.0]	3.6 [4.4	4.0 [4.8]	2.0 [2.4]	2.4 [2.8]	2.8 [3.2]	3.6 [4.4]
Firm sandy glacial clay(1)	13	9 - 15	2.4 [3.2]	2.8 [3.2]	3.2 [4.0]	3.6 [4.4]	3.2 [4.0]	3.6 [4.4	4.0 [4.8]	2.0 [2.4]	2.4 [2.8]	2.8 [3.2]	3.6 [4.4]
Firm - very firm glacial clay(1)	14	11 - 17	2.8 [3.6]	2.8 [4.0]	3.2 [4.8]	3.6 [5.6]	4.0 [4.8]	4.4 [5.2	4.8 [5.6]	2.4 [3.2]	2.8 [3.6]	3.2 [4.0]	4.0 [5.2]
Very firm glacial clay(1)	24	17 - 30	2.8 [3.6]	2.8 [4.0]	3.2 [4.8]	3.6 [5.6]	3.2 (3) [4.8]	3.6 (3) [5.6]	4.4 (3) [6.4]	2.4 [3.2]	2.8 [3.6]	3.2 [4.0]	4.0 [5.2]
Very firm sandy glacial clay(1)	25	15 - 30	3.2 [4.0]	2.8 [4.0]	3.2 [4.8]	3.6 [5.6]	3.2 (3) [4.8]	3.6 (3) [5.6]	4.4 (3) [6.4]	2.4 [3.2]	2.8 [3.6]	3.2 [4.0]	4.0 [5.2]
Cohesive or glacial material(1)	> 35	---	(2)	2.8 [4.0]	3.2 [4.8]	3.6 [5.6]	(2)	(2)	(2)	2.0 (4) [3.2]	2.4 (4) [4.0]	2.8 (4) [4.4]	3.6 (4) [5.6]

Table notes:

(1) <u>**For double entries the upper value is for an embedded pile within 30 feet of the natural ground elevation, and the lower value [ ] is for pile depths more than 30 feet below the natural ground elevation.**</u>

(2) Do not consider use of this pile type for this soil condition, wood with N > 25, prestressed concrete with N > 35, or steel pipe with N > 40.

(3) Prestressed concrete piles have proven to be difficult to drive in these soils. Prestressed piles should not be driven in glacial clay with consistent N > 30 to 35.

(4) Steel pipe piles should not be driven in soils with consistent N > 40.

Step 5 – Select a resistance factor to estimate pile length based on the soil profile and construction control

In this step, the final design engineer first characterizes the site as cohesive, mixed, or non-cohesive based on Table 5.4 and the soil profile.

Table 5.4. Track 3 Example 1: Soil classification table

<table>
<tr><th rowspan="2">Generalized Soil Category</th><th colspan="4">Soil Classification Method</th></tr>
<tr><th>AASHTO</th><th>USDA Textural</th><th colspan="2">BDM 6.2.7 Geotechnical Resistance Chart</th></tr>
<tr><td rowspan="14">Cohesive</td><td rowspan="14">A-4, A-5, A-6, and A-7</td><td rowspan="14">Clay
Silty clay
Silty clay loam
Silt
Clay loam
Silt loam
Loam
Sandy clay</td><td rowspan="6">Loess</td><td>Very soft silty clay</td></tr>
<tr><td>Soft silty clay</td></tr>
<tr><td>Stiff silty clay</td></tr>
<tr><td>Firm silty clay</td></tr>
<tr><td>Stiff silt</td></tr>
<tr><td>Stiff sandy clay</td></tr>
<tr><td rowspan="8">Glacial Clay</td><td>Firm silty glacial clay</td></tr>
<tr><td>Firm clay (gumbotil)</td></tr>
<tr><td>Firm glacial clay</td></tr>
<tr><td>Firm sandy glacial clay</td></tr>
<tr><td>Firm-very firm glacial clay</td></tr>
<tr><td>Very firm glacial clay</td></tr>
<tr><td>Very firm sandy glacial clay</td></tr>
<tr><td>Cohesive or glacial material</td></tr>
<tr><td rowspan="7">Non-Cohesive</td><td rowspan="7">A-1, A-2, and A-3</td><td rowspan="7">Sandy clay loam
Sandy loam
Loamy sand
Sand</td><td rowspan="7">Alluvium Or Loess</td><td>Stiff sandy silt</td></tr>
<tr><td>Silty sand</td></tr>
<tr><td>Clayey sand</td></tr>
<tr><td>Fine sand</td></tr>
<tr><td>Coarse sand</td></tr>
<tr><td>Gravely sand</td></tr>
<tr><td>Granular material (N>40)</td></tr>
</table>

Only the 9 ft Layer two of silty sand is classified as non-cohesive. The remainder of the profile is classified as cohesive and most likely will represent more than 70 percent of the pile embedment length. Thus, the soil is expected to fit the cohesive classification, and the resistance factor selection from the three available choices below is 0.70:

φ = 0.70 for cohesive soil, averaged over the full depth of estimated pile penetration
φ = 0.70 for mixed soil, averaged over the full depth of estimated pile penetration
φ = 0.60 for non-cohesive soil, averaged over the full depth of estimated pile penetration

Step 6 – Calculate the required nominal pile resistance, R_n

The required nominal pile resistance is as follows:

$$R_n = \frac{\sum \eta\gamma Q + \gamma_{DD} DD}{\varphi} = \frac{128 + 0}{0.70} = 183 \text{ kips/pile}$$

where

$\sum\eta\gamma Q = \gamma Q = 128$ kips (Step 3)

$\gamma_{DD}DD = 0$ (no downdrag)

$\varphi = 0.70$ (Step 5)

Step 7 – Estimate contract pile length, L

Based on the nominal resistance values in Step 4, the cumulative nominal geotechnical resistance, $R_{n\text{-}BB}$, per pile is calculated as follows, where D = depth in feet below the bottom of footing:

$D_0 = 0$ ft, $R_{n\text{-}BB0} = 0$

$D_1 = 6$ ft, $R_{n\text{-}BB1} = R_{n\text{-}BB0} + (0.8 \text{ kips/ft}) (6 \text{ ft}) = 4.8$ kips

$D_2 = 6 + 9 = 15$ ft, $R_{n\text{-}BB2} = R_{n\text{-}BB1} + (1.2 \text{ kips/ft}) (9 \text{ ft}) = 4.8 + 10.8 = 15.6$ kips

$D_3 = 15 + 8 = 23$ ft, $R_{n\text{-}BB3} = R_{n\text{-}BB2} + (2.8 \text{ kips/ft}) (8 \text{ ft}) = 15.6 + 22.4 = 38.0$ kips

$D_4 = 23 + 65 = 88$ ft, $R_{n\text{-}BB4} = R_{n\text{-}BB3} + (3.2 \text{ kips/ft}) (65 \text{ ft}) = 38.0 + 208.0 = 246.0$ kips

A graphic presentation of the estimated nominal geotechnical resistance per pile versus depth is presented in Figure 5.3.

From the graph, the depth below the footing necessary to achieve 183 kips is about 68 ft and may be computed as follows:

$D_L = 23 + (183\text{-}38.0)/3.2 = 68$ ft

The contract pile length includes a 2 ft embedment in the footing and a 1 ft allowance for cutoff due to driving damage:

L = 68 + 2 + 1 = 71 ft

The length for steel H-piles is specified in 5 ft increments (BDM 6.2.4.1). Therefore, the contract pile length is 70 ft.

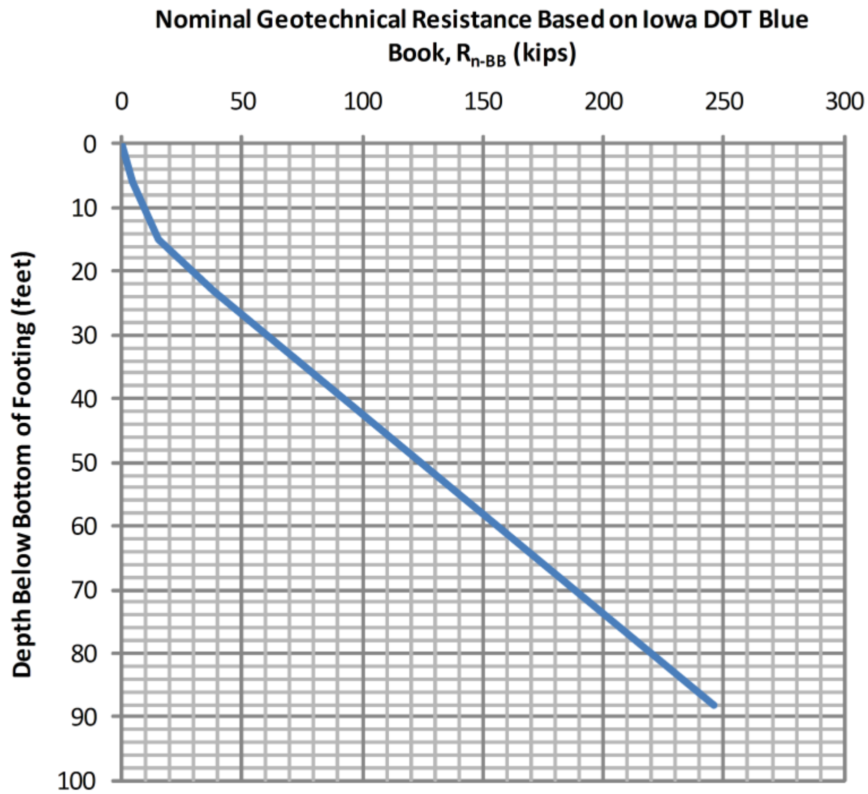


Figure 5.3. Track 3 Example 1: A plot of nominal geotechnical resistance versus depth

At this point, the embedded pile length is known and it is necessary to check the for resistance factor:

% cohesive soil = [(67-9)/67] (100) = 87% > 70%

Therefore, the resistance factor for cohesive soil is the correct choice.

If the resistance factor were incorrect, the engineer would need to repeat Steps 6 and 7 (although, in this example, the mixed soil classification would not result in numeric changes).

Step 8 – Estimate target nominal pile driving resistance, R_{ndr-T}

For a driven H-pile with no planned retap and use of PDA/CAPWAP and WEAP analysis for construction control, the following resistance factors, φ, are recommended to estimate the target nominal pile driving resistance:

φ_{EOD} = 0.75 for cohesive soil, averaged over the full depth of estimated pile penetration

φ_{SETUP} = 0.40 for cohesive soil, averaged over the full depth of estimated pile penetration

φ = 0.70 for mixed soil, averaged over the full depth of estimated pile penetration

φ = 0.70 for non-cohesive soil, averaged over the full depth of estimated pile penetration

For a normal construction schedule, pile setup at 1 day is the most appropriate choice. Therefore, the nominal pile resistance during construction, R_n, will be determined at EOD by scaling back setup gain, and, then, adjusting retaps to account for setup.

$\Sigma\eta\gamma Q + \gamma_{DD}DD \leq \varphi R_n$ where η = load modifier = 1.0 (BDM 6.2.3.1)

Let $R_n = R_T$ = nominal pile resistance at time T (days) after EOD.

$$R_{EOD} \geq \frac{\sum \eta\gamma Q + \gamma_{DD}DD}{\varphi_{EOD} + \varphi_{SETUP}(F_{SETUP} - 1)}$$

where

$\Sigma\eta\gamma Q = \gamma Q$ = 128 kips, (Step 2)

$\gamma_{DD}DD = 0$ (no downdrag)

F_{SETUP} = Setup Ratio = R_T/R_{EOD}

To determine the setup ratio, the soil profile was used to calculate the average SPT N-value for cohesive soil penetrated by the driven pile over the contract pile length, as follows:

Calculated average SPT N-value = [(6′)(4) + (8′)(11) + (67′-23′)(12)]/(67′-9′) = 11

The average SPT N-value of 11 yields a Setup Ratio, F_{SETUP}, of 1.61 from Figure 5.4.

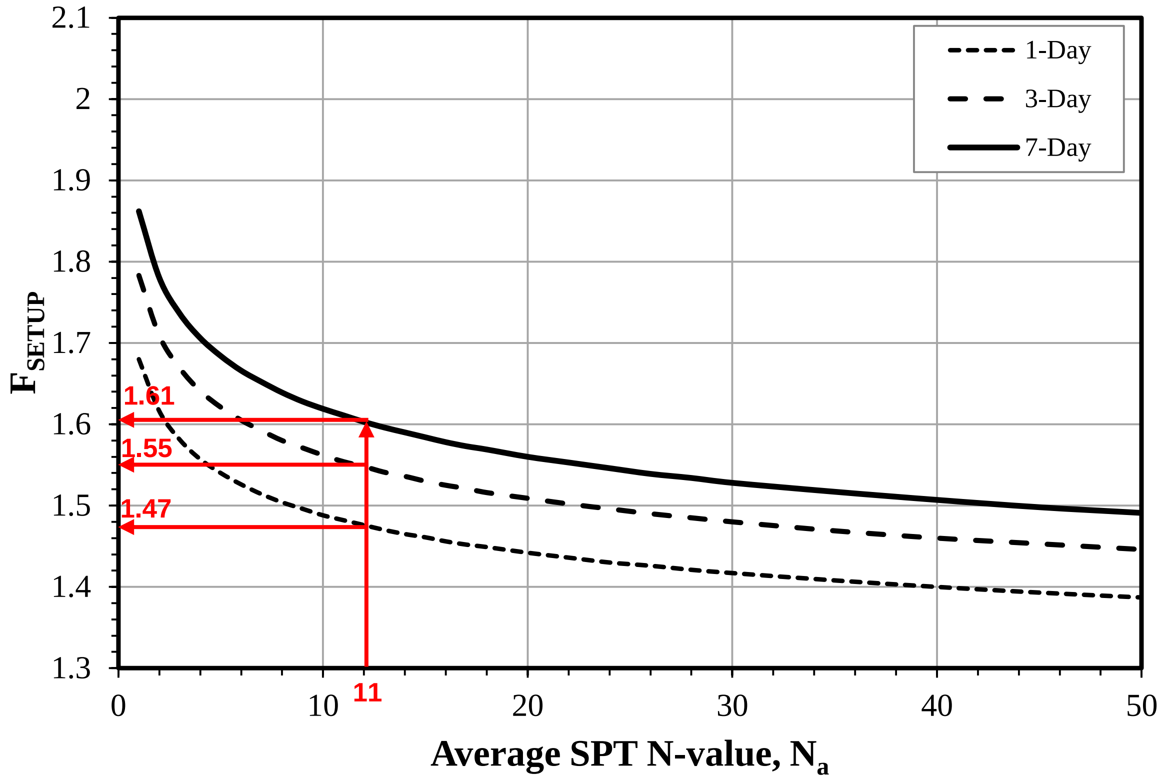


Figure 5.4. Track 3 Example 1: Pile setup factor chart

Let φ_{TAR} = Resistance factor for target nominal resistance ≤ 1.00

$= \varphi_{EOD} + \varphi_{SETUP}(F_{SETUP} - 1)$ and $R_{ndr\text{-}T} = R_{EOD}$

The target pile driving resistance at EOD is as follows:

$$R_{ndr-T} = R_{EOD}$$

$$\geq \frac{\sum \eta\gamma Q + \gamma_{DD}DD}{\varphi_{TAR}}$$

$$\geq \frac{\sum \eta\gamma Q + \gamma_{DD}DD}{\varphi_{EOD} + \varphi_{SETUP}(F_{SETUP} - 1)}$$

$$\geq \frac{128 + 0}{(0.75) + (0.40)(1.61 - 1)} = \frac{128}{0.99}$$

= 129 kips/pile

The target nominal geotechnical resistance at 1 day retap, then, is as follows:

$R_{1\text{-day}} = (129.0)(1.47) = 189.6$ kips = 95 tons

The target nominal geotechnical resistance at 3 day retap, then, is as follows:

$R_{3\text{-day}} = (129.0)(1.55) = 200.0$ kips = 100 tons

The target nominal geotechnical resistance at 7 day retap, then, is as follows:

$R_{7\text{-day}} = (129.0)(1.61) = 207.7$ kips = 104 tons

Step 9 – Prepare CADD notes for bridge plans

At this point, the final design engineer selects the appropriate CADD notes and adds the specific pile load values to the notes.

Abutment piles design note

THE CONTRACT LENGTH OF 70 FEET FOR THE WEST ABUTMENT PILES IS BASED ON A COHESIVE SOIL CLASSIFICATION, A TOTAL FACTORED AXIAL LOAD PER PILE (P_U) OF 128 KIPS, AND A GEOTECHNICAL RESISTANCE FACTOR (PHI) OF 0.75.

THE NOMINAL AXIAL BEARING RESISTANCE FOR CONSTRUCTION CONTROL WAS DETERMINED FROM A COHESIVE SOIL CLASSIFICATION AND A GEOTECHNICAL RESISTANCE FACTOR (PHI) OF 0.99.

Abutment piles driving note

THE REQUIRED NOMINAL AXIAL BEARING RESISTANCE FOR WEST ABUTMENT PILES IS 65 TONS AT END OF DRIVE (EOD). IF RETAPS ARE NECESSARY TO ACHIEVE BEARING, THE REQUIRED NOMINAL AXIAL BEARING RESISTANCE IS 95 TONS AT ONE-DAY RETAP, 100 TONS AT THREE-DAY RETAP, OR 104 TONS AT SEVEN-DAY RETAP. THE PILE CONTRACT LENGTH SHALL BE DRIVEN AS PER PLAN UNLESS PILES REACH REFUSAL. CONSTRUCTION CONTROL REQUIRES A WEAP ANALYSIS, BEARING GRAPH, PDA AND CAPWAP ANALYSIS.

Step 10 – Check the design

Within the Iowa DOT Office of Bridges and Structures, a final design engineer other than the bridge designer is assigned to give the bridge design an independent check when final plans are complete. During the checking process, the final design engineer reviews the soils package to ensure all recommendations were followed and also checks structural, geotechnical, and drivability aspects of the design.

For this example, only the structural and geotechnical aspects would be checked because pile driving stresses will be relatively low. (For simplicity, the structural design was not shown in this example.)

Other design organizations may perform checks at various stages of design rather than upon plan completion.

----------------------END DESIGN AND BEGIN CONSTRUCTION PHASE--------------------

Step 11 – Prepare bearing graph

After the bridge contract is let and prior to start of pile driving, the contractor completes Hammer Data sheets for use of the planned pile driving hammer. The Hammer Data sheets include all pertinent information including the cap (helmet) number and hammer identification information with details, hammer cushion, and pile cushion (where required), as well as pile size, pile length, and estimated pile driving resistance.

The Office of Construction uses the data received to complete a WEAP analysis for construction control during pile driving. Results from the WEAP analysis are then used to prepare an LRFD Driving Graph (without the factor of safety used for allowable stress design). The Driving Graph includes curves of nominal driving resistance versus blows per ft and identifies specific driving conditions where driving stress is a concern.

Step 12 – Observe construction, record driven resistance, and resolve any construction issues

During pile driving, the construction inspector performs PDA analysis with CAPWAP signal processing. Pile stress and movement are monitored, and driving resistance is calculated in real time to verify the pile reaches target driving resistance. The construction inspector enters the EOD information on the driving log.

If the recorded pile driving resistance at EOD is less than the target pile nominal driving resistance, the pile is retapped with PDA/CAPWAP about 24 hours after EOD. (The retap is a remedial measure that makes use of setup for an individual pile. If the 24 hour retap does not indicate sufficient driven resistance, an extension will be added the same day rather than wait to retap another day.)

5.2. Track 3 Example 2: Driven H-Pile in Cohesive Soil and Construction Control Based on Wave Equation and Planned Retap at 3 Days

Table 5.5. Track 3 Example 2: Design and construction steps

Design Step	
1	Develop bridge situation plan (TS&L)*
2	Develop soils package, including soil borings and foundation recommendations*
3	Determine pile arrangement, pile loads, and other design requirements*
4	Estimate the nominal geotechnical resistance per foot of pile embedment
5	Select a resistance factor to estimate pile length based on the soil profile and construction control
6	Calculate the required nominal pile resistance, R_n
7	Estimate contract pile length, L
8	Estimate target nominal pile driving resistance, $R_{ndr\text{-}T}$
9	Prepare CADD notes for bridge plans
10	Check the design depending on bridge project and office practice
Construction Step	
11	Prepare bearing graph
12	Observe construction, record driven resistance, and resolve any construction issues

* These steps determine the basic information for geotechnical pile design and vary depending on bridge project and office practice

Within the Iowa DOT Office of Bridges and Structures, the design steps that determine the basic information necessary for geotechnical design of a steel H-pile generally follow Steps 1 through 3. The steps involve communication among the preliminary design engineer, soils design engineer, and final design engineer.

In other organizations, the basic information may be determined differently, but that process generally should not affect the overall geotechnical design of the pile in Steps 4 through 9.

Step 1 – Develop bridge situation plan (or TS&L)

For a typical bridge, the preliminary design engineer plots topographical information, locates the bridge, determines general type of superstructure, location of substructure units, elevations of foundations, hydraulic information (if needed), and other basic information to characterize the bridge. The preliminary design engineer then prepares the TS&L sheet that shows a plan and longitudinal section of the bridge.

For this example, the TS&L gives the following information needed for design of abutment piles:

- Three-span, 240 ft prestressed concrete beam superstructure
- Seven D-beam cross section

- Zero skew
- Integral abutments
- Pile foundations with 10 ft prebored holes
- Bottom of west abutment footing at natural ground elevation

Step 2 – Develop soils package, including soil borings and foundation recommendations

Based on locations of the abutments, the soils design engineer orders soil borings (typically at least one per substructure unit). Upon receipt of the boring logs, the engineer arranges for them to be plotted on a longitudinal section, checks any special geotechnical conditions on the site, and writes a recommendation for foundation type with any applicable special design considerations.

For this example, the engineer recommends the following:

- Piles driven into very firm glacial clay
- Steel H-piles for the integral abutments
- Structural Resistance Level – 1 (which does not require a driving analysis by the Office of Construction during design (BDM 6.2.6.1). SRL-1 allows the designer to consider both friction and end bearing.)
- Normal driving resistance (This will lead to φ_c = 0.6 for the structural check.)
- No special site considerations for stability, settlement, or lateral movement (Therefore, a Service I load will not be required for design.)
- Standard construction control based on WEAP analysis with three-day planned retap (At present, the planned retap is not usual Iowa DOT practice.)

The soil profile is as follows.

- Stratum 1, topsoil 3 ft
- Stratum 2, firm glacial clay 27 ft, average N-value = 11
- Stratum 3, very firm glacial clay 50 ft, average N-value = 25

Step 3 – Determine pile arrangement, pile loads, and other design requirements

The final design engineer begins design of the abutment piles with the TS&L and the soils design package. Because the bridge has a prestressed concrete beam superstructure and integral abutments, the engineer selects HP 10×57 piles, following Bridge Design Manual policy (BDM 6.5.1.1.1).

Based on total Strength I abutment load and the Bridge Design Manual policy for pile spacing and number of piles (BDM 6.5.4.1.1), the final design engineer determines the following:

- Strength I factored load for abutment (not including wing extension) piles = 900 kips

- Grade 50, HP 10×57 piles
- Nominal structural resistance per pile at SRL-1 = 243 kips (BDM Table 6.2.6.1-1)
- Nominal maximum structural resistance for an integral abutment pile with 10ft prebore = 365 kips (BDM Table 6.5.1.1.1-1)
- Minimum number of piles based on structural resistance = 900/(0.6)(243) = 6.2, rounded up to 7
- Minimum number of piles based on superstructure cross section: 7 beams, therefore, 7 piles (BDM 6.2.4.1)
- Seven piles with two wing extension piles as shown in Figure 5.5, if geotechnical resistance is sufficient
- Required factored geotechnical resistance per pile = 900/7 = 128.6 kips (or rounded to129 kips for the plan note)

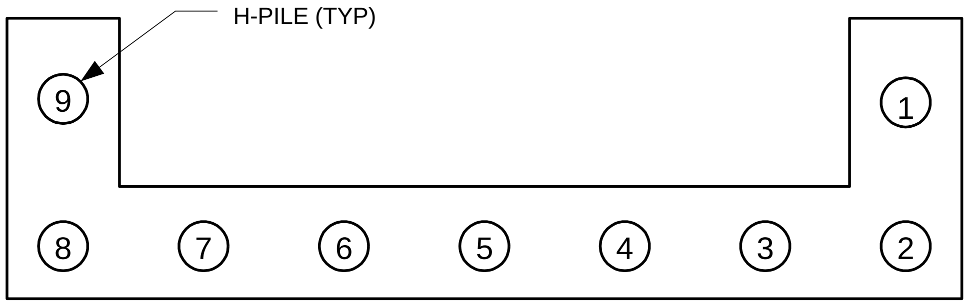


Figure 5.5. Track 3 Example 2: Pile arrangement at an abutment

Because the bridge characteristics fall within integral abutment policy, the site has no unusual characteristics, the soils design engineer did not require further analysis, the project does not require staged construction, and construction will not be accelerated or delayed, there will be no need for lateral load or special analysis of the abutment piles. The piles may be simply designed for applied vertical load.

Step 4 – Estimate the nominal friction and end bearing geotechnical resistance

Based on the west abutment soil profile and BDM Table 6.2.7, the final design engineer estimates the nominal resistances for friction and end bearing shown in Table 5.6.

Table 5.6. Track 3 Example 2: Estimated nominal geotechnical resistance

Soil Stratum	Soil Description	Stratum Thickness (ft)	Average SPT N Value (blows/ft)	Estimated Nominal Resistance for Friction Pile (kips/ft)	Estimated Nominal Resistance for End Bearing (ksi)
1	Topsoil	3 below natural ground	---	---	---
2	Firm Glacial Clay	20 below prebore	11	2.8	---
3	Very Firm Glacial Clay (30 ft below the natural ground elevation)	50	25	4.0	2

Step 5 – Select a resistance factor to estimate pile length based on the soil profile and construction control

For a driven H-pile with construction control using WEAP, the following resistance factor is recommended to estimate the contract pile length for friction bearing in cohesive soil. Only cohesive soil was present below the west abutment.

$\varphi = 0.65$ for cohesive soil, averaged over the full depth of estimated pile penetration

Step 6 – Calculate the required nominal pile geotechnical resistance, R_n

The required nominal pile resistance is as follows:

$R_n = 128.6/0.65 = 197.8$ kips

Step 7 – Estimate contract pile length, L

Based on the nominal resistance values in Step 4, the cumulative nominal geotechnical resistance, $R_{n\text{-}BB}$, per pile is calculated as follows, where D = depth in feet below the bottom of footing (which, in this example, also is the depth below natural ground elevation):

D_0 = 0 ft, $R_{n\text{-}BB0}$ = 0

D_1 = 10 ft, $R_{n\text{-}BB1} = R_{n\text{-}BB0} + 0 = 0$

D_2 = 10 + 20 = 30 ft, $R_{n\text{-}BB2} = R_{n\text{-}BB1}$ + (2.8 kips/ft) (20 ft) = 0 + 56.0 = 56.0 kips

D_3 = 30 + x ft, $R_{n\text{-}BB3} = R_{n\text{-}BB2}$ + (2 ksi) (16.8 in^2) = 56.0 + 33.6 = 89.6 kips

D_4 = 30 + x ft, x = (197.8 kips – 89.6 kips)/4.0 kips/ft = 27.1 ft, D_4 = 30 + 27.1 = 57.1 ft

The contract pile length includes a 2 ft embedment in the abutment footing and a 1 ft allowance for cutoff due to driving damage:

L = 57.1 + 2 + 1 = 60.1 ft

The length for steel H-piles is specified in 5 ft increments (BDM 6.2.4.1). Therefore, the contract pile length is rounded to 60 ft.

Step 8 – Estimate target nominal pile driving resistance, $R_{ndr\text{-}T}$

During the construction stage, the pile will be retapped at 3 days; however, the basic retap information was developed for a seven-day retap. Thus, the target nominal pile driving resistance for a three-day retap was corrected based on the seven-day information.

First, select the construction resistance factor:

φ = 0.70 for cohesive soil, with retap test 7 days after EOD

Then, determine the nominal geotechnical bearing resistance per pile at 7 day retap.

R_n = 128.6/0.70 = 183.7 kips

The average SPT N-value over the length of estimated pile embedment is needed for the setup factor chart.

N_a = [(20)(11) + (27)(25)]/47 = 19

From the setup factor chart for seven-day retap, as shown in Figure 5.6:

R_n/R_{EOD} = 1.57

The target nominal geotechnical resistance at EOD is as follows:

R_{EOD} = 183.7/1.57 = 117.0 kips = 59 tons

Determine the nominal resistance at 3 days from the setup factor chart for three-day retap, as shown in Figure 5.6:

$R_n/R_{EOD} = 1.52$

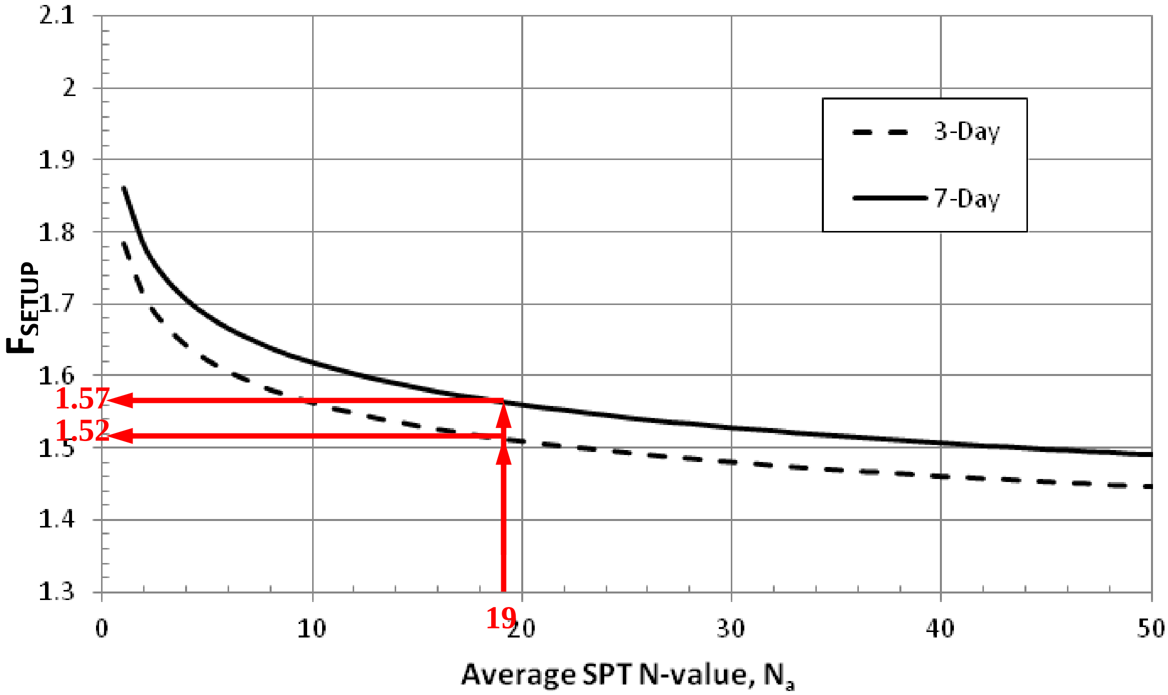


Figure 5.6. Track 3 Example 2: Pile setup factor chart

The target nominal geotechnical resistance at 3 day retap, then, is as follows:

$R_{3\text{-day}} = (117.0)(1.52) = 177.8$ kips = 89 tons

Step 9 – Prepare CADD notes for bridge plans

At this point, the final design engineer selects the appropriate CADD notes and adds the specific pile load values to the notes.

Abutment piles design note

THE CONTRACT LENGTH OF 60 FEET FOR THE WEST ABUTMENT PILES IS BASED ON A COHESIVE SOIL CLASSIFICATION, A TOTAL FACTORED AXIAL LOAD PER PILE (P_U) OF 129 KIPS, AND A GEOTECHNICAL RESISTANCE FACTOR (PHI) OF 0.65.

THE NOMINAL AXIAL BEARING RESISTANCE FOR CONSTRUCTION CONTROL WAS DETERMINED FROM A COHESIVE SOIL CLASSIFICATION AND A GEOTECHNICAL RESISTANCE FACTOR (PHI) OF 0.70.

Abutment piles driving note

> THE REQUIRED NOMINAL AXIAL BEARING RESISTANCE FOR WEST ABUTMENT PILES IS 59 TONS AT END OF DRIVE (EOD) AND 89 TONS NOMINAL RETAP RESISTANCE AT 3 DAYS AFTER EOD. PILES MUST BE RETAPPED AT THREE DAYS WITH A REQUIRED NOMINAL AXIAL BEARING RESISTANCE OF 89 TONS. THE PILE CONTRACT LENGTH SHALL BE DRIVEN AS PER PLAN UNLESS PILES REACH REFUSAL. CONSTRUCTION CONTROL REQUIRES A WEAP ANALYSIS AND BEARING GRAPH AND A RETAP AT THREE DAYS AFTER EOD.

Step 10 – Check the design

Within the Iowa DOT Office of Bridges and Structures, a final design engineer other than the bridge designer is assigned to give the bridge design an independent check when final plans are complete. During the checking process, the final design engineer reviews the soils package to ensure all recommendations were followed and also checks structural, geotechnical, and drivability aspects of the design.

For this example, only the structural and geotechnical aspects would be checked because pile driving stresses will be relatively low.

Other design organizations may perform checks at various stages of design rather than upon plan completion.

-----------------------END DESIGN AND BEGIN CONSTRUCTION PHASE---------------------

Step 11 – Prepare bearing graph

After the bridge contract is let and prior to start of pile driving, the contractor completes Hammer Data sheets for use of the planned pile driving hammer. The Hammer Data sheets include all pertinent information including the cap (helmet) number and hammer identification information with details, hammer cushion, and pile cushion (where required), as well as pile size, pile length, and required (or target) nominal axial pile driving resistance.

For state projects, the Office of Construction uses the data received to complete a WEAP analysis for construction control during pile driving. Results from the WEAP analysis are then used to prepare an LRFD Driving Graph as shown in Figure 5.7 (without the factor of safety used for allowable stress design). The Driving Graph includes hammer stroke height curves that relate blows per ft to nominal driving resistance, and identifies specific driving conditions where driving stress is a concern. Figure 5.7 shows the LRFD Driving Graph for the west abutment.

Special Driving Conditions	Stroke (ft)	**Monitor at 10 Blow Increments**	**Do NOT Exceed**	**Project No:**	Design Example DGT32	**Graph No:**	XX-XXXX-XX-XXX
				Design No:	XXX	**Hammer No:**	XXXXXX
	7	-----	-----	**County:**	XXXXX	**Cap No:**	XXX
	8	-----	-----	**Location:**	West Abutment	**Pile Type:**	HP 10x57
Blows per foot	9	-----	-----	**Hammer:**	Delmag D19-42	**Pile Length:**	60

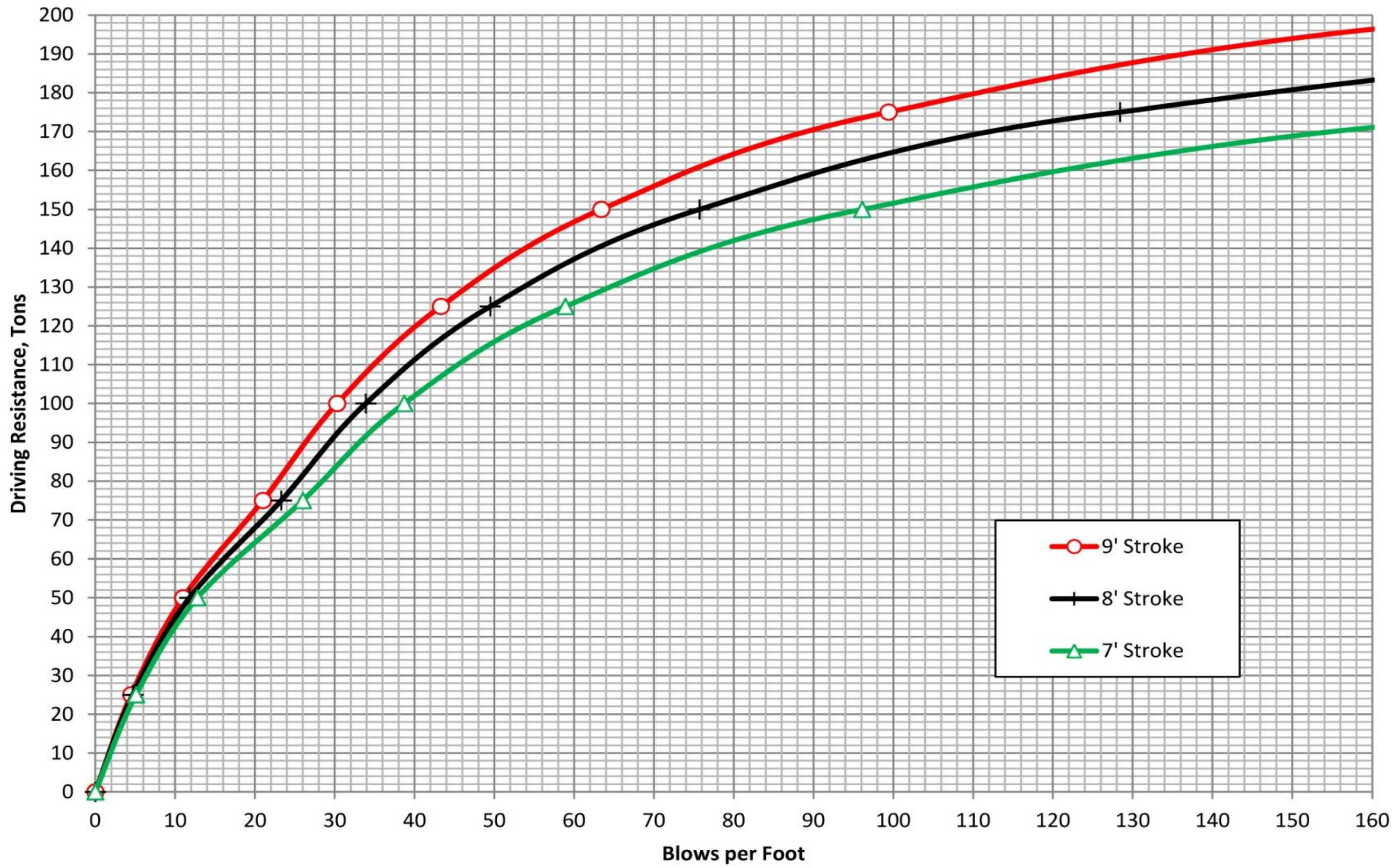


Figure 5.7. Track 3 Example 2: WEAP bearing graph for the west abutment

Step 12 – Observe construction, record driven resistance, and resolve any construction issues

During pile driving, the construction inspector records the hammer stroke and number of blows to advance the pile an equivalent penetration of 1 ft, and, then, converts the recorded information with the Driving Graph to record the driven resistance per pile at EOD. This information is shown in Figure 5.8 for this example.

In this example, the inspector would record the EOD values and observe and record retaps three days after EOD. Unless otherwise noted on the plans, the number of retaps required would follow Iowa DOT policy in the standard specifications (IDOT SS 2501.03, M, 5).

At EOD at Pile 8, the construction inspector recorded a driving resistance of 56 tons, which is less than the target nominal pile driving resistance of 59 tons at EOD. However, no immediate pile extension is needed for Pile 8 given construction control is based on planned retap at 3 days.

Three days after EOD, Pile 8 was retapped, and the construction inspector recorded a driving resistance of 92 tons, which is greater than the target nominal pile driving resistance of 89 tons for three-day retap. Therefore, Pile 8 meets the design requirement and no pile extension is needed.

Form 830209(E) 9/06

Iowa Department of Transportation

ENGLISH LOG OF PILING DRIVEN WITH WAVE EQUATION

Project No. Someplace in Iowa

County XXX

Design No. XXX

Contractor XXXX

Driving Graph No. XX-XXXX-XX-XXX

Nominal Driving Resistance 59 (EOD) / 89 (3-Day Restrike) Tons

Pile (Type and Size) HP 10x57
(Wood, Steel or Concrete)

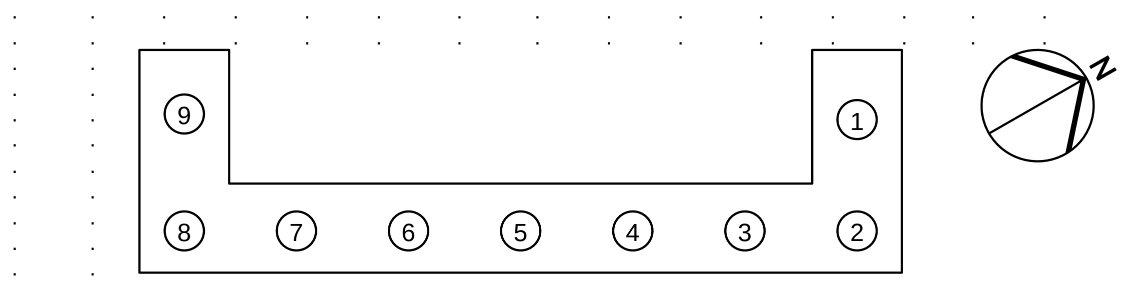
Hammer (Type & Model) Delmag D19-42
(Gravity or Diesel manufacturer and model)

Foundation Description West Abutment
(North abut, Pier 1, etc.)

Station of Foundation C.L. XXX+XX

Sketch foundation below, number each pile and show steel H-pile orientation as installed. Note battered piles on sketch,and give the amount of batter. Place name and certificate number of welder below if welding was necessary. Forward copies, including driving graph, as outlined in the construction manual. Note on drawing which pile has been logged.

Batter Piling ________ in the direction shown.



		(1)					RETAP (2)				PILE EXTENSIONS (3)					
Pile No.	Date Driven	Plan Length (ft.)	Length Cutoff (0.0 ft.)	Blows Per Foot	Ram Rise (ft.)	Driven Resistance (Tons)	Date	Ram Rise (ft.)	Blows Per Foot	Driven Resistance (Tons)	Length Added (0.0 ft.)	Length Cutoff (0.0 ft.)	Ram Rise (ft.)	Blows Per Foot	Driven Resistance (Tons)	Welds (Count)
1	05-17-10	60	1.0	18	7.5	62	05-20-10	8	34	100						
2	05-17-10	60	1.0	21	8	68	05-20-10	7	36	95						
3	05-17-10	60	1.0	20	7	63	05-20-10	7.5	39	105						
4	05-17-10	60	1.0	25	8	78	05-20-10	8.5	40	115						
5	05-17-10	60	1.0	16	9	62	05-20-10	9	32	103						
6	05-18-10	60	1.0	20	8.5	70	05-21-10	8.5	38	111						
7	05-18-10	60	1.0	17	7.5	60	05-21-10	7	39	100						
8	05-18-10	60	1.0	14	7	56	05-21-10	7.5	32	92						
9	05-18-10	60	1.0	19	8.5	67	05-21-10	8	33	98						
---	---	---	---	---	---	---										

Total Welds: ________

(1) Record in the Remarks section below if the pile length is anything other than the plan length at the beginning of drive.

(2) Indicate date of retap in date column (1 day delay min.). List only pile actually checked.

(3) Additional pile length to be authorized by Construction Office.

Plan Length: ________ Feet

Extensions: ________ Feet

Total: ________ Feet

Welders Name: ____________ Lab No.: ________ Exp. Date: ________

Remarks: ____

______________ Inspector

________ Date

______________________ Project Engineer

Distribution: Construction (original), District, Project File

Figure 5.8. Track 3 Example 2: Pile driving log

CHAPTER 6. SUMMARY

The outcomes of three research projects (TR-573, -583, and -584) sponsored by the IHRB and Iowa DOT led to the development of the regional LRFD method for driven pile foundations in Iowa. The research outcomes are presented at the project web site (http://srg.cce.iastate.edu/lrfd/) in the three report volumes entitled Development of LRFD Procedures for Bridge Pile Foundations in Iowa:

- Volume I: An Electronic Database for PIle Load Tests (PILOT)
- Volume II: Field Testing of Steel Piles in Clay, Sand, and Mixed Soils and Data Analysis
- Volume III: Recommended Resistance Factors with Consideration of Construction Control and Setup

Using the PILOT database and the 10 field test results, resistance factors were calibrated for various static analysis methods. Among the various methods, the in-house Iowa Blue Book method (based on the Geotechnical Resistance Charts in Appendix A) was recommended for design of steel H-piles. Similarly, resistance factors were calibrated for various dynamic formulas, WEAP and CAPWAP.

Following the examination of efficiencies of different methods, the modified Iowa ENR formula, WEAP, and CAPWAP are recommended for the construction control of steel H-piles, while the modified Iowa ENR formula is recommended for the construction control of timber piles. In addition, LRFD recommendations with consideration of pile setup and construction control were developed.

By incorporating the LRFD resistance factors developed in Volume III and adopting the AASHTO LRFD Bridge Design Specifications (2010), as well as the Iowa DOT Bridge Design Manual (2010) as it is being rewritten under the new title of LRFD Bridge Design Manual (December 2011), LRFD design guidance for driven piles is presented in this volume.

Chapter 2 outlines the concept of three tracks, provides pile design flow charts, and incudes the templates and instructions for CADD design and driving notes for abutment piles and pier piles, along with a brief description of each design example in this volume.

Track 1 (Chapter 3) consists of seven design examples that use WEAP as the construction control method to define the pile driving criteria. The applications of LRFD in three different soil categories (cohesive, non-cohesive, and mixed soils, as defined in Appendix B) are illustrated in Track 1.

Track 2 (Chapter 4) consists of two examples that use the modified Iowa ENR formula as the construction control method to define pile driving criteria. The LRFD application to timber piles is also demonstrated in this track.

Track 3 (Chapter 5) demonstrates two design examples for projects that require special construction control procedures using PDA/CAPWAP, WEAP and/or planned retaps.

Supplementary materials, design formulation, resistance factors, and other recommendations are included in Appendices A through H.

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NOTATIONS

CAPWAP	CAse Pile Wave Analysis Program
D	Depth of a single pile below the bottom of footing
D_L	Depth of a single pile below the bottom of footing estimated using Blue Book necessary to achieve the nominal pile resistance
DD	Downdrag load
DD_{BB}	Downdrag load estimated using Blue Book
E	Hammer energy per blow = W × H
ENR	Modified Iowa Engineering News Record formula
EOD	End of driving
F_{eb}	Fraction for end bearing
F_{fr}	Fraction of friction resistance
F_{SETUP}	Setup Ratio = R_T/R_{EOD}
H	Hammer stroke
kips	kilo pound
L	Contract pile length
L_{br}	Embedded pile length in bedrock
M	Weight of pile, drive cap (helmet, cushion, striker plate, and pile inserts if used), drive anvil, and follower (if applicable), in tons.
N_a	Average SPT N-value (Appendix D)
PDA	Pile driving analyzer
PILOT	PIle Load Tests (database)
P_u	Total factored axial load per pile
Q	Applied axial load on a single pile
R_{scour}	Pile resistance due to scour
R_{EOD}	Pile resistance at end of driving
R_n	Nominal pile resistance
$R_{n\text{-}BB}$	Cumulative nominal geotechnical resistance per pile estimated using Blue Book
$R_{ndr\text{-}T}$	Target pile driving resistance
R_{sdd}	Nominal driving resistance that accounts for the downdrag load, which is equal to DD_{BB}
R_{setup}	Increase in pile resistance after end of driving due to soil setup
R_T	Nominal pile resistance at time T (days) after EOD
R_{UP}	Uplift pile resistance
$R_{1\text{-}day}$	Target nominal geotechnical resistance at 1 day retap
$R_{3\text{-}day}$	Target nominal geotechnical resistance at 3 day retap
$R_{7\text{-}day}$	Target nominal geotechnical resistance at 7 day retap
S	Average pile penetration in inches per blow for the last 10 blows
SPT	Standard Penetration Test
TS&L	Type, Size, and Location
W	Weight of ram (unless the hammer has free fall, hammer efficiency should be considered in the value of "W")
WEAP	Wave Equation Analysis Program
η	Load modifier
γ	Load factor

γ_{DD}	Load factor for downdrag load
φ	Resistance factor (Appendix C)
φ_{EOD}	Resistance factor for driving pile resistance obtained at EOD (R_{EOD})
φ_{SETUP}	Resistance factor for pile setup resistance (R_{setup})
φ_{TAR}	Resistance factor for target nominal pile resistance
φ_{UP}	Resistance factor for uplift resistance

APPENDIX A. UNIT GEOTECHNICAL RESISTANCE

The unit geotechnical resistance for side resistance and end bearing are based on the Geotechnical Resistance Charts (BDM 6.2.7), as included in Table A.1 and Table A.2.

Note that for non-cohesive soil, groundwater can significantly reduce the effective stress and resulting nominal pile bearing resistance. This is of particular concern at a bridge, which spans a river, that is founded on friction pile driven in granular soil below the phreatic surface.

The Iowa DOT recommends that a separate analysis that accounts for the effective overburden pressure acting on piling that is founded in non-cohesive soil, to verify that the estimated pile length is reasonable.

Further discussion about effective stress methods of analysis to estimate required pile lengths is presented in Publication No. FHWA NHI-05-042, *Design and Construction of Driven Pile Foundations*. The impact of effective stress on the nominal pile bearing resistance can be checked with the DRIVEN computer program. The DRIVEN Program User's Manual (Mathias and Cribbs 1998) and software Version 1.2, released in March 2001, can be downloaded from http://www.fhwa.dot.gov/engineering/geotech/software.cfm.

Table A.1. BDM nominal geotechnical end bearing chart

LRFD DRIVEN PILE FOUNDATION GEOTECHNICAL RESISTANCE CHART, ENGLISH UNITS													
SOIL DESCRIPTION	**BLOW COUNT N-VALUE**		**ESTIMATED NOMINAL RESISTANCE VALUES FOR END BEARING PILE**										
			WOOD PILE, KIPS (1), (3)	**STEEL "H", GRADE 50, KIPS / SQUARE INCH (KSI)**			**PRESTRESSED CONCRETE, KIPS (2)**			**STEEL PIPE, KIPS (4)**			
	MEAN	**RANGE**		**10**	**12**	**14**	**12**	**14**	**16**	**10**	**12**	**14**	**18**
Granular material													
	<15	---	(5)	(5)	(5)	(5)	(5)	(5)	(5)	(5)	(5)	(5)	(5)
Fine or medium sand	15	---	32	(5)	(5)	(5)	60	84	108	32	48	64	108
Coarse sand	20	---	44	(5)	(5)	(5)	84	116	148	44	64	88	144
Gravelly sand	21	---	44	(5)	(5)	(5)	84	116	148	44	64	88	144
	25	---	56	(5)	(5)	(5)	(7)	(7)	(7)	(7)	(7)	(7)	(7)
	---	25-50	(6)	[2-4]	[2-4]	[2-4]	(6), (7)	(6), (7)	(6), (7)	(7)	(7)	(7)	(7)
	---	50-100	(6)	[4-8]	[4-8]	[4-8]	(6)	(6)	(6)	(7)	(7)	(7)	(7)
	---	100-300	(6)	[8-16]	[8-16]	[8-16]	(6)	(6)	(6)	(7)	(7)	(7)	(7)
	---	>300	(6)	[18]	[18]	[18]	(6)	(6)	(6)	(7)	(7)	(7)	(7)
Bedrock													
	---	100-200	(6)	[12]	[12]	[12]	(6)	(6)	(6)	(7)	(7)	(7)	(7)
	---	>200	(6)	[18]	[18]	[18]	(6)	(6)	(6)	(7)	(7)	(7)	(7)
Cohesive material													
	12	10-50	16	(5)	(5)	(5)	28	40	52	16	24	32	52
	20	---	24	[1]	[1]	[1]	44	64	84	28	36	52	84
	25	---	32	[2]	[2]	[2]	60	84	108	32	48	64	108
	50	---	(6)	[4]	[4]	[4]	116 (6)	164 (6)	212 (6)	56	96	128	212
	100	---	(6)	[7]	[7]	[7]	(6)	(6)	(6)	(6)	(6)	(6)	(6)

(1) Wood piles shall not be driven through soils with N > 25.
(2) With prestressed concrete piles the preferred N for soil at the tip ranges from 25 to 35. Prestressed concrete piles have been proven to be difficult to drive in very firm glacial clay and very firm sandy glacial clay. Prestressed concrete piles should not be driven in glacial clay with consistent N > 30 to 35.
(3) End bearing resistance values for wood piles are based on a tip area of 72 in^2. Values shall be adjusted for a different tip area.
(4) Steel pipe piles should not be driven in soils with consistent N > 40. See the 1994 soils information chart (BDM 6.2.1.) for end bearing when a conical driving point is used.
(5) Do not consider end bearing.
(6) Use of end bearing is not recommended for timber piles when N > 25 or for prestressed concrete piles when N > 35 or for any condition identified with this note.
(7) End bearing resistance shall be 0.0389 x "N" value (ksi).

Table A.2. BDM nominal geotechnical side resistance chart

LRFD DRIVEN PILE FOUNDATION GEOTECHNICAL RESISTANCE CHART, ENGLISH UNITS													
SOIL DESCRIPTION	**BLOW COUNT**		**ESTIMATED NOMINAL RESISTANCE VALUES FOR FRICTION PILE IN KIPS PER FOOT [KIPS / FT]**										
	N-VALUE		**WOOD**	**STEEL "H" GRADE 50**			**PRESTRESSED CONCRETE**			**STEEL PIPE**			
	MEAN	**RANGE**	**PILE**	**10**	**12**	**14**	**12**	**14**	**16**	**10**	**12**	**14**	**18**
Alluvium or Loess													
Very soft silty clay	1	0 - 1	0.8	0.4	0.8	0.8	0.8	0.8	0.8	0.4	0.4	0.4	0.8
Soft silty clay	3	2 - 4	1.2	0.8	1.2	1.2	0.8	0.8	0.8	0.8	0.8	0.8	1.2
Stiff silty clay	6	4 - 8	1.6	1.2	1.6	2.0	1.2	1.6	2.0	1.2	1.2	1.6	2.0
Firm silty clay	11	7 - 15	2.4	2.0	2.4	2.8	2.4	2.8	3.2	1.6	2.0	2.4	2.8
Stiff silt	6	3 - 7	1.6	1.2	1.6	1.6	1.6	1.6	1.6	1.2	1.2	1.6	1.6
Stiff sandy silt	6	4 - 8	1.6	1.2	1.6	1.6	1.6	1.6	1.6	1.2	1.2	1.6	1.6
Stiff sandy clay	6	4 - 8	1.6	1.2	1.6	2.0	2.0	2.0	2.4	1.2	1.6	1.6	2.0
Silty sand	8	3 - 13	1.2	1.2	1.2	1.6	1.6	1.6	1.6	0.8	0.8	1.2	1.6
Clayey sand	13	6 - 20	2.0	1.6	2.0	2.8	2.4	2.4	2.8	1.6	2.0	2.4	2.8
Fine sand	15	8 - 22	2.4	2.0	2.4	2.8	2.4	2.8	3.2	1.6	2.0	2.4	2.8
Coarse sand	20	12 - 28	3.2	2.8	3.2	3.6	3.2	3.6	4.0	2.0	2.4	2.8	3.6
Gravelly sand	21	11 - 31	3.2	2.8	3.2	3.6	3.6	3.6	4.0	2.0	2.4	2.8	3.6
Granular material	> 40	---	(2)	4.0	4.8	5.6	(2)	(2)	(2)	(2)	(2)	(2)	(2)
Glacial Clay													
Firm silty glacial clay	11	7 - 15	2.8	2.4	2.8	3.2	2.8	3.2	3.6	2.0	2.4	2.4	3.2
Firm clay (gumbotil)	12	9 - 15	2.8	2.4	2.8	3.2	2.8	3.2	3.6	2.0	2.4	2.4	3.2
Firm glacial clay[1]	11	7 - 15	2.4 [3.2]	2.8 [3.2]	3.2 [4.0]	3.6 [4.4]	3.2 [4.0]	3.6 [4.4]	4.0 [4.8]	2.0 [2.4]	2.4 [2.8]	2.8 [3.2]	3.6 [4.4]
Firm sandy glacial clay[1]	13	9 - 15	2.4 [3.2]	2.8 [3.2]	3.2 [4.0]	3.6 [4.4]	3.2 [4.0]	3.6 [4.4]	4.0 [4.8]	2.0 [2.4]	2.4 [2.8]	2.8 [3.2]	3.6 [4.4]
Firm - very firm glacial clay[1]	14	11 - 17	2.8 [3.6]	2.8 [4.0]	3.2 [4.8]	3.6 [5.6]	4.0 [4.8]	4.4 [5.2]	4.8 [5.6]	2.4 [3.2]	2.8 [3.6]	3.2 [4.0]	4.0 [5.2]
Very firm glacial clay[1]	24	17 - 30	2.8 [3.6]	2.8 [4.0]	3.2 [4.8]	3.6 [5.6]	3.2 (3) [4.8]	3.6 (3) [5.6]	4.4 (3) [6.4]	2.4 [3.2]	2.8 [3.6]	3.2 [4.0]	4.0 [5.2]
Very firm sandy glacial clay[1]	25	15 - 30	3.2 [4.0]	2.8 [4.0]	3.2 [4.8]	3.6 [5.6]	3.2 (3) [4.8]	3.6 (3) [5.6]	4.4 (3) [6.4]	2.4 [3.2]	2.8 [3.6]	3.2 [4.0]	4.0 [5.2]
Cohesive or glacial material[1]	> 35	---	(2)	2.8 [4.0]	3.2 [4.8]	3.6 [5.6]	(2)	(2)	(2)	2.0 (4) [3.2]	2.4 (4) [4.0]	2.8 (4) [4.4]	3.6 (4) [5.6]

(1) For double entries the upper value is for an embedded pile within 30 ft of the natural ground elevation, and the lower value [ ] is for pile depths more than 30 ft below the natural ground elevation.
(2) Do not consider use of this pile type for this soil condition, wood with N > 25, prestressed concrete with N > 35, or steel pipe with N > 40.
(3) Prestressed concrete piles have proven to be difficult to drive in these soils. Prestressed piles should not be driven in glacial clay with consistent N > 30 to 35.
(4) Steel pipe piles should not be driven in soils with consistent N > 40.

APPENDIX B. GENERALIZED SOIL CATEGORY

Using Table B.1, the generalized soil category (cohesive, mixed, or non-cohesive) at the substructure location is needed to select resistance factors for side resistance. A definition of the soil classification methods based on the investigation of AbdelSalam et al. (2011b) is described in this appendix to facilitate determination of the generalized soil category.

To determine which generalized soil category to use, the cumulative length of cohesive and non-cohesive soil should be determined over the penetration length for the entire pile as follows.

- The cohesive category should be used when at least 70 percent of the cumulative embedment length is estimated to penetrate cohesive soil
- The non-cohesive category should be used when no more than 30 percent of the cumulative embedment length is predicted to penetrate cohesive soil
- The mixed category should be used when 31 to 69 percent of the cumulative embedment length is predicted to penetrate cohesive soil

In this approach, the soil type for each layer should be identified according to the Unified Soil Classification System (USCS) and all soil layers along the pile length are assumed to contribute to support the pile. In addition, the following should be noted:

- The generalized soil category is only dependent on the overall percentages of cohesive/non-cohesive layer classification along the embedded pile. In other words, the soil profile classification is independent of how much load each layer individually is able to resist by friction and how much load is resisted in end bearing.
- The strata that are neglected in pile resistance during the design stage, such as the soil above the scour depth and/or the soil above the neutral plane where downdrag is a concern, should be included in the driving resistance for the construction stage. If such a condition is anticipated during the design stage, both of the pertinent soil categories should be considered to estimate pile length.
- The generalized soil category can also change, when the originally-designed pile length cannot achieve the required capacity and the subsequent additional pile penetration may alter the type of soil profile originally selected during design. This may happen when the soil profile is near the boundary of the 70% rule. Therefore, it is recommended to check the generalized soil category during the design stage if pile extensions may be needed. Pile resistance should be revised accordingly if pile extension results in a change in the generalized soil category.

The generalized soil category only applies to the side friction component of geotechnical pile resistance. The end bearing component of geotechnical pile resistance is based on the soil stratum that the pile is tipped out in only.

Table B.1. Table of soil classification method

Generalized Soil Category	Soil Classification Method			
	AASHTO	USDA Textural	BDM 6.2.7 Geotechnical Resistance Chart	
Cohesive	A-4, A-5, A-6, and A-7	Clay Silty clay Silty clay loam Silt Clay loam Silt loam Loam Sandy clay	Loess	Very soft silty clay
				Soft silty clay
				Stiff silty clay
				Firm silty clay
				Stiff silt
				Stiff sandy clay
			Glacial Clay	Firm silty glacial clay
				Firm clay (gumbotil)
				Firm glacial clay
				Firm sandy glacial clay
				Firm-very firm glacial clay
				Very firm glacial clay
				Very firm sandy glacial clay
				Cohesive or glacial material
Non-Cohesive	A-1, A-2, and A-3	Sandy clay loam Sandy loam Loamy sand Sand	Alluvium Or Loess	Stiff sandy silt
				Silty sand
				Clayey sand
				Fine sand
				Coarse sand
				Gravely sand
				Granular material (N>40)

APPENDIX C. RESISTANCE FACTORS

Common resistance factors used in the design examples are listed in Tables C.1, C.2 and C.3.

Resistance factors for the service limit states shall be taken as 1.0, except as provided for overall stability. Resistance factors at the extreme limit state shall be taken as 1.0, except that for uplift resistance of piles the resistance factor shall be taken as 0.80 or less. Changed foundation conditions resulting from scour shall be considered at the extreme event limit state.

Design of pile foundations at the strength limit state should include consideration of the nominal geotechnical and structural resistances of the foundation elements. The design of pile foundations at the strength limit state should consider the following:

- Structural resistance
- Loss of lateral and vertical support due to scour at the design flood event
- Axial compression resistance for single piles
- Pile group compression resistance
- Uplift resistance for single piles
- Uplift resistance for pile groups
- Pile punching failure into a weaker stratum below the bearing stratum
- Single pile and pile group lateral resistance
- Constructability, including pile drivability

For piles tipped out in bedrock at the strength limit state, a resistance factor of 0.70 is recommended for both design and construction. Based on successful past practice with the Iowa Blue Book, a resistance factor of 0.70 (rounded down from an interim factor of 0.725) is assumed for both contract length and driving resistance with respect to rock. When driving to bedrock, it is quite possible that piles will be driven to refusal.

Uplift resistance for driven piling should be reduced in accordance with the AASHTO LRFD Specifications. To maintain consistency with past practice, use 75 percent of the factored skin frictional resistance for driven piling to compute the factored uplift resistance for single piles. This means that the resistance factors in Table C.1 have been multiplied by 0.75 and rounded to the nearest 0.05 to compute uplift resistance for single friction piles. Resistance factors for design of single piles in axial tension (uplift) are presented in Table C.2.

The resistance factors presented herein, for the strength limit state, account for resistance capacity gain due to pile setup for friction pile driven in cohesive soil; and the resistance factors presented herein ignore pile setup for friction pile driven in non-cohesive and mixed soil types. Calibration of the resistance factors was based on the target nominal resistance capacity that is achieved at 7 days after EOD. To accommodate typical Iowa DOT construction practice, it has been assumed that planned retap tests for construction control may be completed three days after EOD.

Table C.1. Resistance factors for design of single pile in axial compression for redundant pile groups (contract length)

Theoretical Analysis [c]	Construction Control (field verification) [a]					Resistance Factor [b]				
	Driving Criteria Basis		PDA/ CAPWAP	Retap Test 3-Days After EOD	Static Pile Load Test	Cohesive			Mixed	Non-Cohesive
	Iowa ENR Formula	WEAP				φ	φ_{EOD}	φ_{setup}	φ	φ
Iowa Blue Book	Yes	-	-	-	-	0.60	-	-	0.60	0.50
	-	Yes [d]	-	-	-	0.65	-	-	0.65	0.55
			Yes	-	-	0.70 [e]	-	-	0.70	0.60
				Yes	-	0.80	-	-	0.70	0.60
			-	-	Yes	0.80	-	-	0.80	0.80

(a) Determine the construction control that will be specified on the Plans to achieve the Target Nominal Driving Resistance.
(b) Resistance factors presented in Table C.1 are for redundant pile groups defined in Appendix H. Refer to LRFD Report Volume III for resistance factors of non-redundant pile groups. A resistance factor of 1.0 shall be used for extreme event limit state.
(c) Use BDM Article 6.2.7 to estimate the theoretical nominal pile resistance, based on the Iowa Blue Book.
(d) Use the Iowa Blue Book soil input procedure to complete WEAP analyses.
(e) Setup effect has been included when WEAP is used to establish driving criteria and CAPWAP is used as a construction control.

Table C.2. Resistance factors for design of single pile in axial tension for redundant pile groups (contract length)

Theoretical Analysis [c]	Construction Control (field verification) [a]					Resistance Factor [b]				
	Driving Criteria Basis		PDA/ CAPWAP	Retap Test 3-Days After EOD	Static Pile Load Test	Cohesive			Mixed	Non-Cohesive
	Iowa ENR Formula	WEAP				φ	φ_{EOD}	φ_{setup}	φ	φ
Iowa Blue Book	Yes	-	-	-	-	0.45	-	-	0.45	0.40
	-	Yes [d]	-	-	-	0.50	-	-	0.50	0.40
			Yes	-	-	0.55 [e]	-	-	0.55	0.45
				Yes	-	0.60	-	-	0.55	0.45
			-	-	Yes	0.80	-	-	0.80	0.80

(a) Determine the construction control that will be specified on the Plans to achieve the Target Nominal Driving Resistance.
(b) Resistance factors presented in Table C.2 are for redundant pile groups defined in Appendix H. Refer to LRFD Report Volume III for resistance factors of non-redundant pile groups. A resistance factor of 0.75 shall be used for extreme event limit state.
(c) Use BDM Article 6.2.7 to estimate the theoretical nominal pile resistance, based on the Iowa Blue Book.
(d) Use the Iowa Blue Book soil input procedure to complete WEAP analyses.

(e) Setup effect has been included when WEAP is used to establish driving criteria and CAPWAP is used as a construction control.

Table C.3. Resistance factors for construction control for redundant pile groups

Theoretical Analysis [c]	Construction Control (field verification) [a]					Resistance Factor [b]				
	Driving Criteria Basis		PDA/ CAPWAP	Retap Test 3-Days After EOD	Static Pile Load Test	Cohesive			Mixed	Non-Cohesive
	Iowa ENR Formula	WEAP				φ	φ_{EOD}	φ_{setup}	φ	φ
Iowa Blue Book	Yes	-	-	-	-	0.55 [f]	-	-	0.55 [f]	0.50 [f]
	-	Yes [d]	-	-	-	-	0.65	0.20	0.65	0.55
			-	Yes	-	0.70	-	-		
			Yes [e]	-	-	-	0.75	0.40	0.70	0.70
				Yes	-	0.80	-	-		
			-	-	Yes	0.80	-	-	0.80	0.80

(a) Refer to the Plans for the specified construction control that is required to achieve the Target Nominal Driving Resistance.
(b) Resistance factors presented in Table C.3 are for redundant pile groups defined in Appendix H. Refer to LRFD Report Volume III for resistance factors of non-redundant pile groups.
(c) Use BDM Article 6.2.7 to estimate the theoretical nominal pile resistance, based on the Iowa Blue Book.
(d) Use the Iowa Blue Book soil input procedure to complete WEAP analyses.
(e) Use signal matching to determine Nominal Driving Resistance.
(f) Reduce the resistance factor to 0.35 for redundant groups of driven timber pile, if the Iowa DOT ENR formula is used for construction control. This is based on Iowa historic timber pile test data. For WEAP construction control to drive timber pile, the resistance factor may be taken as 0.40.

APPENDIX D. SETUP FACTOR CHART

For piles driven through cohesive soil profiles, the pile setup chart shown in Figure D.1 can be used to estimate the increase in pile driving resistance due to setup.

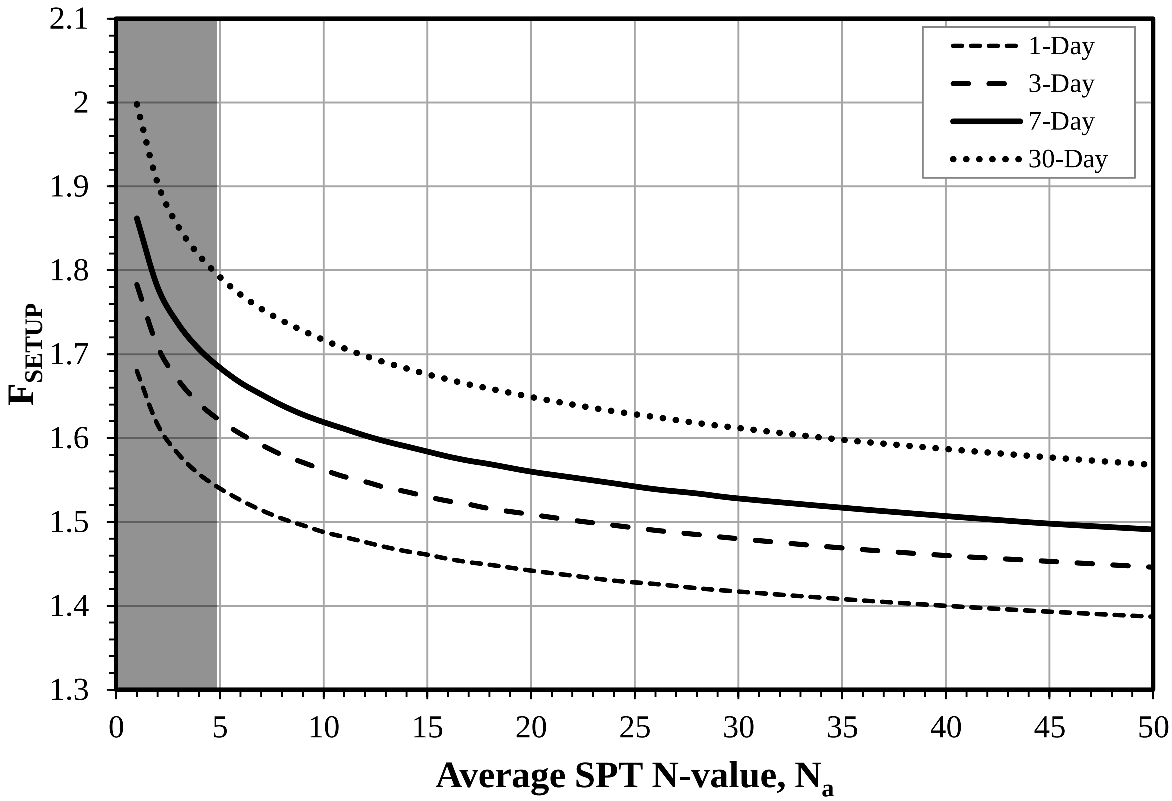

Figure D.1. Pile setup factor chart for WEAP as a construction control method

Note that the average SPT N-value (N_a) is calculated by weighing the measured uncorrected N-value (N_i) at each cohesive soil layer (i) along the pile shaft by its thickness (l_i) for a total of (n) cohesive layers situated along the embedded pile length, which is expressed as:

$$N_a = \frac{\sum_{i=1}^{n} N_i l_i}{\sum_{i=1}^{n} l_i}$$

This chart is used to estimate the nominal pile driving resistance at 3 days after EOD, with the resistance factor based on a planned retap at 7 days after EOD. See Track 3 Example 2 for details.

For a soft clay layer with a SPT N-value smaller than five or an undrained shear strength (S_u) smaller than 1.04 ksf (50 kPa), the pile setup chart should be used with caution. Pile setup has been observed above and below water table as reported in Volume II (Ng et al. 2011). Because of this, no special treatment of the water table is suggested in pile design.

APPENDIX E. DERIVATION OF EQUATIONS FOR PILE DRIVING RESISTANCE AT EOD (R_{EOD}) THAT ACCOUNTS FOR PILE SETUP WITH NO PLANNED RETAP

From BDM 6.2.3.1

$$\Sigma\eta\gamma Q + \gamma_{DD}DD \leq \varphi R_n \text{ where } \eta = 1.0 \quad \text{(E-1)}$$

Let $R_n = R_T$ = nominal pile resistance at time T (days) after EOD.

For analysis, assume R_T is determined during construction at T days after EOD.

Factored Resistance

$$\varphi R_T = \varphi_{EOD}R_{EOD} + \varphi_{SETUP}R_{SETUP} \quad \text{(E-2)}$$

where

R_{EOD} = nominal pile resistance at EOD

R_{SETUP} = Gain in nominal pile resistance due to pile setup at time T (days) after EOD

The φ used in φR_T varies; φ_{EOD} is a constant; and φ_{SETUP} is a constant

Nominal Resistance

$$R_T = R_{EOD} + R_{SETUP} = R_{EOD}\,(F_{SETUP}) \quad \text{(E-3)}$$

where

F_{SETUP} = Setup Factor = R_T/R_{EOD}

Rearrange Equation E-3 to yield the following:

$$R_{SETUP} = R_{EOD}\,(F_{SETUP}) - R_{EOD} = R_{EOD}\,(F_{SETUP} - 1) \quad \text{(E-4)}$$

Substitute Equation E-4 into Equation E-2, and, then, substitute Equation E-2 into Equation E-1, to yield the following:

$$\begin{aligned}\Sigma\eta\gamma Q + \gamma_{DD}DD &\leq \varphi_{EOD}R_{EOD} + \varphi_{SETUP}R_{SETUP} \\ &= \varphi_{EOD}R_{EOD} + \varphi_{SETUP}\,R_{EOD}\,(F_{SETUP} - 1) \\ &= R_{EOD}\,[\varphi_{EOD} + \varphi_{SETUP}\,(F_{SETUP} - 1)] \quad \text{(E-5)}\end{aligned}$$

where

φ_{TAR} = Resistance factor for target nominal resistance ≤ 1.00

$\varphi_{TAR} = \varphi_{EOD} + \varphi_{SETUP}\,(F_{SETUP} - 1) \leq 1.0$

Rearrange Equation E-5, to yield the following:

$$R_{EOD} \geq \frac{\sum \eta\gamma Q + \gamma_{DD} DD}{\varphi_{EOD} + \varphi_{SETUP}(F_{SETUP} - 1)} \qquad \text{(E-6)}$$

APPENDIX F. RECOMMENDATIONS FOR DRIVING STEEL H-PILES INTO ROCK

The recommendations in Appendix F are included to supplement design guidance for driving steel H-piles into rock. When driving steel H-piles to rock, the piles should be driven to penetrate the rock a reasonable amount to achieve full end bearing and provide lateral support at the tip.

The designer needs to include the estimated penetration length in the total contract length. Recommendations from the 1989/1994 Blue Book are given in Table F.1. The Iowa DOT does not include side friction resistance within the length that piles penetrate rock.

Table F.1. Recommended H-pile penetration into bedrock

Rock Classification	Recommended Penetration (ft)
Broken Limestone	8 - 12 (where practical)
Shale or Firm Shale	8 - 12
Medium Hard Shale, Hard Shale, or Siltstone	4 - 8
Sandstone, Siltstone, or Shale ($N \geq 200$)	3
Solid Limestone	1 - 3

APPENDIX G. ADDITIONAL RECOMMENDATIONS FROM THE BLUE BOOK

The recommendations in Appendix G are taken from the Blue Book to supplement design guidance considering end bearing, steel pipe pile driving points, and timber piles.

End Bearing: The designer should average N-values over a distance 8 ft above and below the pile tip to determine the appropriate end bearing value.

The designer shall not set the pile tip at a contact layer because end bearing may not be fully mobilized at that elevation. It has been the Iowa DOT Office of Bridges and Structures practice to extend piles designed for end bearing at least 5 ft into the bearing layer, possibly because of the 12 in. concrete pile example in Blue Book Appendix D. For larger than 12 in. piles, the office now recommends extending the piles at least five diameters into the bearing layer as indicated in the track examples.

Steel Pipe Pile Driving Points: The Blue Book recommends a flat plate for most soils, and a flat plate is shown on the P10L standard sheet. The sheet also shows an optional driving point consisting of welded cross plates.

Conical points discussed in the Blue Book have not been shown on office standard sheets since the P10 sheet dated March 1953, but conical points currently are available for some pipe pile sizes. Although the Blue Book has a method to determine bearing with conical points, the notation in the formula and graph is inconsistent and not totally defined. If the designer decides to use conical driving points, they should seek additional information.

Timber Piles: The Blue Book notes that in the majority of (Iowa static) load tests of timber piles, the piles yielded (began to settle more than the allowed amount) at no more than 75 tons (150 kips). The Blue Book also suggests that the “ultimate load” (nominal resistance) should not exceed 60 tons (120 kips) for short to medium piles.

APPENDIX H. RECOMMENDATIONS FOR PILES DRIVEN TO BEDROCK AND ADDITIONAL DRIVEN PILE TYPES

The recommendations in Appendix H are included to supplement design guidance on piles driven to bedrock and on other pile types as well as additional design and construction recommendations.

Piles Driven to Bedrock: The Office of Bridges and Structures has calibrated end bearing design and construction control resistance factors (φ_s) for piles driven to bedrock to past practice using a value of 0.70 (rounded down from an interim, estimated value of 0.725). If the friction bearing capacity above bedrock is significant (above about 25 percent) it may be included in the total pile capacity but with the resistance factors appropriate for friction bearing only.

Prestressed Concrete and Steel Pipe Piles: For prestressed concrete and steel pipe driven piles, the designer shall use the same design and construction resistance factors as for steel H-piles (Appendix C).

No estimate for cutoff needs to be included when determining prestressed concrete pile length; however, a one-ft allowance for cutoff should be included when determining pipe pile length. Pile length for both pile types should be rounded to the nearest ft.

Timber Piles: The designer shall use the same design resistance factors (φ_s) as for steel H-piles (Appendix C, Table C.1). However, for construction control, the resistance factors shall be 0.40 for WEAP control and 0.35 for the modified Iowa DOT formula control. The 0.35 resistance factor has been determined from Iowa load test data in the PILOT database, and the 0.40 is appropriate for the better construction control of a WEAP analysis as per the 2010 AASHTO LRFD Specifications.

For timber piles, 1 ft should be added to the length for cutoff due to driving damage. Pile length should be rounded to the nearest 5 ft.

To avoid overdriving timber piles, driving shall not exceed 110 tons with modified Iowa ENR formula construction control.

Minimum Pile Length: The Iowa DOT Office of Bridges and Structures is considering policy for determining minimum pile length. The final policy may not be the same as indicated in Track 1 Examples 2, 6, and 7.

Retaps: For cohesive soils, retaps may not be exactly at 1, 3, or 7 days. In general, retaps may be performed within 12 hours of the target day: 12 to 36 hours for 1 day, 60 to 84 hours for 3 day, and 156 to 180 hours for 7 day.

Linear interpolation may be used between 1 day and 3 day and between 3 day and 7 day, but not between EOD and 1 day.

For non-cohesive and mixed soils, the retap value is the same as the EOD value.

Redundancy: The resistance factors in Tables C.1 through C.3 are for redundant pile groups, usually a group with a minimum of five piles. For typical bridges, the Office of Bridges and Structures considers the following pile groups to be redundant: four abutment piles, five pier piles, five bent piles. For pile groups with fewer piles, the resistance factors in the Appendix C tables need to be adjusted downward. The designer should use Volume III as a reference for the adjustments.

SPT N-values: All of the pile designs in the examples are based on uncorrected N-values. The designer should not adjust N-values for depth or 60 percent efficiency.