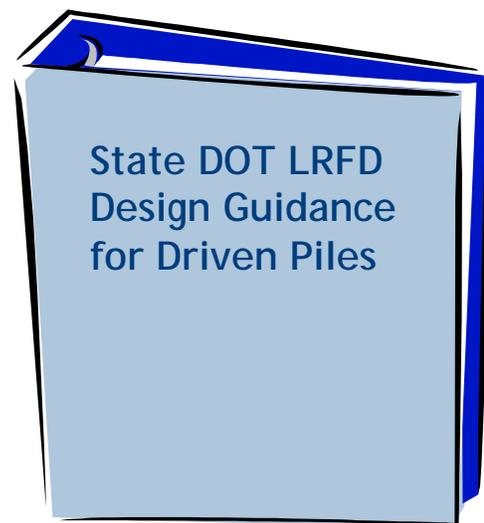
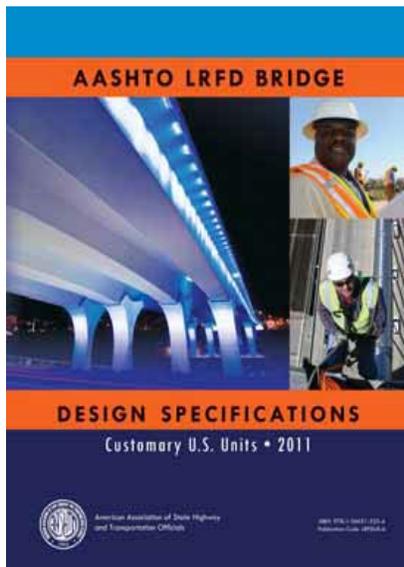




Implementation of AASHTO LRFD Design Specifications for Driven Piles



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Technical Report Documentation Page

1. Report No. FHWA-RC-13-001	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle IMPLEMENTATION OF AASHTO LRFD DESIGN SPECIFICATIONS FOR DRIVEN PILES		5. Report Date November 2013	
		6. Performing Organization Code	
7. Author(s) Naser Abu-Hejleh, Ph.D., P.E.; William M. Kramer, P.E.; Khalid Mohamed, P.E.; James H. Long, Ph.D., P.E.; and Mir A. Zaheer, P.E.		8. Performing Organization Report No.	
9. Performing Organization Name and Address FHWA Resource Center (see below for address)		10. Work Unit No. (TR AIS)	
		11. Contract or Grant No.	
12. Sponsoring Agency Name and Address Federal Highway Administration Resource Center 4749 Lincoln Mall Drive, Suite 600 Matteson, IL 60443		13. Type of Report and Period Covered	
		14. Sponsoring Agency Code	
15. Supplementary Notes: This report is issued by the FHWA Resource Center as a deployment aid to help highway agencies develop LRFD-based design specifications for driven piles that explicitly cover LRFD limit states, estimated pile length and maximum supported load, drivability analysis, setup, and load tests. Also, design charts are presented as an effective way to communicate design results. This report is intended to reinforce and support the design guidance provided by the AASHTO and FHWA technical references cited herein.			
16. Abstract. This report is intended to provide a technical resource for highway engineers responsible for the development of Load and Resistance Factor Design (LRFD) specifications for driven piles based on the 2012 AASHTO LRFD Bridge Design Specifications. It addresses many of the issues and problems that highway agencies face in implementing LRFD design for driven piles. First, the report describes the AASHTO LRFD design limit states for driven piles, the design information obtained by addressing these limit states, and the overall design process needed to address them. Next, the report describes with examples the design procedure required to address all the strength limit states for the axial compression resistance of a single pile: geotechnical, drivability, and structural. These limit states are considered to determine the maximum factored axial compression load that can be applied to the top of a pile, Q_{fmax} . The geotechnical strength limit state is addressed by using both static analysis methods (e.g., the β -method) and field analysis methods (e.g., wave equation analysis) to determine the pile nominal bearing resistance at various depths and the pile length, L , needed to support a given factored axial compression load applied to the top of a pile, Q_f . For the field analysis methods, a new procedure to improve the agreement between the pile lengths estimated in the design and finalized in the field is presented. The advantages of static load tests and accounting for setup are demonstrated. Drivability analysis using wave equation analysis is employed to estimate the maximum length a pile can be safely driven to without damage, L_{max} . Safe drivability is addressed in the design by keeping the pile length less than or equal to L_{max} . The report also discusses addressing the drivability and structural limit states by fitting to local ASD practices. The design results obtained from addressing the three strength limit states for a single pile (geotechnical, structural, drivability) include a Q_f vs. depth curve and pile bearing resistance vs. depth curves up to Q_{fmax} and L_{max} . These results are summarized in a design chart that can be used by the foundation designers to optimize and finalize LRFD design for a pile group, such as obtaining pile length and required field bearing resistance. The report presents and solves a comprehensive LRFD Design Example problem to demonstrate the development and application of design charts using static and field analysis methods. Finally, the report describes how to ensure that all LRFD design limit states for driven piles are met in the field during construction.			
17. Key Words: FHWA, AASHTO, Driven Piles, Design, LRFD, ASD, Pile Length, Implementation, Limit States, Strength Limit State, Resistance, Static Analysis Methods, Dynamic Analysis Methods, Setup, Load Test, Drivability, Wave Equation Analysis.		18. Distribution Statement No restrictions. This document is available to the public from the sponsoring agency.	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 71	22. Price

SI CONVERSION FACTORS				
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm ²	square millimeters	0.0016	square inches	in ²
m ²	square meters	10.764	square feet	ft ²
m ²	square meters	1.195	square yards	yd ²
ha	hectares	2.47	acres	ac
km ²	square kilometers	0.386	square miles	mi ²
VOLUME				
ml	milliliters	0.034	fluid ounces	fl oz
l	liters	0.264	gallons	gal
m ³	cubic meters	35.71	cubic feet	ft ³
m ³	cubic meters	1.307	cubic yards	yd ³
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
tons	tons	1.103	tons	tons
TEMPERATURE				
°C	Celsius	1.8°C + 32	Fahrenheit	°F
WEIGHT DENSITY				
kN/m ³	kilonewton / cubic meter	6.36	poundforce / cubic foot	pcf
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kN	kilonewtons	225	poundforce	lbf
kPa	kilopascals	0.145	poundforce / square inch	psi
kPa	kilopascals	20.9	poundforce / square foot	psf

PREFACE

This report is issued by the FHWA Resource Center as a deployment aid to help highway agencies develop LRFD-based design specifications for driven piles that explicitly cover LRFD limit states, estimated pile length and maximum supported load, drivability analysis, setup, and load tests. Also, design charts are presented as an effective way to communicate design results. This report is intended to reinforce and support the design guidance provided by the AASHTO and FHWA technical references cited herein.

This report is intended to provide a technical resource for highway engineers responsible for the development of Load and Resistance Factor Design (LRFD) design specifications for driven piles based on the 2012 AASHTO LRFD Bridge Design Specifications. It addresses many of the issues and problems that highway agencies face in implementing LRFD design for driven piles, such as: (a) clarification of the AASHTO LRFD design limit states for driven piles and the overall design process used to address them; (b) large differences between the contract pile lengths estimated in the design phase and the ordered pile lengths finalized in the field; (c) determination of the maximum factored axial compression load that can be applied to the top of a pile, Q_{fmax} ; and (d) consideration of setup in LRFD pile design. The report describes in detail the design procedure required to address all the strength limit states for the axial compression resistance of a single pile: geotechnical, drivability, and structural. The design results obtained from addressing these three strength limit states are summarized in a design chart that can be used by the foundation designers to optimize and finalize LRFD design for a pile group, such as obtaining pile length and required field bearing resistance. A comprehensive LRFD Design Example problem is presented and solved to demonstrate the development and application of design charts using both static and field analysis methods.

The materials in this report will be of immediate interest to State DOT geotechnical and structural engineers involved in the LRFD design of driven piles and development of LRFD design specifications for driven piles. It will help them develop for driven piles more accurate and economical LRFD design methods than commonly used in practice. Implementation of the new LRFD platform provides an excellent opportunity for State DOTs to change and improve their design practices for driven piles by implementing the design recommendations presented in this report.

The authors wish to thank Mr. Jerry A. DiMaggio (SHRP2 Implementation Manager, the National Academies) for his technical input and reviews of an early draft of this report, and Ms. Andrea Thomas of CTC & Associates for her assistance with copyediting the final manuscript. The authors would also like to acknowledge Dr. Scott Anderson and Mr. Silas Nichols for their technical reviews and continuous support of this work.

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LIST OF SYMBOLS AND ABBREVIATIONS

New Definitions and Notation Introduced in this Report are Provided in Italics

AASHTO	American Association of State Highway and Transportation Officials
A_s	Pile steel cross-sectional area
ASD	Allowable stress design
BOR	Beginning of redrive (or restrrike)
bpi	Blows per inch
DD	Downdrag load
DOT	Department of transportation
D_{scour}	<i>Combined scour depth due to local scour, contraction, and degradation scour</i>
EOD	End of initial pile driving
FHWA	Federal Highway Administration
FS	Factor of safety
ft	Foot (or feet)
ft^2	Square foot (or feet)
f_y	Steel yield strength
GL	<i>Geotechnical resistance losses due to downdrag, scour, liquefaction, and future increases of groundwater level.</i>
GWL	Groundwater level
IGM	Intermediate geomaterial
in	Inch (or inches)
in^2	Square inch (or inches)
ksf	kips per square foot
ksi	kips per square inch
Pile length (length)	Vertical pile penetration or depth from ground surface.
L	<i>The pile length required to address the geotechnical strength limit state for compression resistance of a single pile.</i>
L_c	<i>The contract pile length needed to address all LRFD design limit states (largest of L, L_e, and L_m).</i>
L_e	<i>The pile length required to address the geotechnical extreme limit state for compression resistance of a single pile.</i>
L_m	<i>The minimum pile length (or penetration, as in AASHTO LRFD) defined as the deepest depth needed to address all of the applicable limit states and design requirements listed in AASHTO LRFD Article 10.7.6 (those not addressed through determination of L and L_e).</i>
L_{max}	<i>The maximum length a pile can be safely driven to without damage.</i>
LRFD	Load and resistance factor design
N_b	Number of hammer blows needed to drive the pile 1 inch, expressed as number of blows per inch (bpi)

NCHRP	National Cooperative Highway Research Program
NHI	National Highway Institute
P_n	Pile nominal axial compression structural resistance of a single pile.
P_{ni}	Nominal structural resistance available to resist the force effect (e.g., axial compression resistance of a single pile) for a given failure mode.
Q_f	<i>The largest factored axial compression load applied to the top of a single pile in a pile group.</i>
Q_{fmax} , $Q_{fmax-geotechnical}$, and $Q_{fmax-structural}$	<i>Q_{fmax} is the maximum factored axial compression load, Q_f, that can be applied to the top of a single pile. Q_{fmax} is obtained as the smaller of the Q_{fmax} value determined based on the pile geotechnical capacity ($Q_{fmax-geotechnical}$) and the Q_{fmax} value determined based on the pile structural capacity ($Q_{fmax-structural}$).</i>
Q_i , γ_i , R_{ni} , and ϕ_i	These terms appear in the general LRFD design equation (Eq. 2.2) to address various limit states for foundations. Q_i is the force effect on the foundation (e.g., axial compression load on a single pile) generated from a load applied to the bridge (e.g., dead load) and γ_i is the load factor for that load; R_{ni} is the nominal geotechnical resistance available to resist the force effect (e.g., pile bearing resistance) and ϕ_i is its resistance factors.
Q_s	<i>The highest service axial compression load applied to the top of a single pile in a pile group.</i>
Q_{smax}	<i>The maximum service axial compression load that can be applied to the top of a single pile.</i>
R_n , R_{nfield} , and R_{nstat}	R_n is the pile long-term nominal bearing (or geotechnical axial compression) resistance, defined as the smallest pile bearing resistance that would always be available to support the applied pile factored axial loads during the entire design life of the pile (or the bridge). R_n can be measured using field analysis methods ($R_n = R_{nfield}$) or estimated using static analysis methods ($R_n = R_{nstat}$).
R_{ndr}	Pile nominal bearing resistance available during driving and at end of initial driving (EOD) conditions.
R_{nre}	<i>Pile short-term nominal bearing resistance, available within a short period of time (often few days) from end of initial driving (EOD). This resistance can be estimated in the design phase using static analysis methods, or measured in the field by restriking the pile or performing a load test.</i>
R_R	Factored pile nominal bearing resistance
R_{R-NET}	Net factored pile nominal bearing resistance
TRB	Transportation Research Board
S_u	Soil undrained shear strength
σ_{dr}	Driving stresses generated during pile driving
σ_{dr-max}	<i>Pile maximum tolerable driving stresses (pile structural resistance during driving)</i>
α , α_{EOD} , and α_{BOR}	<i>Resistance median bias factors that define the bias between a specified static analysis method and a specified field analysis method (α) at EOD conditions (α_{EOD}) and at BOR conditions (α_{BOR}).</i>
γ , γ_{ave} , and γ_p	Load factor for structural loads (γ), average load factor (γ_{ave}), and load factor for downdrag load (γ_p)

γ_{sat}	Soil saturated unit weight
ϕ , ϕ_{dyn} , and ϕ_{stat}	Resistance factor for the method used to determine the pile nominal bearing (geotechnical axial compression) resistance. For field analysis methods (dynamic analysis methods and the static load test), $\phi = \phi_{\text{dyn}}$. For static analysis methods, $\phi = \phi_{\text{stat}}$.
ϕ_{da}	Resistance factor for pile drivability analysis.
ϕ_{str}	Resistance factor for pile axial compression structural resistance.

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND AND PURPOSE

In 2000, the American Association of State Highway and Transportation Officials (AASHTO) recommended, and the Federal Highway Administration (FHWA) concurred, that all State departments of transportation (DOTs) should follow Load and Resistance Factor Design (LRFD) principles in the design of all new highway bridges by October 2007. The LRFD platform will replace the allowable stress design (ASD) platform. FHWA has developed several National Highway Institute (NHI) training courses and LRFD-based technical manuals to assist DOTs in implementing LRFD platform in the design of foundations, including driven piles. However, DOTs still encounter issues and problems in implementing LRFD design for driven piles.

The primary goal of this report is to assist State DOTs in the development of LRFD design guidance for driven piles based on the 2012 AASHTO LRFD Bridge Design Specifications (referred to hereafter as “AASHTO LRFD”). This report addresses many of the issues and problems that highway agencies face in implementing LRFD design for driven piles.

Note that in this report, “pile length” is defined as pile penetration or depth from ground surface.

1.2 AASHTO LRFD BRIDGE DESIGN SPECIFICATIONS FOR DRIVEN PILES

Section 10 in AASHTO LRFD (2012) presents the LRFD design specifications for bridge foundations (spread footings, driven piles, drilled shafts, and micropiles) at the service, strength, and extreme event limit states. Foundation loads and structural and hydraulic designs are summarized in Section 10 and described in more detail in Sections 2 to 8. Section 10 discusses the following key topics:

- Article 10.4 describes the determination and selection of the soil and rock properties needed for foundation design and construction.
- Tolerable foundation movements at the service limit state are discussed in Article 10.5.2.
- Resistance factors for bridge foundations at all limit states, ϕ , are described in Article 10.5.5.
- Article 10.7 presents the design specifications for driven piles at all limit states. The service, strength, and extreme event limit states are described in Articles 10.7.2, 10.7.3, and 10.7.4 of the specifications, respectively. Figure 1.1 summarizes the main given and required design information for a single pile and a group of driven piles. Article 10.7.3.3

describes the pile length estimates needed for construction contract documents, L_c , and Article 10.7.6 presents the limit states and design requirements needed to determine the minimum pile length, L_m (referred to as “minimum pile penetration” in AASHTO LRFD). Article 10.7.3.8 discusses two types of methods for determining the nominal bearing (or geotechnical axial compression) resistances of a single pile at the strength limit: static analysis methods (e.g., the β -method) and field analysis methods (e.g., wave equation analysis). In Articles 10.7.3.3 and 10.7.7, the resistances determined through these methods are used to estimate the pile length, L , needed to support a given factored axial compression load applied to the top of a single pile, Q_f , at the strength limit state (see Figure 1.1).

- **Static analysis methods** (e.g., α - and β -methods; AASHTO LRFD Article 10.7.3.8.6). According to the AASHTO LRFD specifications, these methods are commonly used for estimating pile quantities in the design phase. The specifications indicate that static analysis may be used to finalize pile lengths in the design phase in cases where field analysis methods are unsuitable for field verification of nominal pile bearing resistance. Examples include projects with small pile quantities or loads, sites with long setup time (e.g., soft silts or clays where setup is long), and when piles will be driven to hard rock (Article 10.7.3.8.6a). Abu-Hejleh et al. (2010) indicated that AASHTO LRFD static analysis methods can be used in all cases to finalize the pile length in the design phase since reliability calibration is employed to develop resistance factors for these methods. With these methods, site variability must be addressed (see Abu-Hejleh et al., 2010).
- **Field analysis methods** (AASHTO LRFD Articles 10.7.3.8.1-5). These methods include the static load test and the following dynamic analysis methods: dynamic testing with signal matching, wave equation analysis, and dynamic formulas. These methods are routinely used by the vast majority of DOTs to verify pile resistances in the field and determine pile length. With these methods, the ordered pile lengths need to be determined in the field after driving test piles. In reality, contractors are often forced to order pile lengths based on the contract pile lengths estimated in the design phase (using the pile bearing resistances obtained with static analysis methods) before project construction begins so as to meet rolling schedules and construction deadlines. In some cases this can lead to large differences between the contract and ordered pile lengths.

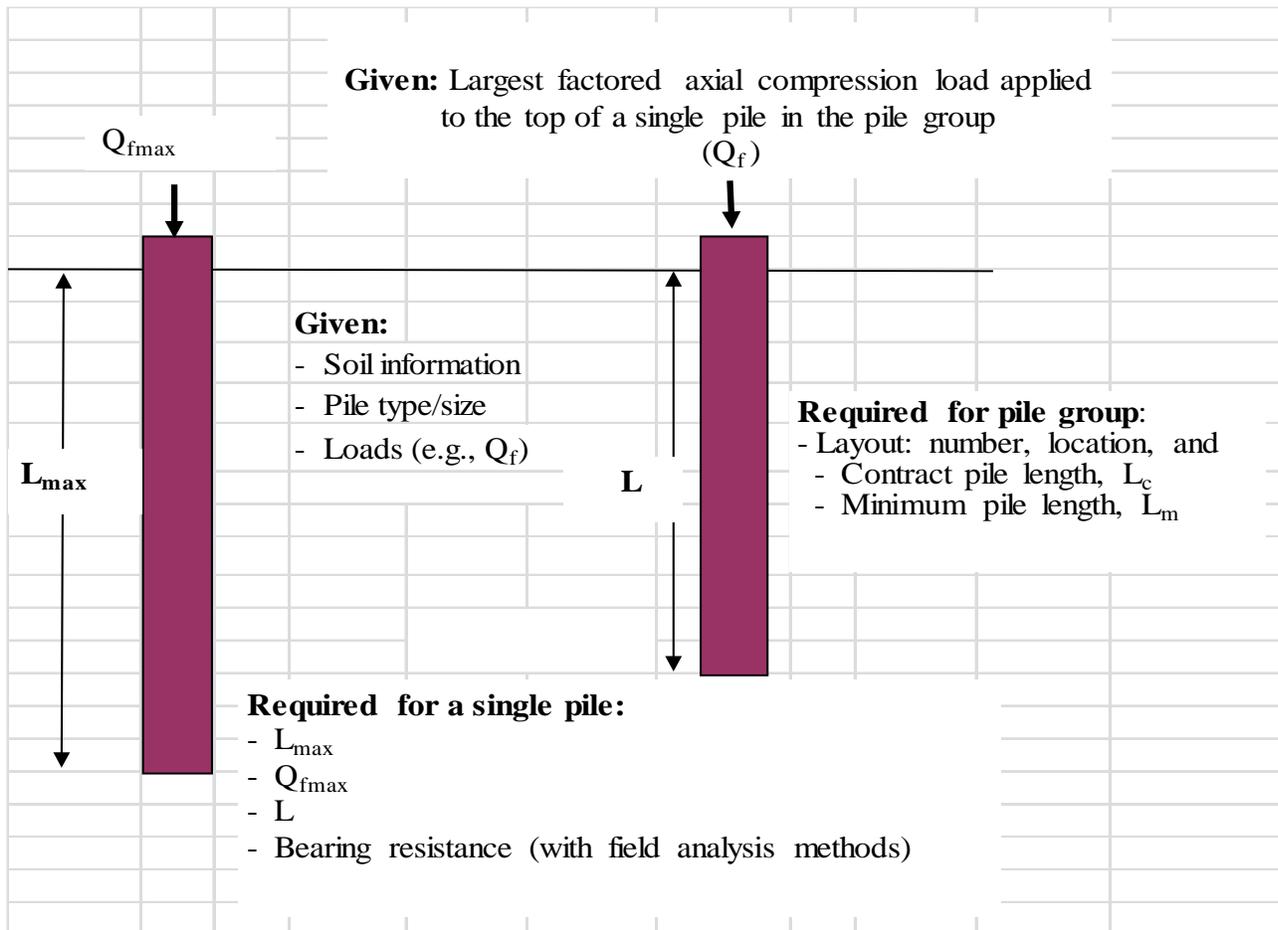


Figure 1.1. Given and Required Design Information for Driven Piles

- Article 10.7 of AASHTO LRFD discusses time-dependent changes in the nominal pile geotechnical resistance after driving due to setup and relaxation, and also discusses geotechnical resistance losses, GL, due to scour, future increases in the groundwater level (GWL), downdrag, and liquefaction. Site-specific setup can lead to savings if it is accounted for in the design. However, this site-specific setup must be verified in the field to be fully considered in the design. Article 10.7.8 describes the drivability analysis.

1.3 FHWA LRFD IMPLEMENTATION REFERENCES FOR DRIVEN PILES

FHWA's ASD-based technical references and training courses on driven piles remain valuable resources for LRFD implementation since they include materials cited in the AASHTO/FHWA LRFD technical references and cover issues that did not change with the transition to the LRFD platform. For example, the AASHTO LRFD design specifications for driven piles refer frequently to the FHWA manual on design and construction of driven piles (Hannigan et al., 2006). Although this manual follows the ASD platform, most of its contents are also applicable to the LRFD platform.

To assist State DOTs in implementing the AASHTO LRFD specifications for the design of driven piles, FHWA developed NHI training course 132082, “LRFD for Highway Bridge Substructures and Earth Retaining Structures,” (NHI, 2005). The course describes and gives examples of the LRFD design of driven piles. The course has been presented to the majority of State DOTs. FHWA has also provided direct technical support to DOTs.

FHWA recently developed a new web-based NHI training course: Course 132083, “Implementation of LRFD Geotechnical Design for Bridge Foundations” (Abu-Hejleh et al., 2010). The goal of this course is to assist DOTs in the successful development of LRFD design guidance for bridge foundations based on the 2010 AASHTO LRFD Bridge Design Specifications and their local experience. The course first presents an LRFD implementation plan of six consecutive steps, and the remainder of the course presents recommendations to assist DOTs with implementation of these steps. The course identifies and describes significant design changes for driven piles in the AASHTO LRFD platform compared with the ASD platform. Three options for LRFD implementation are thoroughly discussed in this course: adopting AASHTO’s LRFD methods, or developing local LRFD design methods by fitting to ASD practices or through reliability analysis of data collected at load test sites. Recommendations for implementation of these three options and for development of LRFD design guidance for bridge foundations are provided.

1.4 DEVELOPMENT AND ORGANIZATION OF THIS REPORT

The majority of LRFD implementation questions received by FHWA have been related to the LRFD design of driven piles. Some of these questions are addressed in the new NHI course described above (Course 132083). However, the following issues still need to be addressed:

- Clarification of the AASHTO LRFD design limit states for driven piles and the overall design process to address these limit states and obtain the design data needed in the construction plans, such as contract pile length and required field bearing resistances. AASHTO LRFD emphasizes the need to address all applicable structural and geotechnical limit states in the LRFD design of foundations, including the drivability limit state for driven piles. Drivability analysis is not specifically addressed in the ASD design platform. Failure to evaluate pile drivability in the design phase is one of the most common deficiencies in driven pile design practices.
- Large differences between the contract pile lengths estimated in the design phase and the ordered pile lengths determined in the field (when field analysis methods are selected in the design to determine pile length).

- Procedures for determining the maximum factored compression load that can be applied to the top of a single pile, Q_{fmax} , and the maximum penetration length that a pile can be safely driven to without damage, L_{max} .
- LRFD designs consideration and advantages of site-specific setup. Setup is common and often results in large increases in pile geotechnical resistances that are not routinely considered by most DOTs.
- LRFD design consideration and advantages of performing static load tests.
- Consideration of downdrag effect in the LRFD design.
- Consideration and advantages of using static analysis methods to finalize the pile length.

To address these issues and supplement NHI Course 132083, the FHWA Resource Center developed this report. The primary goal of this report is to assist highway engineers in developing LRFD design guidance for driven piles based on the 2012 AASHTO LRFD Bridge Design Specifications. Following this introductory chapter, this report provides five additional chapters to achieve this goal:

Chapter 2: LRFD Design Limit States and Design Process for Driven Piles. This chapter briefly describes the AASHTO LRFD design limit states for driven piles, the information obtained by addressing these limit states, and the overall design process needed to address them. The report focuses on the strength limit states for compression resistance of a single pile: geotechnical, drivability, and structural. The design results obtained from addressing these three strength limit states include a Q_f vs. depth curve and pile bearing resistance vs. depth curves up to Q_{fmax} and L_{max} . It is recommended to summarize these results in a design chart that can be used by the foundation designers to optimize and finalize LRFD design for a pile group by checking various limit states and obtaining pile length and required field bearing resistance. Finally, this chapter presents a comprehensive LRFD Design Example problem; a step-by-step solution to this problem is presented in Chapters 3 to 5.

Chapter 3: Nominal Bearing Resistances of a Single Pile. This chapter describes the procedure for determining the available nominal pile bearing resistances at various depths using static analysis methods and field analysis methods (e.g., wave equation analysis). The pile bearing resistances needed to solve the LRFD Design Example problem are also presented.

Chapter 4: Structural and Drivability Strength Limit States. This chapter describes the procedure used to address these limit states for the axial compression resistance of a single pile, and describes using wave equation analysis to perform drivability analysis and determine L_{max} . The results of these limit states that are needed to solve the LRFD Design Example problem are also presented.

Chapter 5: Geotechnical Strength Limit State and Design Charts. This chapter describes: (a) development of Q_f vs. depth curves for static and field analysis methods by addressing the strength limit state for the geotechnical axial compression resistance of a single pile; (b) determination of Q_{fmax} by addressing all strength limit states for compression resistance of a single pile (drivability, structural, and geotechnical); (c) development of design charts based on fitting to ASD practices; and (d) a solution to the LRFD Design Example problem that demonstrates the development and application of design charts for static and field analysis methods.

Chapter 6: Construction of Driven Piles. This chapter briefly describes how to ensure that all LRFD design limit states for driven piles are met in the field during construction, and outlines the design and construction data that should be compiled by DOTs to facilitate future improvements to their local LRFD design methods.

Notes.

1. The guidance presented in this report is applicable to piles driven into soils (including dense glacial tills) and soft rocks, where piles can be safely driven through them, and the required design pile length is controlled by both the geotechnical base and side resistances. The report does not cover the design of driven piles bearing on top of hard rocks. The ability of a pile to substantially penetrate rocks without damage during driving is what distinguishes soft rocks from hard rocks. Piles cannot safely penetrate hard rocks, so they should be seated on top of them; in this case the design is controlled by the pile structural resistance. According to Article 10.7.3.2.2 of AASHTO LRFD (2012), soft rocks can be penetrated safely by a pile during driving and should be analyzed in the same manner as soils.
2. This report doesn't provide a complete guidance on implementation of the AASHTO LRFD Bridge Design Specifications for driven piles. In addition to this report, State DOTs should review all references listed in this chapter (e.g., the most updated AASHTO LRFD specifications, the FHWA manual on design and construction of driven piles). In the next few years, the FHWA will update the current ASD NHI training course (132021) on driven piles to be LRFD based and to recognize the latest AASHTO LRFD Bridge Design Specifications.
3. It is assumed in this report that readers are familiar with common concepts used in the design and construction of driven piles, such as setup, downdrag, and test piles.

CHAPTER 2

LRFD DESIGN LIMIT STATES AND DESIGN PROCESS FOR DRIVEN PILES

This chapter briefly describes the AASHTO LRFD design limit states for driven piles, the design information obtained by addressing these limit states, and the overall design process needed to address them. Chapters 3 to 5 describe in detail the design procedures used to address the strength limit states for the compression resistance of a single pile.

2.1 AASHTO LRFD DESIGN LIMIT STATES FOR BRIDGE FOUNDATIONS

A limit state is a condition beyond which a bridge component ceases to satisfy the provisions for which it was designed. The structural and geotechnical failure modes for foundations that can lead to bridge failure are grouped into three distinct structural and geotechnical limit states (see Sections 1 and 3 and Articles 10.5.1 to 10.5.4 of the AASHTO LRFD specifications):

- **Service limit states.** The failure modes in these limit states are related to function and performance problems of the bridge caused by its foundation under loads and conditions applied continuously or frequently during the bridge design life. For example, in LRFD design, foundations must have adequate structural and geotechnical resistances to keep bridge displacements to a tolerable level.
- **Strength limit states.** The failure modes in these limit states are related to the strength and stability of the foundation under loads and conditions applied continuously or frequently during the bridge design life. In LRFD design, foundations must have adequate structural and geotechnical resistances to resist the loads applied to them with an adequate margin of safety against damage or collapse.
- **Extreme event limit states.** The failure modes in these limit states are related to the strength and stability of the foundation under loads and conditions applied during certain events that have a return period greater than the bridge design life; for example, failures under major earthquakes or floods. In LRFD design, the foundation must have adequate structural and geotechnical resistances to withstand the extreme events the bridge may experience during its life without causing collapse of the bridge. The design concern is survival of the bridge and protection of life safety (some damage to the structure is allowable).

To prevent foundation failures, AASHTO LRFD design specifications require that the summation of factored force effects on the foundation be less than or equal to the summation of the foundation factored nominal geotechnical resistances for all applicable geotechnical limit states. In addition, the summation of the factored force effects on the foundation must be less than or equal to the summation of the foundation factored nominal structural resistances for all

applicable structural limit states. These requirements are illustrated in the following equations:

$$\sum \gamma_i Q_i \leq \sum \phi_i R_{ni} \text{ for all applicable geotechnical limit states} \quad (2.1)$$

and

$$\sum \gamma_i Q_i \leq \sum \phi_{str} P_{ni} \text{ for all applicable structural limit states} \quad (2.2)$$

where:

- \sum indicates summation for a failure mode (e.g., bearing failure of a pile) identified in the limit state.
- Q_i is the force effect on the foundation (e.g., axial compression load on a single pile) from a load applied on the bridge (e.g., dead load) and γ_i is the load factor for that load.
- R_{ni} is the nominal geotechnical resistance available to resist the force effect (e.g., pile bearing resistance) and ϕ_i is its resistance factor.
- P_{ni} is the nominal structural resistance available to resist the force effect (e.g., axial compression resistance of a single pile) and ϕ_{str} is its resistance factor.

The 2012 AASHTO LRFD specifications emphasize the need to address all applicable structural and geotechnical limit states in the design, including the drivability limit state for driven piles.

The LRFD design limit states for driven piles can be grouped into three categories:

- Strength limit states for axial compression resistance of a single pile.
- Extreme event limit states for axial compression resistance of a single pile.
- Other geotechnical and structural limit states.

These limit states are briefly described in the following sections.

2.2 STRENGTH LIMIT STATES FOR AXIAL COMPRESSION RESISTANCE OF A SINGLE PILE

Figure 2.1 summarizes the given and required design information needed to address the strength limit states for a single pile subjected to compression loads. Q_f is defined as the largest factored axial compression load applied to the top of a single pile in a pile group. Q_{fmax} is defined as the maximum Q_f that meets all the strength limit states for compression resistance of a single pile (geotechnical, drivability, and structural). L_{max} is defined as the maximum length the pile can be safely driven to without damage.

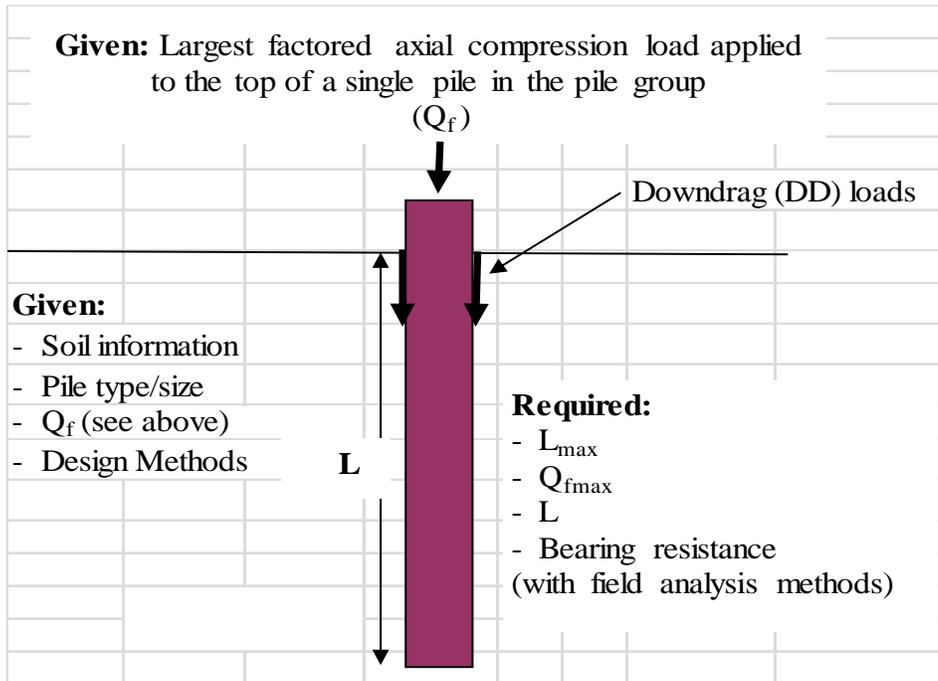


Figure 2.1. Given and Required Design Information Needed to Address the Strength Limit States for the Axial Compression Resistance of a Single Pile

2.2.1 Downdrag Effects and Factored Axial Compression Loads

According to the 2012 AASHTO LRFD (AASHTO Articles 3.11.8, 10.7.1.6.2, and 10.7.3.7), downdrag effect should be considered in the design of all deep foundations at all limit states. The downdrag effect should be applied in the design twice: as an additional axial compression load and as an additional lost nominal geotechnical resistance. According to AASHTO LRFD, downdrag loads (DD) and resistances at the strength limit are the same and equal to the nominal geotechnical side resistances of the soil layers located in and above the lowest layer contributing to downdrag.

The total factored axial compression load for a single pile at the strength limit state is equal to the summation of the factored compression load applied to the top of the pile (Q_f) and the factored downdrag load ($\gamma_p DD$), or

$$Q_f + \gamma_p DD \quad (2.3)$$

The load factor for downdrag, γ_p , is a function of the method selected to determine the side resistance or skin friction (see Table 3.4.1-2 in AASHTO LRFD).

Note. In June 2013, the AASHTO Subcommittee on Bridges and Structures approved changes to address downdrag effect in the design of drilled shafts. According to the revised AASHTO Articles 10.8.1.6.2 and 10.8.3.4, the downdrag effect at the strength limit state could be eliminated in some cases. It is expected that similar changes to the design of driven piles could be approved by AASHTO in the future. This would impact the procedure considered in this report to address the downdrag effect (e.g., reduce or eliminate the downdrag effect at the strength limit state).

2.2.2 Geotechnical Strength Limit State

The governing equation for the strength limit state for the axial compression geotechnical resistance of a single pile (Figure 2.1) is:

$$Q_f + \gamma_p DD \leq \phi R_n \quad (2.4)$$

where R_n is the nominal bearing resistance of a single pile and ϕ is the geotechnical resistance factor for the method employed to determine R_n . For static analysis methods (see AASHTO LRFD Article 10.7.3.8.6), $R_n = R_{nstat}$ and $\phi = \phi_{stat}$. For field analysis methods (see Articles 10.7.3.8.2-5), $R_n = R_{nfield}$ and $\phi = \phi_{dyn}$. Note that bearing resistance is also called axial compression geotechnical resistance. AASHTO LRFD Article 10.5.5.2.3 and Table 10.5.5.2.3-1 present and discuss the geotechnical resistance factors at the strength limit state.

Addressing the geotechnical strength limit state will generate:

- A Q_f vs. depth curve that provides the pile lengths, L , needed to support various factored axial compression loads applied to the top of the pile (Q_f).
 - With static analysis methods, the pile length, L , that the pile will be driven to in the field will be determined.
 - With field analysis methods, two design outputs will be obtained:
 - The required field bearing resistance needed to determine pile length in the field (AASHTO LRFD Articles 10.7.3.8, 10.7.7, and 10.7.9). The strength limit state must be met in the field by driving the pile to a length (vertical penetration depth) where the required field bearing resistance is achieved or exceeded.
 - An estimate of the pile length, L , needed to achieve the required field bearing resistance (Article 10.7.3.3). This length, estimated in the design phase, may be different from the length determined in the field.

The field analysis methods do not provide the R_{field} resistances needed for the estimation of the pile length, L , in the design phase. AASHTO LRFD (Articles C10.7.3.7 and 10.7.3.3) allows the use of static analysis resistance predictions to obtain this information, such as $R_{\text{field}} = R_{\text{nstat}}$. AASHTO LRFD Equation C10.7.3.3.-1 suggests using the resistance factor for the static analysis method, ϕ_{stat} , with R_{nstat} to estimate the pile length for the field methods. Using R_{nstat} and ϕ_{stat} in the design may lead to differences between the pile length estimated in the design and the pile length finalized during construction using field analysis methods. Some State DOTs employ an oversimplified approach of combining the ϕ_{dyn} from the field analysis method with the R_{nstat} estimated from the static analysis method (factored bearing resistance = $\phi_{\text{dyn}} R_{\text{nstat}}$) to estimate the pile length. This is not theoretically accurate since the resistance factor from the field method is matched with the resistance predictions from the static analysis method. Chapter 3 of this report describes a new procedure for estimating R_{field} resistances in the design phase that is expected to improve the agreement between the pile length estimated in the design, L , and pile length finalized in the field.

Note: In this report, the phrase “design method” refers to the method selected in the design phase to determine the pile length at the strength limit state, either a static or field analysis method.

2.2.3 Drivability Analysis

Based on AASHTO LRFD Articles 10.7.8 and 10.7.3, drivability analysis should be performed in the design to ensure that piles can be driven in the field without damage to the required bearing resistance or length (or penetration or depth) specified in the design. In this analysis, consider the loads induced by the selected driving hammer, using a load factor of 1 for all types of hammers (see Article C10.5.5.2.3). Article 10.7.8 recommends performing the drivability analysis using a wave equation analysis program to estimate driving stresses, σ_{dr} , and blow counts, N_{b} , often expressed as number of blows per inch (bpi). According to AASHTO LRFD (2012) and the FHWA manual on driven piles (Hannigan et al., 2006), the governing equations for drivability are:

$$\sigma_{\text{dr}} \leq \phi_{\text{da}} \sigma_{\text{dr-max}} \quad (2.5)$$

$$2.5 \leq N_{\text{b}} \text{ (bpi)} \leq 10 \quad (2.6)$$

where $\sigma_{\text{dr-max}}$ is the pile structural resistance during driving (or the maximum tolerable driving stress) and ϕ_{da} is its resistance factor. AASHTO LRFD Article 10.7.8 provides recommendations for the evaluation of $\sigma_{\text{dr-max}}$ for different pile types and with both compression and tension

driving stresses. Resistance factors (ϕ_{da}) for different pile types are presented in AASHTO LRFD Table 10.5.5.2.3-1.

As demonstrated in Chapter 4 of this report, L_{max} can be obtained from drivability analysis as the pile length (or penetration or depth) where the limiting conditions on driving stresses ($\phi_{da} \sigma_{dr-max}$) or blow counts (2.5 or 10 bpi) are reached. Then, L_{max} can be used to check pile drivability in the design by not allowing the required design pile length to exceed L_{max} . For example, to check estimated pile length, L , ensure that:

$$L \leq L_{max} \quad (2.7)$$

In the field analysis methods, L is an estimate of the length needed to achieve the required field bearing resistance in the field. Using this length, L , to check drivability is equivalent to using the required field bearing resistance to check drivability.

2.2.4 Structural Strength Limit State

The governing equation for the strength limit state for the axial compression structural resistance of a single pile (Figure 2.1) is:

$$Q_f + \gamma_p DD \leq \phi_{str} P_n \quad (2.8)$$

AASHTO LRFD Sections 5, 6, and 7 describe the methods used to predict the axial compression structural resistance, P_n , for different pile types and their resistance factors (ϕ_{str}). The structural limit state is addressed using the following equation:

$$Q_f \leq Q_{fmax} \quad (2.9)$$

2.2.5 Design Chart

The design information obtained from addressing the three strength limit states for the axial compression resistances of a single pile can be summarized in a design chart (as shown in Figure 2.2) that includes:

- Curves of various types of nominal bearing resistances at various depths up to L_{max}
- A curve of factored loads (Q_f) vs. depth up to Q_{fmax}

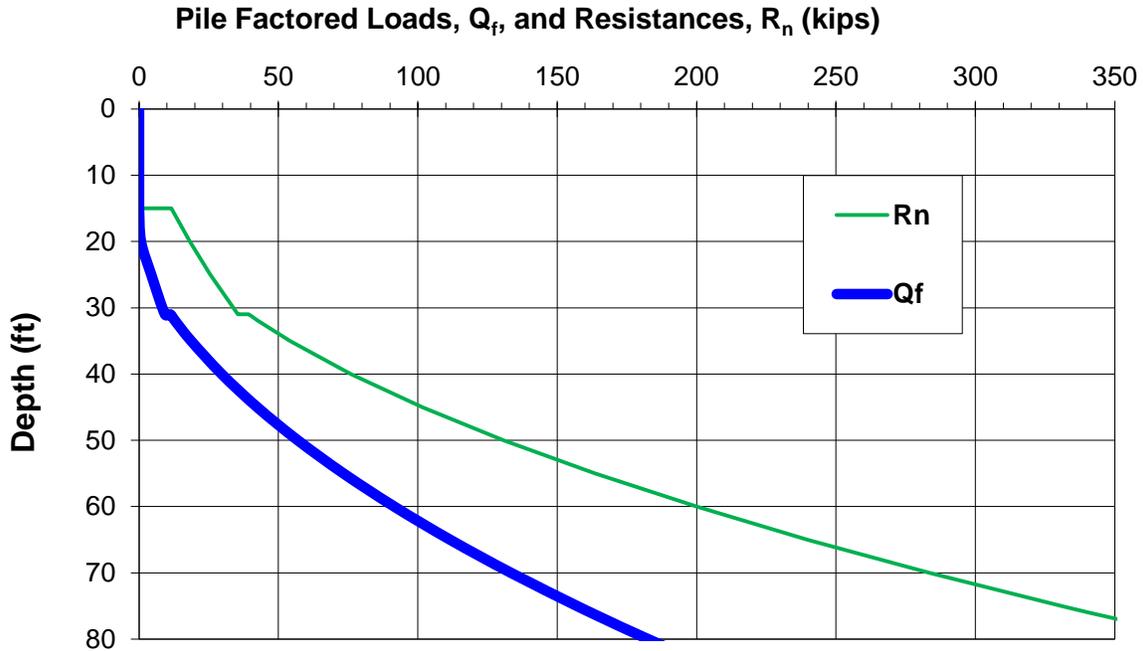


Figure 2.2. Sample Design Chart ($L_{\max} = 80$ ft, $Q_{f\max} = 182.6$ kips)

Chapters 3 to 5 of this report describe how to develop and use the design chart and provide step-by-step examples. For a given pile and design method for determining pile bearing resistances and length (a static or field analysis method), the design chart can be developed in two major steps, described below and summarized in Figure 2.3.

Step 1. Determine the available nominal bearing resistances at various depths using:

- a) The selected static analysis method.
- b) The design method selected to determine the pile length in the design phase, either a static analysis method or a field method. These resistances could be the same as in Step 1a.
- c) Wave equation analysis (needed for the drivability analysis performed in Step 2b). These resistances could be the same as in Step 1b if wave equation analysis is selected in the design to determine the pile bearing resistances and length.

Step 2. Address the strength limit states for the axial compression resistances of a single pile, using:

- a) The structural limit state.
- b) Drivability analysis using wave equation analysis, and determine L_{\max} .
- c) The geotechnical strength limit state to develop the Q_f vs. depth curve.
- d) All of the above strength limit states to determine $Q_{f\max}$.

The design chart allows the designer to check the various limit states and obtain both the required pile length, L , and the required field bearing resistance for any given factored axial compression load applied to the top of the pile, Q_f .

2.3 EXTREME EVENT LIMIT STATES FOR THE AXIAL COMPRESSION RESISTANCE OF A SINGLE PILE

The governing equations for the extreme event limit states for the geotechnical and structural axial compression resistances of a single pile are similar to those used for the strength limit states (Eqs. 2.4 and 2.8). Addressing the geotechnical limit state will generate the pile length (L_e) and the required field bearing resistance.

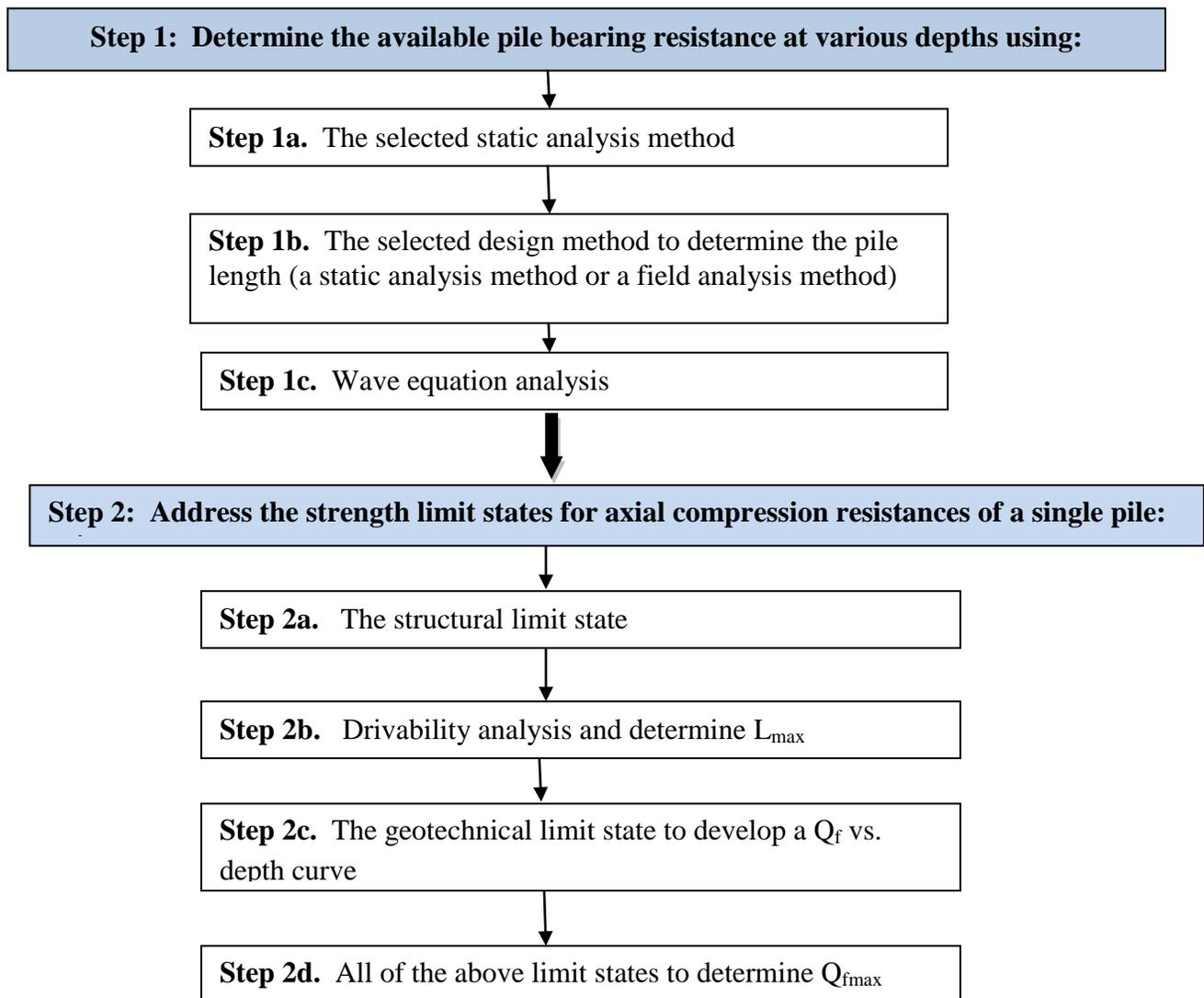


Figure 2.3. Steps in Developing a Design Chart

2.4 OTHER GEOTECHNICAL AND STRUCTURAL LIMIT STATES

Article 10.7 of AASHTO LRFD (2012) describes several other geotechnical and structural limit states in addition to those described in the previous two sections, which addressed compression resistance of a single pile at the strength and extreme event limit states. These additional limit states control the determination of the minimum pile length, L_m , defined as the deepest depth (or penetration) needed to address the following limit states and requirements (described in AASHTO LRFD Article 10.7.6), if applicable:

- Service limit states (e.g., settlement and lateral deflection).
- Axial uplift and lateral resistances at the strength and extreme event limit states.
- Compression resistance of a pile group at the strength limit state (Article 10.7.3.9). This requirement is not included in Article 10.7.6.

These limit states, together with those described in Sections 2.3 and 2.4 of this report, should satisfy the design requirements caused by downdrag, scour, and liquefaction. See the references presented in Section 1.3 of this report for more information on addressing these limit states and determining minimum pile length, L_m .

2.5 CONTRACT AND ORDERED PILE LENGTHS

Based on AASHTO LRFD Article 10.7.3.3, the contract pile length, L_c , is defined in this report as the length needed to address all the LRFD design limit states for driven piles, or as the largest of the: (a) pile length (L) required to address the geotechnical strength limit state for compression resistance of a single pile (Section 2.2.2 of this report); (b) pile length (L_e) required to address the geotechnical extreme event limit state for compression resistance of a single pile (Section 2.3); and (c) L_m required to address all other limit states (Section 2.4). To address drivability at all LRFD design limit states, consider either of the following two equations:

$$L \leq L_{\max}, L_e \leq L_{\max}, \text{ and } L_m \leq L_{\max} \text{ or } L_c \text{ (contract pile length)} \leq L_{\max} \quad (2.11)$$

If a static analysis method is selected to determine the pile length in the design phase, the contract pile length represents the length the piles need to be driven to in the field (the basis for the ordered length for production piles), since there will be no verification of resistance in the field. With the field analysis methods, there are two types of pile lengths:

- **Contract pile length**, determined as described above (the largest of L , L_e , and L_m). According to AASHTO LRFD Articles 10.7.3.3 and 10.7.3.1, the contract pile length is an estimate of the required pile quantities and should be used only as a basis for bidding, not for ordering piles.
- **Ordered pile length for production piles**, determined in the field as the length needed

to achieve both the required field bearing resistance (to address the strength and extreme event limit states for the axial compression resistances of a single pile) and the minimum pile length, L_m (AASHTO LRFD Article 10.7.9).

2.6 LRFD DESIGN PROCESS FOR DRIVEN PILES

Section 2.4 of the FHWA manual on design and construction of driven piles (Hannigan et al., 2006) presents an ASD design process for driven piles; an example problem is provided in Section 12 of the manual. Figure 2.4 presents the flow chart for this design process with 18 blocks. Addressing the design steps in Blocks 1 through 8 leads to the development of candidate driven piles and preliminary loads acting on the pile group. As the step in Block 8 is completed, it is suggested that designers also identify the candidate design methods for determining the pile bearing resistances and length (static analysis and/or field analysis methods). It is recommended that designers consider the static load test as a candidate design method. To develop an LRFD design process with steps similar to the ASD design steps presented in Blocks 8 to 18 of Figure 2.4, consider the recommendations presented next.

Preliminary Design Phase. For the candidate pile types and design methods selected to determine the pile bearing resistances and length, develop Q_f vs. depth curves up to Q_{fmax} and L_{max} by addressing all the strength limit states for compression resistance of a single pile following the procedure presented in Figure 2.3. An example is presented in Figure 2.5. These curves, together with cost considerations for candidate piles, can be used to limit the number of candidate pile types (to one or two) and design methods (to one or two) for the trial pile group sizing. The outcomes of the preliminary design phase are Q_f vs. depth curves up to Q_{fmax} and L_{max} for a limited number of combinations of candidate pile types/sizes and design methods.

Final Design Phase. Use the final foundation loads and the Q_f vs. depth curves up to Q_{fmax} and L_{max} obtained in the preliminary design phase to develop trial layouts for pile group (number, location, and depth) and for pile cap (size and thickness) that meet all applicable structural and geotechnical limit states (e.g., L_m and $L \leq L_{max}$, and $Q_f \leq Q_{fmax}$). Design the trial layouts to the extent needed to approximately estimate their total costs. Based on a comparison of the total costs of various trial layouts, select the most cost-effective combination of pile type/size and design method, and develop a design chart for this combination as described in Section 2.2.5.

The design chart (Figure 2.2) provides a simple, flexible approach that foundation designers can use to optimize and finalize the LRFD design for a pile group by checking various limit states (e.g., L_m and $L \leq L_{max}$, and $Q_f \leq Q_{fmax}$) and obtaining the data needed in the construction plans, such as pile length, L , and required field bearing resistance. For example, the design chart can be

effectively used to evaluate various layouts for a pile group and select the most cost-effective layout (number of piles, location, and length).

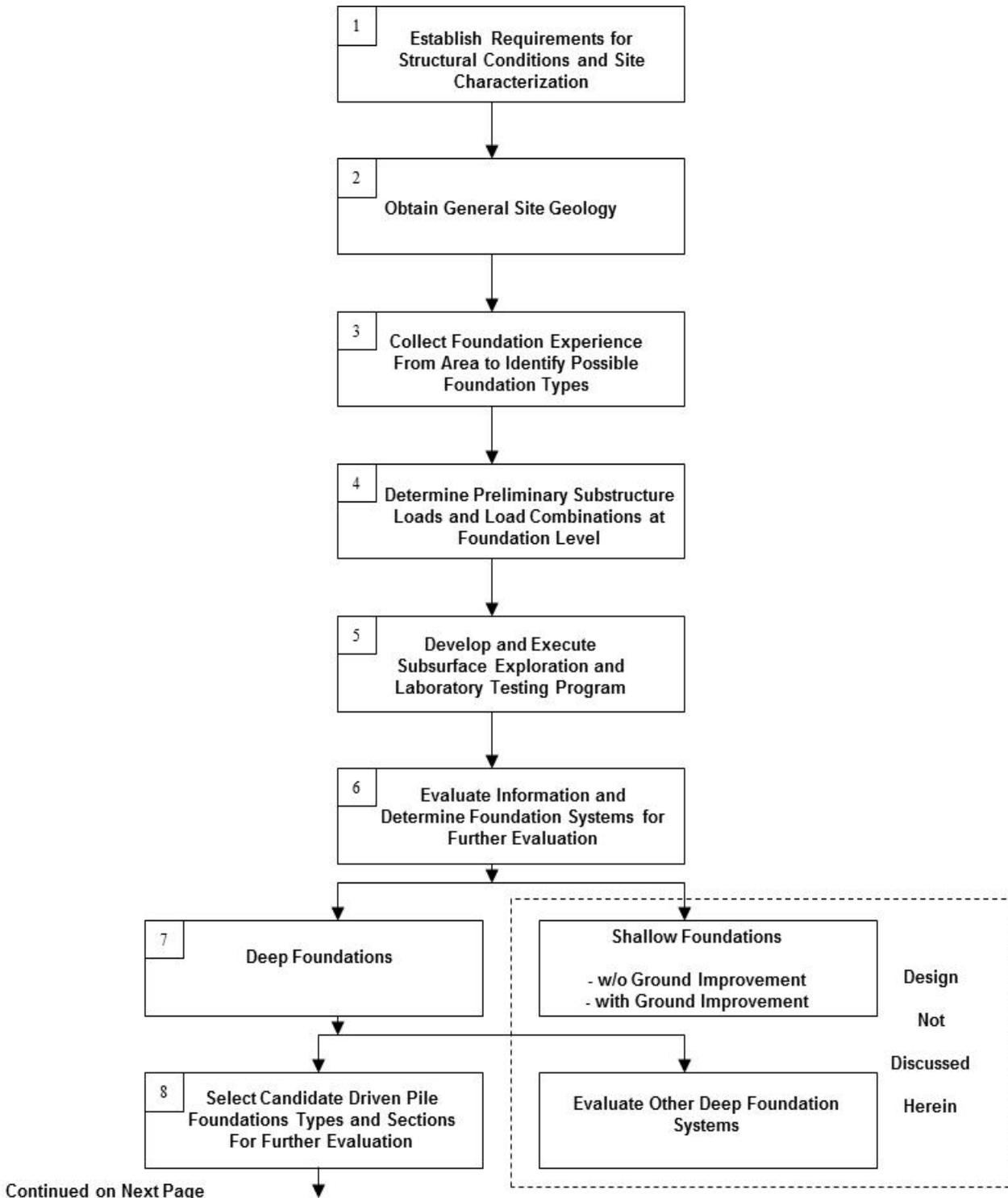


Figure 2.4. ASD Design Process for Driven Piles (Hannigan et al., 2006)

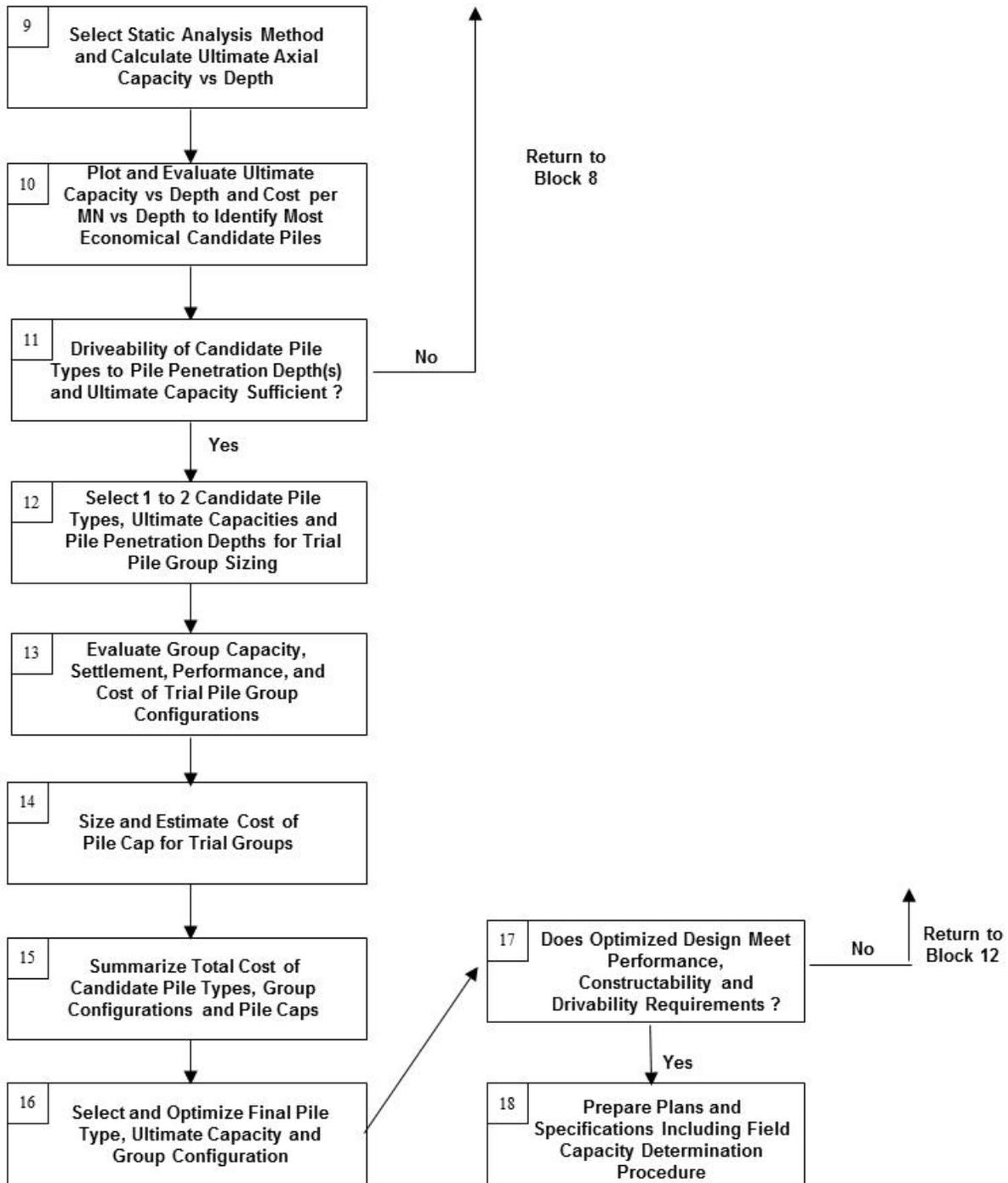


Figure 2.4 (continued). ASD Design Process for Driven Piles (Hannigan et al., 2006)

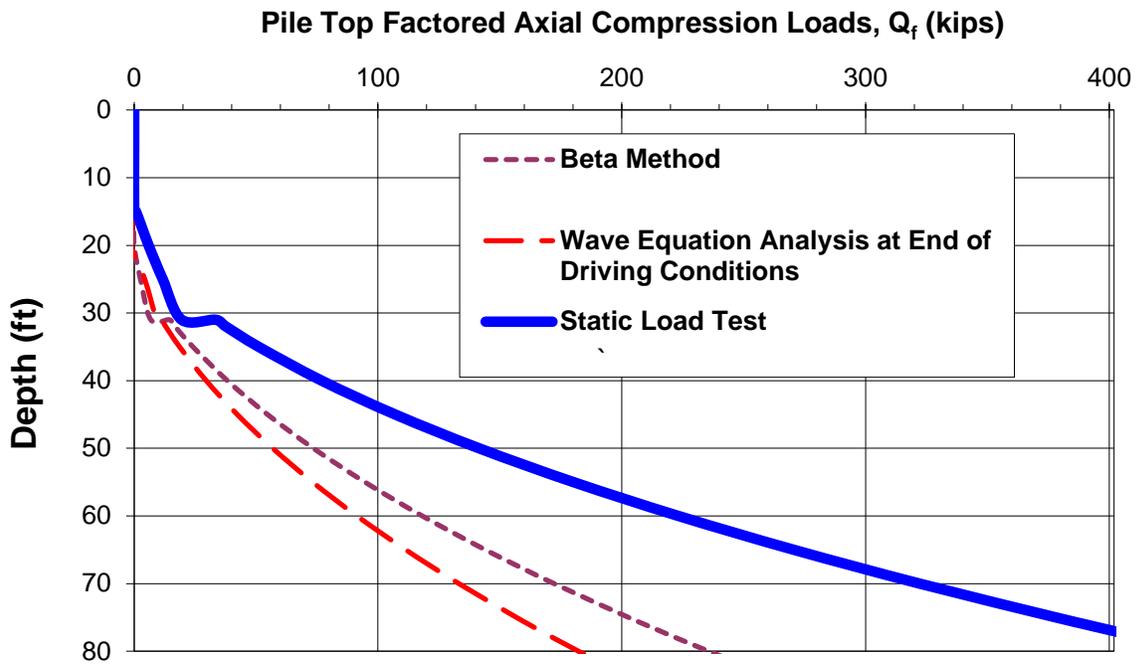


Figure 2.5. Evaluating Candidate Design Methods in the Preliminary Design Phase

2.7 LRFD DESIGN EXAMPLE PROBLEM

To demonstrate the LRFD design procedure presented in this report, an example problem is developed and solved step by step in Chapters 3 to 5. Figure 2.6 illustrates the details of this example. There are two soil layers: loose silty sand with no setup that extends to a depth of 31 ft from the ground surface, underlain by hard overconsolidated clay with an estimated setup factor of 50 percent (%). The top 15 ft of the loose silty sand layer will settle sufficiently to mobilize downdrag. The load factor for the downdrag load, γ_p , at the strength limit state is given as 1.4. The pile type is a 12x53 H-pile with steel yield strength, f_y , of 50 ksi; steel area, A_s , of 15.5 in²; box area of 1 ft²; and box perimeter of 4 ft. A structural resistance, ϕ_{tr} , at the strength limit state of 0.53 is recommended for the axial compression structural resistance.

The solution of the LRFD Design Example requires:

- I. Developing design charts for a 12x53 H-pile using the following four design methods to determine the pile bearing resistances and length:**
 1. β -method: a static analysis method with a resistance factor of 0.25 (AASHTO LRFD Table 10.5.5.2.3-1).
 2. Wave equation analysis at end of driving (EOD) conditions with a resistance factor of 0.5 (AASHTO LRFD Table 10.5.5.2.3-1).
 3. Wave equation analysis at beginning of restrike (BOR) conditions with a resistance

factor of 0.5 (AASHTO LRFD Table 10.5.5.2.3-1).

4. Based on fitting to the Iowa ASD procedure for wave equation analysis at EOD conditions.

II. Using the developed design charts to:

- Check the limit states for the following combinations of applied factored loads, Q_f , at the strength limit state, and minimum pile lengths, L_m : $(Q_f, L_m) = (100 \text{ kips}, 40 \text{ ft})$; $(100 \text{ kips}, 65 \text{ ft})$; $(100 \text{ kips}, 85 \text{ ft})$; and $(300 \text{ kips}, 65 \text{ ft})$ and identify the combinations that meet the limit states. Note that these combinations may not be realistic in an actual design, but were selected to demonstrate the design solutions for various scenarios that may be encountered in an actual design.
- Determine the contract pile length and the required field bearing resistances (if needed) for the combinations of Q_f and L_m that meet the limit states. It is given that the contract pile length and required field bearing resistance are not controlled by the extreme event limit states for the axial compression resistance of a single pile.

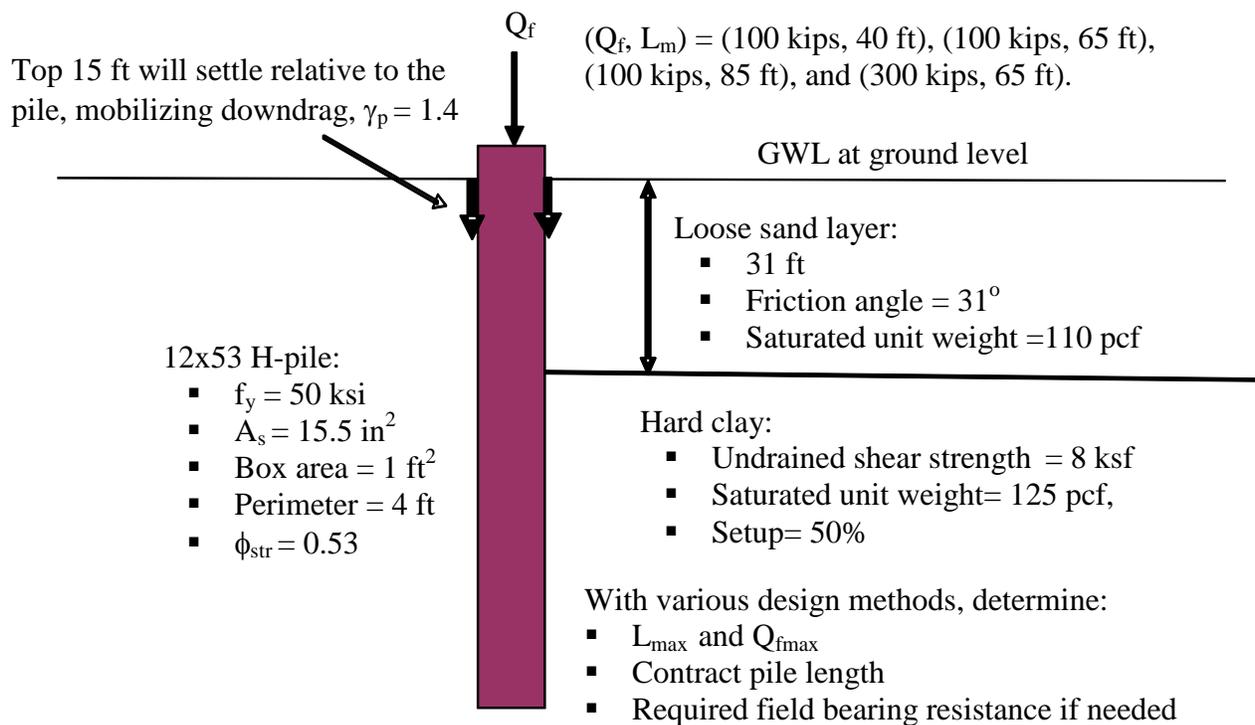


Figure 2.6. Details of the LRFD Design Example

CHAPTER 3

NOMINAL BEARING RESISTANCES OF A SINGLE PILE

This chapter describes Step 1 of the design procedure for developing a design chart for static and field analysis methods (Figure 2.3), which calls for determination of the available nominal bearing geotechnical resistances of a single pile at various depths. It also presents the bearing resistances needed to solve the LRFD Design Example and develop design charts.

3.1 TYPES OF PILE BEARING RESISTANCE

Both static and field analysis methods can be used to determine three types of nominal bearing resistance at three times:

- Resistance mobilized during pile driving, available until the end of driving (EOD), R_{ndr} .
- Short-term resistance (R_{nre}) available within a short period of time (often a few days) from EOD. The length of time is specified when field methods are selected to determine R_{nre} . The R_{nre} resistance includes the permanent changes in the pile's geotechnical resistances that occur after EOD (i.e., soil setup or relaxation). Soil setup (expressed as a percentage, or %) is defined as $100(R_{\text{nre}} - R_{\text{ndr}})/R_{\text{ndr}}$. If no changes in resistance (i.e., no setup or relaxation) occur after initial driving, then $R_{\text{nre}} = R_{\text{ndr}}$.
- Long-term resistance, available during the entire bridge/foundation design life (R_{n}). This is the resistance needed in LRFD design (Eq. 2.4). It is defined as the minimum pile bearing resistance that would always be available to support the applied pile factored axial loads during the entire design life of the bridge. It does not include the portion of the geotechnical resistance, defined as geotechnical resistance losses (GL), that may be present at EOD or shortly after EOD (included in R_{ndr} or R_{nre}) but would not be available during the entire bridge design life. Geotechnical resistance losses can be generated from downdrag, scour, liquefaction, and future increases of the groundwater level (GWL). Note that:
 - $R_{\text{n}} = R_{\text{nstat}}$ when R_{n} is determined through static analysis methods.
 - $R_{\text{n}} = R_{\text{nfield}}$ when R_{n} is determined through field analysis methods.

3.2 BEARING RESISTANCES FROM STATIC ANALYSIS METHODS

The static analysis methods used in LRFD design are described in AASHTO LRFD Article 10.7.3.8.6. These methods have two main components: (a) soil/rock strength properties collected from a subsurface exploration program (e.g., undrained shear strength, S_u) during

design, and (b) analytical models (or equations) used to estimate resistances (e.g., α -, β -, and Nordlund methods). Based on the analysis presented by Hannigan et al. (2006), the three types of bearing resistance at various depths are determined using static analysis methods in the following order:

- I. **R_{nre} (short-term resistance).** This is estimated from the side and base resistances of all the soil layers around the pile, including contributions from those layers that could eventually contribute to geotechnical resistance losses due to downdrag, scour, or liquefaction.
- II. **R_{ndr} (resistance at end of driving).** This is estimated from R_{nre} and the given time-dependent changes in resistance after driving (e.g., setup). For example, $R_{ndr} = R_{nre}/(1 + \text{setup})$ if setup is expected, and $R_{ndr} = R_{nre}$ if there is no setup. Site-specific setup factors are needed to determine R_{ndr} .

Profiles of R_{ndr} and R_{nre} vs. depth corresponding to the field conditions expected during pile driving and at restrike conditions, respectively, are needed in the design. Use the level of GWL expected during pile driving in the estimation of R_{nre} and R_{ndr} .

- III. **R_n or R_{nstat} (long-term resistance).** Compute this resistance using the same procedure used to compute R_{nre} and the following guidelines: (a) Use the highest GWL expected during the design life of the bridge, which can be different than GWL at time of driving; (b) Subtract the geotechnical resistance losses that will not be available to support the foundation loads during the entire bridge design life. The geotechnical resistance losses (GL) that should not be considered in computing R_{nstat} at the strength limit state are:

- **Downdrag (DD) effect** (AASHTO LRFD Articles 10.7.3.7 and 3.11.8). Assume zero bearing resistance ($R_{nstat} = 0$) for the soil layers located in and above the lowest soil layer contributing to downdrag. GL is the nominal side geotechnical resistances of these soil layers (equal to DD load). To compute R_{nstat} , consider only the pile base and side resistances of the soil layers located below the lowest soil layer contributing to downdrag ($R_{nstat} = R_{nre} - GL$). Downdrag effects not only decrease R_{nstat} resistances, but also add loads (see Section 2.2.1 of this report).
- **Scour effect.** For estimation of the total scour depth, D_{scour} , of a single pile at the strength limit state, consider Hannigan et al. (2006) and the FHWA's recently published Hydraulic Engineering Circular No. 18 (HEC-18) (Arneson et al., 2012). In computing R_n , consider the consequences of removal of soil layers within the scour depth (AASHTO LRFD Articles 3.7.5, 2.6.4.2, and

10.7.3.6).

- Assume zero bearing resistance ($R_{nstat} = 0$) for all soil layers within the total scour depth, D_{scour} .
- For the soil layers located below D_{scour} , compute R_{nstat} assuming no soil layers present above them. Consider zero vertical effective stresses only within the portion of the scour depth subject to degradation and contraction, but not within the lower portion generated from local scour (Hannigan et. al., 2006).
- GL due to scour can be computed at various depths as $R_{nre} - R_{nstat}$. Use the expected depth at the bottom of the pile to generate GL for design.

The soil at any given depth can only contribute to losses due to either downdrag or scour, but not both. Scour is likely to remove the soil causing downdrag. If both scour and downdrag are possible during the design life, develop two profiles of R_{nstat} vs. depth and consider both profiles in the design.

LRFD Design Example. The first step to solve this example is described below; the remaining steps in the solution are discussed later in this chapter and in Chapters 4 and 5. In this example, the β -method is selected to determine the pile bearing resistances from the static analysis needed to develop design charts (Step 1a in Figure 2.3). Figure 3.1 shows the results of calculating the available pile bearing resistances (R_{nre} , R_{nstat} , and R_{ndr}) at various depths using the β -method. These results are obtained as follows:

1. To generate the R_{nre} vs. depth profile:
 - a. The unit side resistance at various depths is computed as:
 - $0.28\sigma'_v$ in the sand layer, where σ'_v is the vertical effective stress.
 - $1.5\sigma'_v$ in the clay layer.
 - b. The unit base resistance is computed as:
 - $28\sigma'_v$ in the sand layer.
 - $9S_u$ or 72 ksf in the clay layer, where S_u is the undrained shear strength (8 ksf).
 - c. The total side resistance in the top 15 ft is computed as 6 kips, so $GL = DD = 6$ kips.
 - d. With a downdrag load of 6 kips, and given a downdrag load factor, γ_p , of 1.4, the factored DD load, $\gamma_p DD$, is 8.4 kips.

2. The R_n or R_{nstat} profile can then be developed as:
 - zero in the top 15 ft, and
 - $R_{nre} - 6$ kips below the 15 ft depth (Figure 3.1).

3. The R_{ndr} profile can then be developed as:
 - In the sand layer, $R_{ndr} = R_{nre}$, since no setup is considered for this layer.
 - In the clay layer, $R_{ndr} < R_{nre}$ due to a setup of 50%. The R_{nre} unit side resistances in the clay layer, computed at various depths as $1.5 \sigma'_v$, are divided by 1.5 to estimate the R_{ndr} unit resistances in the clay layers at various depths. The R_{ndr} unit base resistance is taken as 72 ksf (it is assumed that setup does not affect base resistance).

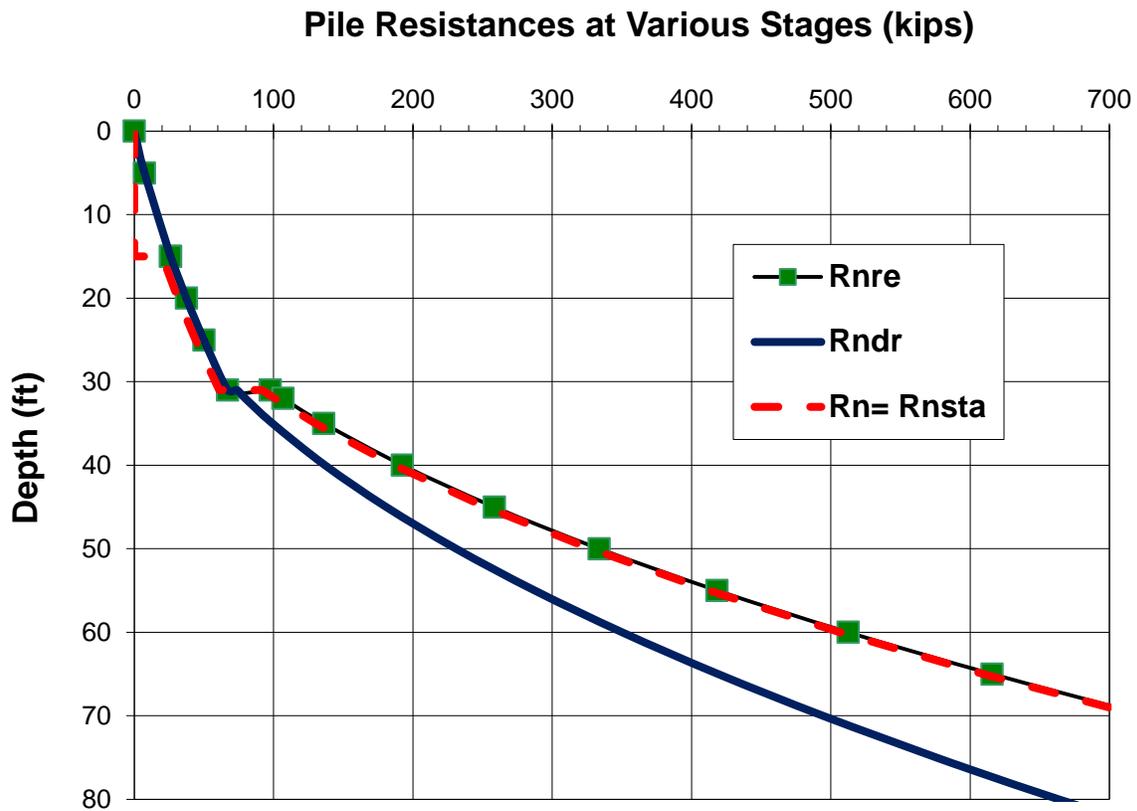


Figure 3.1. LRFD Design Example: Pile Bearing Resistances from the β -Method

3.3 BEARING RESISTANCES FROM FIELD ANALYSIS METHODS

3.3.1 Determination of Bearing Resistances in the Field

There are two types of methods to determine the pile nominal bearing resistance in the field:

- I. **Field dynamic analysis methods** (AASHTO LRFD Article 10.7.3.8.3-5). These methods include dynamic testing with signal matching, wave equation analysis, and dynamic formulas. These methods have two main components: an analytical model and the driving information needed as input for the analytical model. This information includes the hammer-developed energy, or stroke; the hammer efficiency; and the penetration resistance (or blow count), N_b , defined as the number of hammer blows needed to drive the pile 1 inch, expressed as blows per inch (bpi). As illustrated in Table 3.1, these methods can be used to determine the nominal bearing resistances in the field during pile driving, at the end of driving (EOD), R_{ndr} , and at beginning of redrive (BOR), R_{nre} , by restriking the pile. The time interval from EOD to BOR is called “restrike time.” AASHTO LRFD (2012) provides recommendations for restrike times for various types of soils.

- II. **Field static load test** (AASHTO LRFD Article 10.7.3.8.2). In this method, the short-term nominal bearing resistance, R_{nre} , at BOR is measured directly in the field after a waiting time following EOD, called “load test time.” AASHTO LRFD (2012) recommends a minimum of 5 days for load test times. It is recommended that the load test be performed after restriking the pile (load test time > restrike time).

Table 3.1. Measuring Pile Bearing Resistance with Field Dynamic Analysis Methods

Time	Depth (ft)	Hammer Blow Count (bpi)	Stroke (ft)	Field Bearing Resistance (kips)
R_{ndr}: Resistance measured during pile driving				
Driving	10	1	5	15
Driving	15	2	6	75
Driving	27	3	6.5	160
End of Driving (EOD)	33	5	6.5	220
R_{nre}: Short-term resistance measured by restriking the pile after a waiting time, called restrike time, from EOD				
Beginning of Redrive (BOR)	33	10	6.5	320

This report focuses only on soil setup (not relaxation) because setup is common and often results in large increases in geotechnical resistances that are not routinely considered by most DOTs. For setup to be directly considered and benefited from in the design, it must be verified in the field by measurements of both R_{ndr} and R_{nre} resistances.

Pile bearing resistances can be measured using field analysis methods at two conditions (see Table 3.1):

- **EOD conditions**, where only R_{ndr} resistances are measured during driving and at EOD and employed to determine the ordered pile length in the field. In this case, the site-specific setup is not verified in the field with restrikes or load tests. Site-specific setup should not be directly considered in the design since it will not be verified in the field. With this condition, R_n is determined as:

$$R_n = R_{nfield} = R_{ndr} - GL \quad (3.1)$$

- **BOR conditions**, where both R_{ndr} and R_{nre} resistances are measured. R_{ndr} resistances are measured during driving and at EOD. R_{nre} resistances are measured at BOR either with restrikes (for dynamic analysis methods) or static load tests, and are employed to determine the ordered pile length in the field (Abu-Hejleh et al., 2010). Site-specific setup is verified in the field through measurements of both R_{ndr} and R_{nre} resistances. With this condition, R_n is determined as:

$$R_n = R_{nfield} = R_{nre} - GL \quad (3.2)$$

As shown in Eqs. 3.1 and 3.2, the benefit of considering site-specific setup is to increase R_n . This will reduce the required design pile lengths.

3.3.2 Estimation of Field Bearing Resistances during Design

In the design phase, pile bearing resistances from field analysis methods, R_{nfield} , are not available to estimate the contract pile length or the GL needed to estimate the required field bearing resistances. AASHTO LRFD (Articles C10.7.3.7 and 10.7.3.3) allows the use of static analysis resistance predictions to obtain this information, such as $R_{nfield} = R_{nstat}$. However, this leads to differences between the pile length estimated in the design using R_{nstat} and the pile length determined in the field using the R_{nfield} resistances. To improve the estimate for contract pile length, it is suggested that designers determine and correct for the bias between the resistances computed with static analysis methods and with field methods. To estimate resistances for field methods in the design phase, AASHTO LRFD (2012) recommends adjusting the static analysis resistance predictions using bias information to

address differences between the static and field methods (Article C10.7.3.3 for pile length and C10.7.3.7 for downdrag and scour losses). However, the AASHTO LRFD specifications do not provide a specific procedure for implementing this adjustment.

We suggest using the following relationship to predict the resistances for a field analysis method, R_{nfield} , from the resistances calculated with a static analysis method, R_{nstat} :

$$R_{nfield} = \alpha R_{nstat} \quad (3.3)$$

where α is the median resistance bias between the field analysis method and the static analysis method. This is expanded to α_{BOR} at BOR conditions, defined as:

$$\alpha_{BOR} = R_{nre} \text{ (field analysis method)} / R_{nre} \text{ (static analysis method)} \quad (3.4)$$

and to α_{EOD} at EOD conditions, defined as:

$$\alpha_{EOD} = R_{ndr} \text{ (field analysis method)} / R_{nre} \text{ (static analysis method)} \quad (3.5)$$

With EOD conditions, only R_{ndr} resistances will be measured in the field and only R_{nre} resistances can be obtained from the static analysis methods because setup will not be directly considered in the design or verified in the field. Therefore, α_{EOD} is defined to estimate the R_{ndr} for the field analysis method from the R_{nre} calculated with the static analysis method. Hence, α_{EOD} accounts for both the resistance bias between the field and static analysis methods and the reduced resistance at EOD conditions due to setup.

As shown in Table 3.2, the resistances for a selected field analysis method can be predicted in the design phase using the resistances estimated with a selected static analysis method as follows:

- **BOR Conditions.** Estimate R_{ndr} , R_{nre} , R_{nstat} , and GL at various depths using the selected static analysis method and multiply them by α_{BOR} to predict at various depths the R_{ndr} , R_{nre} , R_{nfield} , and GL, respectively, for the selected field analysis method.
- **EOD Conditions.** Estimate R_{nre} , R_{nstat} , and GL at various depths using the selected static analysis method and multiply them by α_{EOD} to predict at various depths the R_{ndr} , R_{nfield} , and GL, respectively, for the selected field analysis method.

Table 3.2. Procedure for Estimating Resistances for a Field Analysis Method from Resistances Calculated with a Static Analysis Method in the Design Phase.

Resistances for a Static Analysis Method <i>LRFD Design Example:</i> <i>β-method</i>	Multiply by	Resistances for a Field Analysis Method <i>LRFD Design Example:</i> <i>Wave equation analysis</i>
BOR Conditions		
$R_{nre}, R_{ndr}, R_{nstat}, GL$	α_{BOR}	$R_{nre}, R_{ndr}, R_{nfield}, GL$
<i>GL = 6 kips</i>	<i>0.58</i>	<i>GL = 0.58 x 6 = 3.5 kips</i>
and		
EOD Conditions		
R_{nre}, R_{nstat}, GL	α_{EOD}	R_{ndr}, R_{nfield}, GL
<i>GL = 6 kips</i>	<i>0.58 for sand and 0.39* for clay</i>	<i>GL = 3.5 kips</i>
* Estimated with site-specific setup factor of 50% as $0.58/(1.5) = 0.39$		

Determination of local α_{BOR} , α_{EOD} , and setup factors. Accurate estimates of pile bearing resistances for the field analysis methods, including wave equation analysis, must be developed in the design phase to allow for better estimation of the pile length, L, and to perform more accurate drivability analysis using wave equation analysis. Therefore, accurate α_{BOR} and α_{EOD} factors must be developed. In addition, developing accurate site-specific setup factors is valuable for the design and construction of driven piles. To develop local α_{BOR} , α_{EOD} , and setup factors, consider the following recommendations:

- 1. Local calibration of field analysis methods.** This calibration can be performed as shown in Table 3.3 by compiling the predicted R_{nre} resistances from the calibrated static analysis method and the measured R_{nre} and R_{ndr} resistances from the calibrated field analysis method at EOD and BOR conditions. Analyze these data to obtain the resistance bias between the static analysis method and the field analysis method at BOR conditions and at EOD conditions. Then, obtain the resistance median bias factors at BOR conditions, α_{BOR} , and at EOD conditions, α_{EOD} . A similar procedure (also shown in Table 3.3) can be used to obtain the median setup factor. Develop α_{BOR} , α_{EOD} , and the setup factor for different combinations of typical conditions encountered in the design and construction of production piles in actual projects. For example, develop these factors for an H-pile driven into sand, using the β -method as the static analysis method and wave equation analysis as the field analysis method, and with the specified restrrike time and procedure.
- 2. Reliability calibration based on load test data.** α_{BOR} can be estimated based on the resistance mean bias, λ , developed in the reliability calibration of resistance factors

(Abu-Hejleh et al., 2010) for the static analysis method, λ_{stat} , and for the field analysis method at BOR conditions, λ_{BOR} , using the equation:

$$\alpha_{BOR} = \lambda_{stat}/\lambda_{BOR} \quad (3.6)$$

Then, based on the expected site-specific setup factors, estimate α_{EOD} as $\alpha_{BOR}/(1 + \text{setup})$. Note that in this approach, α_{BOR} and α_{EOD} represent the mean (not median) resistance bias factors, so they are approximate solutions. It is important to select λ_{stat} and λ_{BOR} parameters that are representative of the typical conditions encountered in the design and construction of production piles in actual projects.

There are uncertainties in the approaches suggested above to predict in the design phase the field pile bearing geotechnical resistances (R_{nfield}). Based on design consequences for overestimating or underestimating these resistances and the confidence in the developed α_{BOR} , α_{EOD} factors, it is recommended to apply an appropriate safety factor to the design results obtained from using these approaches.

Table 3.3. Developing the Median: Resistance Bias Factors Between a Field Analysis Method and a Static Analysis Method and Setup Factor.

R_{nre} Resistances from Static Analysis Method (kips)	Resistances from Field Analysis Method (kips)				Setup (%) (R_{nre}-R_{ndr})/R_{ndr}
	R_{ndr}	α_{EOD} (Field R_{ndr}/ Static R_{nre})	R_{nre}	α_{BOR} (Field R_{nre}/ Static R_{nre})	
625	410	0.66	512	0.82	25
633	504	0.80	610	0.96	21
571	308	0.54	381	0.67	24
489	409	0.84	470	0.96	15
853	475	0.56	590	0.69	24
550	426	0.78	533	0.97	25
817	412	0.50	515	0.63	25
Median		0.66		0.82	23

LRFD Design Example. In this example, wave equation analysis was selected as the design method both to determine the pile bearing resistances for estimation of the pile length and to perform the drivability analysis. Therefore, the same resistances from the wave equation analysis are needed in Steps 1b and 1c to develop the design chart. The resistances for the wave equation analysis presented in Figure 3.2 are developed as follows:

1. **Determination of α_{BOR} .** For both the sand and clay layers, α_{BOR} is estimated as $0.61/1.05 = 0.58$ based on $\lambda_{stat} = 0.61$ reported for the β -method (Paikowsky et al., 2004) and $\lambda_{BOR} = 1.05$ reported for wave equation analysis (Smith et al., 2010).
2. **Determination of α_{EOD} .** With $\alpha_{BOR} = 0.58$ for both the sand and clay soils, α_{EOD} is estimated as 0.58 for the sand (no setup) and as $0.58/(1 + 0.5) = 0.39$ for the clay layer (setup of 50%).
3. Use the procedure in Table 3.2 to estimate the R_{nre} , R_{ndr} , and R_{nfield} resistances for the wave equation analysis method at BOR conditions using α_{BOR} (presented in Figure 3.2), and using R_{ndr} , R_{nre} , and R_{nstat} estimated using the β -method (in Figure 3.1).
4. Use the procedure in Table 3.2 to estimate the R_{ndr} and R_{nfield} resistances for the wave equation analysis method at EOD conditions using α_{EOD} (presented in Figure 3.2), and using R_{nre} and R_{nstat} resistances estimated using the β -method (presented in Figure 3.1). Note that the R_{ndr} resistances at EOD and BOR conditions are the same.
5. With GL estimated as 6 kips using the β -method, GL for the wave equation analysis is computed as $0.58 \times 6 = 3.5$ kips at both EOD and BOR conditions (the value is the same for both conditions since GL is developed in a sand layer with no setup).

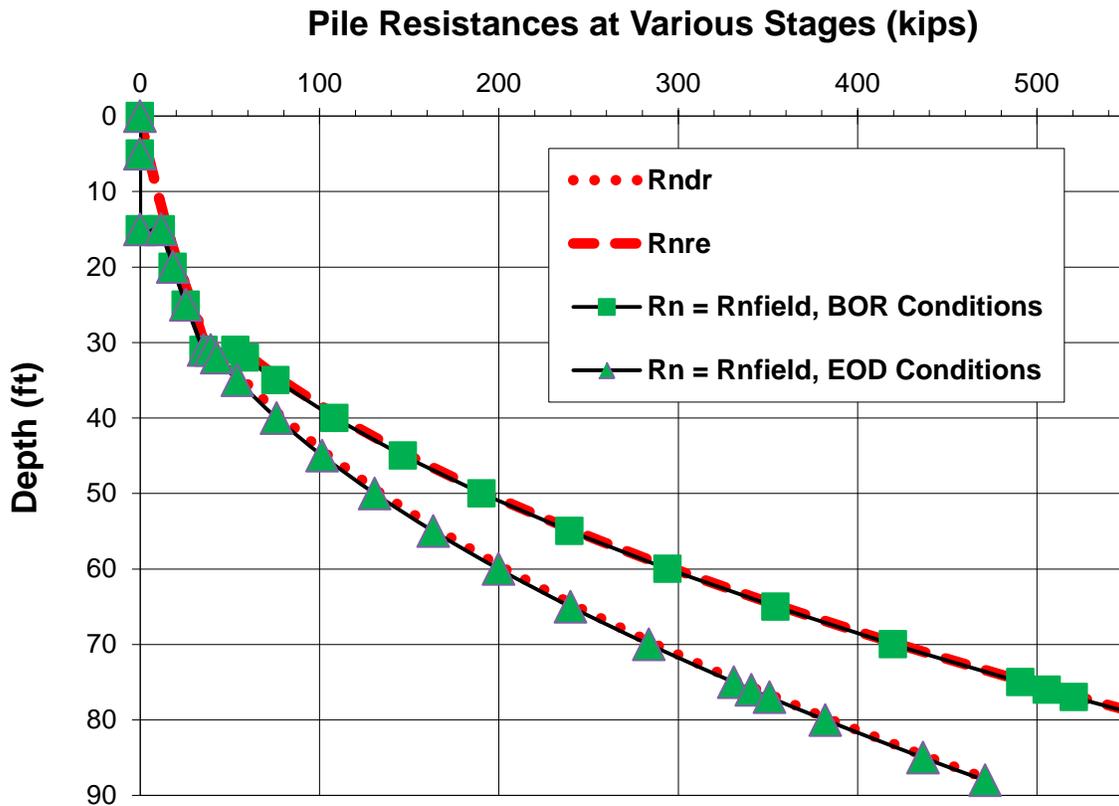


Figure 3.2. LRFD Design Example: Pile Bearing Resistances for Wave Equation Analysis at EOD and BOR Conditions

CHAPTER 4

STRUCTURAL AND DRIVABILITY STRENGTH LIMIT STATES

This chapter describes Steps 2a and 2b of the procedure for developing a design chart (Figure 2.3), which call for addressing the structural and drivability strength limit states for the axial compression resistances of a single pile, and using wave equation analysis to perform drivability analysis and determine L_{\max} . This chapter also presents the results of these limit states needed to develop design charts for the LRFD Design Example.

4.1 STRUCTURAL STRENGTH LIMIT STATE

The governing LRFD design equation for the strength limit state for the axial compression structural resistance of a single pile is:

$$Q_f + \gamma_p DD \leq \phi_{\text{str}} P_n \quad (4.1)$$

$Q_{\text{fmax-structural}}$ is defined as the maximum factored axial compression load, Q_f , that can be applied to the top of a single pile based on the pile structural capacity, which can be computed based on Eq. 4.1 as $Q_{\text{fmax-structural}} = \phi_{\text{str}} P_n - \gamma_p DD$. AASHTO LRFD Sections 5, 6, and 7 describe the methods used to predict the axial compression structural resistance, P_n , for different pile types, which have varying resistance factors (ϕ_{str}). Assuming full embedment of the pile (no scour), the axial compression structural resistance is computed as $P_n = A_s f_y$ for an H-pile, where A_s is the pile steel area. Per AASHTO LRFD Article 6.5.4.2, ϕ_{str} is 0.5 for the axial compression resistance of H-piles subjected to severe driving conditions where use of a pile tip is necessary. A larger structural resistance factor of 0.6 is recommended for H-piles in good driving conditions where use of a pile tip is not necessary. In the LRFD Design Example, a structural resistance factor of 0.53 is selected.

LRFD Design Example: Determination of $Q_{\text{fmax-structural}}$

- The factored downdrag load, $\gamma_p DD$, is estimated in Section 3.2 as 8.4 kips.
- For a 12x53 H-pile with $f_y = 50$ ksi, $A_s = 15.5 \text{ in}^2$, and $\phi_{\text{str}} = 0.53$, $Q_{\text{fmax-structural}}$ is estimated as $0.53 \times 50 \times 15.5 - 8.4 = 402$ kips.

4.2 DRIVABILITY ANALYSIS AND DETERMINATION OF L_{MAX}

4.2.1 Governing Equations for Drivability Analysis

Based on AASHTO LRFD (Articles 10.7.8 and 10.7.3.1), drivability analysis should be conducted in the design phase to ensure that the pile can be safely driven in the field without damage to the design required bearing resistance or length (e.g., L , L_m , or L_c). In this analysis, consider the loads induced from the selected driving hammer, using a load factor of 1 for all types of hammers (see Article C10.5.5.2.3). Article 10.7.8 recommends performing the drivability analysis using wave equation analysis to estimate driving stresses, σ_{dr} , and blow counts, N_b , often expressed as number of blows per inch (bpi). The first governing equation for the drivability analysis is:

$$\sigma_{dr} \leq \phi_{da} \sigma_{dr-max} \quad (4.2)$$

where σ_{dr-max} is the pile structural resistance during driving (or the maximum tolerable driving stress) and ϕ_{da} is its resistance factor. AASHTO LRFD Article 10.7.8 provides recommendations for the evaluation of σ_{dr-max} for different pile types and with both compression and tension driving stresses. Resistance factors (ϕ_{da}) for different pile types are presented in AASHTO LRFD Table 10.5.5.2.3-1. Based on the FHWA manual on design and construction of driven piles (Hannigan et al., 2006), the second governing equation for the drivability analysis is:

$$2.5 \leq N_b \leq 10 \quad (4.3)$$

According to AASHTO LRFD (commentary section), the upper limit on the blow count is 10 to 15 blows per inch (bpi). Both AASHTO LRFD and the FHWA manual on driven piles allow for a higher upper limit on the blow count in some cases, such as if a higher blow count is required just at the end of driving, or if restrikes are limited to test piles rather than production piles.

Driving the pile to the bearing resistance or length required to address various LRFD limit states will generate various driving stresses (σ_{dr}) and blow counts (N_b) that can be estimated from the wave equation analysis described above (e.g., using hammer loads). Drivability at all limit states is addressed if all driving stresses and blow counts meet Eqs. 4.2 and 4.3.

New Governing Equation for Drivability Analysis. L_{max} is determined as the pile length (or penetration or depth) where the limiting conditions on driving stresses ($\phi_{da} \sigma_{dr-max}$) or blow counts

(2.5 or 10 bpi) are reached. L_{\max} can be used as follows to address drivability at all LRFD design limit states:

$$L \leq L_{\max}, L_e \leq L_{\max}, \text{ and } L_m \leq L_{\max} \quad (4.4)$$

or

$$\text{Contract pile length } (L_c) \leq L_{\max} \quad (4.5)$$

The contract pile length, L_c , is defined as the length needed to address all the LRFD design limit states for driven piles, including the pile length (L) needed to address the geotechnical strength limit state for compression resistance of a single pile. In the field analysis methods, L is an estimate of the pile length needed to achieve the required bearing resistance in the field at the strength limit state. Using this pile length, L , to check drivability is equivalent to using the required field bearing resistances to check drivability. Therefore, Eq. 4.4 or 4.5 will check drivability to the required bearing resistances and depths needed to address all LRFD design limit states (per AASHTO LRFD Article 10.7.8).

4.2.2 Conditions for Checking Pile Drivability

L_{\max} needs to be evaluated and the drivability limit state per Eq. 4.4 (or Eq. 4.5) needs to be checked at two conditions:

- **Driving conditions.** This condition includes end of driving (EOD) conditions. At this condition, Eq. 4.4 (or Eq. 4.5) should always be met using all the design methods selected to determine pile bearing resistances and length. It is important to ensure that the pile can be safely driven to: (a) the required minimum pile length, L_m ; (b) the required length determined with static analysis methods; and (c) the required R_{ndr} resistances determined through all field analysis methods (the static load test and dynamic analysis methods at EOD and BOR conditions).
- **Restrike conditions.** At restrike conditions, L_{\max} is the maximum pile length the pile can be driven to for verification of setup without damaging the pile. Driving the pile to depths beyond the L_{\max} for restrike conditions to verify additional resistance from setup may damage the pile. Therefore, the smaller L_{\max} for restrike conditions needs to be considered in evaluating the drivability limit state per Eq. 4.4 (or Eq. 4.5) when site-specific setup will be verified in the field with restrikes (as is the case when dynamic analysis methods at BOR conditions are selected to determine pile length). Drivability evaluation at restrike conditions is not needed if field verification of site-specific setup is not needed; for example, when selecting the static load test or dynamic analysis methods at EOD conditions or static analysis methods to finalize pile length. Drivability evaluation at restrike conditions is also not needed for checking drivability to the minimum pile length.

4.2.3 Wave Equation Analysis

With wave equation analysis, there are two options for evaluating drivability: the bearing option and the drivability option (see Hannigan et al., 2006). For both options, the following information is needed:

- Soil and pile design information, and the common or most likely range of local driving (hammer) systems.
- Predictions of R_{nre} vs. depth and/or R_{ndr} vs. depth determined with the wave equation analysis. Presently, these resistances are estimated using one of the static analysis methods, which could be different than those measured in the field. Therefore, it is recommended to estimate these field resistances in the design as discussed before (see Table 3.2), by using both resistances of the selected static analysis method, together with α_{BOR} and α_{EOD} , defined as the median resistance factors between the wave equation analysis method at BOR and EOD conditions and the selected static analysis method. This will improve accuracy of the wave equation analysis for drivability.

It is recommended to adopt the drivability option because it is more accurate than the bearing option. With this option, the output results for the driving and restrike conditions are blow counts and driving stresses at various depths. Based on these results, L_{max} for the driving and restrike conditions can be identified at the depth where the limiting conditions on driving stresses or blow count are reached. With this determination of L_{max} , the drivability limit state can be met with Eq. 4.4.

If the bearing option is selected for evaluating drivability, then the required R_{ndr} and R_{nre} resistances needed for this option should be determined from the wave equation analysis predictions for R_{ndr} and R_{nre} at the contract pile length. At the required R_{ndr} and R_{nre} , the driving stresses and blow counts can be determined and compared with the limiting conditions on driving stresses or blow count, per Eqs. 4.2 and 4.3.

LRFD Design Example: Determination of L_{max} . The wave equation analysis program used to solve this example is the GRLWEAP program (Hannigan et al., 2006). The drivability option is selected in the wave equation analysis for evaluation of drivability.

Input data:

- The estimated R_{ndr} and R_{nre} resistance vs. depth curves for the wave equation analysis in Figure 3.2 are copied to the design chart (Figure 4.1).

- Several types of hammers were evaluated in the drivability analysis. A D30-23 diesel hammer was selected because it is a commonly available hammer. A hammer efficiency of 80% was selected.
- The maximum tolerable driving stress, σ_{dr-max} , for steel is $0.9f_y = 45$ ksi, and the maximum permissible penetration resistance is 10 bpi.
- The drivability resistance factor, ϕ_{da} , for steel is 1.

Output results. The results of drivability analysis in terms of blow counts and compression stresses at various depths for driving and restrike conditions are provided in Figure 4.2. L_{max} is obtained from Figure 4.2 at the depth where the limiting conditions for driving stresses (45 ksi) or blow count (10 bpi) are met: 87 ft for driving conditions and 73 ft for restrike conditions. To account for uncertainties in the procedure suggested in this report to predict in the design the pile geotechnical resistances from the wave equation analysis, conservative (smaller) L_{max} values of 80 ft for driving conditions and 70 ft for restrike conditions are selected to solve the LRFD design example.

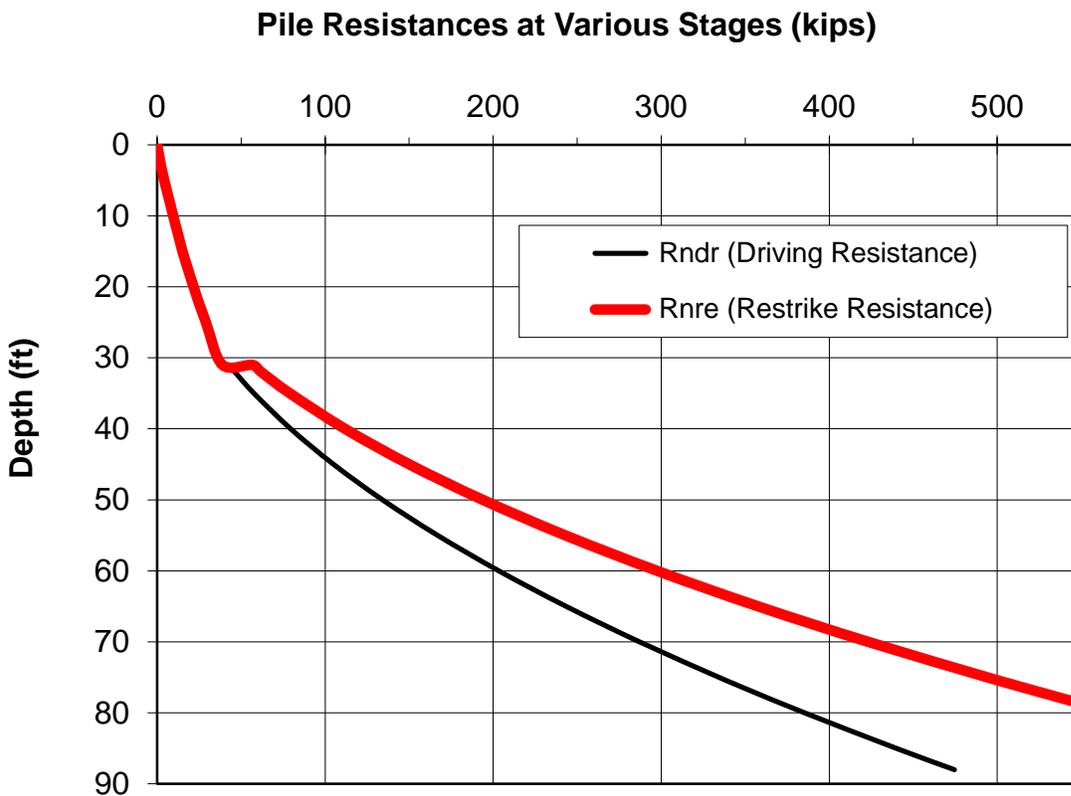


Figure 4.1. LRFD Design Example: Pile Bearing Resistances for Wave Equation Analysis Needed in Drivability Analysis

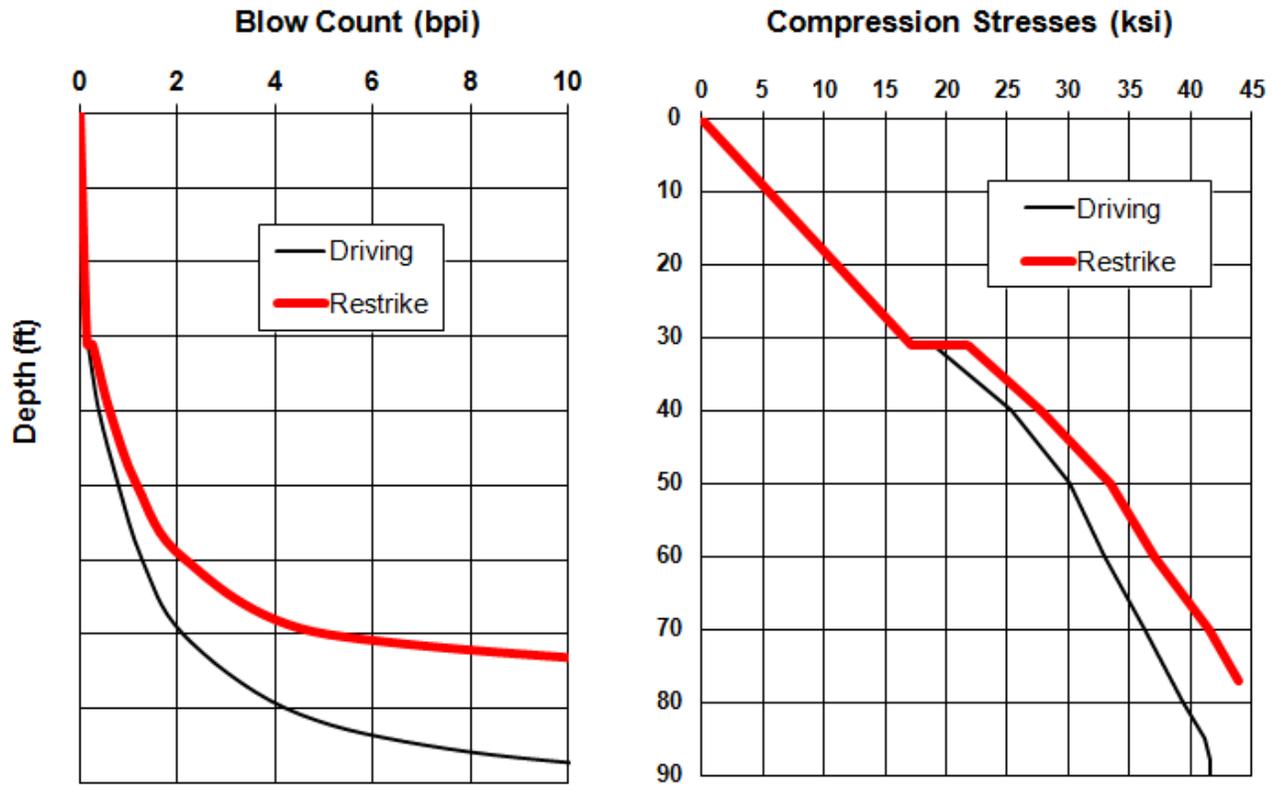


Figure 4.2. LRFD Design Example: Drivability Results from Wave Equation Analysis

CHAPTER 5

GEOTECHNICAL STRENGTH LIMIT STATE AND DESIGN CHARTS

This chapter begins by describing Steps 2c and 2d of the procedure for developing a design chart (Figure 2.3), which call for addressing the geotechnical strength limit states for the axial compression resistances of a single pile to develop a Q_f vs. depth curve, and for determining Q_{fmax} . Next, this chapter provides the final solution to the LRFD Design Example, demonstrating the development and application of the design charts with the selection of both static and field analysis methods to determine pile bearing resistances and length. In the final section, developing a design chart based on fitting to ASD practices is discussed and demonstrated.

5.1 GEOTECHNICAL STRENGTH LIMIT STATE

The governing equation for this limit state is:

$$Q_f \leq \phi R_n - \gamma_p DD \quad (5.1)$$

After the available R_n is determined at various depths using static and field analysis methods, the factored nominal bearing resistance (R_R) at various depths can be computed as:

$$R_R = \phi R_n \quad (5.2)$$

Using the downdrag load (DD) determined with the static analysis method, the net factored nominal bearing resistance (R_{R-NET}) at various depths can be computed as:

$$R_{R-NET} = \phi R_n - \gamma_p DD \quad (5.3)$$

There are two options to address the strength limit state and estimate the pile length, L , needed to support a given factored axial compression load applied to the top of the pile (Q_f):

- Identify the depth where the available R_n resistance is equal to the required R_n resistance, computed as:

$$\text{Required } R_n = (Q_f + \gamma_p DD) / \phi \quad (5.4)$$

- Identify the depth where the net factored nominal bearing resistance is equal to the factored axial compression load applied to the top of the pile (Q_f):

$$R_{R\text{-NET}} = Q_f = \phi R_n - \gamma_p DD \quad (5.5)$$

The net factored bearing resistance values ($R_{R\text{-NET}}$) at various depths provide the minimum pile lengths, L , needed to support various Q_f loads. By equating the applied factored loads, Q_f , to $R_{R\text{-NET}}$ using Eq. 5.5, a Q_f vs. depth curve can be developed in the design chart and used to estimate the required pile length, L , needed to support any applied Q_f load. This curve provides the designer with a simple, flexible approach to determining pile length, L , especially with continuous changes in the applied Q_f loads during design.

Static analysis methods. Using static analysis methods, the net factored nominal bearing resistance at various depths, $R_{R\text{-NET}}$, can be computed as:

$$R_{R\text{-NET}} = \phi_{\text{stat}} R_{\text{nstat}} - \gamma_p DD \quad (5.6)$$

By equating the factored loads, Q_f , to $R_{R\text{-NET}}$, or $Q_f = \phi_{\text{stat}} R_{\text{nstat}} - \gamma_p DD$, a Q_f vs. depth curve can be developed in the design chart and used to estimate the pile length, L , needed to support any applied Q_f load.

Field analysis methods. Using these methods, the strength limit state, $Q_f \leq \phi R_{\text{nfield}} - \gamma_p DD$, must be met in the design phase and in the field by developing:

- An estimate of the pile length, L . As with static analysis methods, the net factored nominal bearing resistance at various depths, $R_{R\text{-NET}}$, can be computed as:

$$R_{R\text{-NET}} = \phi_{\text{dyn}} R_{\text{nfield}} - \gamma_p DD \quad (5.7)$$

By equating the factored loads, Q_f , to $R_{R\text{-NET}}$, or $Q_f = \phi_{\text{dyn}} R_{\text{nfield}} - \gamma_p DD$, a Q_f vs. depth curve can be developed in the design chart and used to estimate the pile length, L , needed to support any applied Q_f load.

- The required field bearing resistance needed to determine the ordered pile length in the field. With field analysis methods, the strength limit state must be met in the field by driving the pile to a length where the required field bearing resistance is achieved. Where R_{ndr} resistances are only measured in the field (at EOD conditions), the required R_{ndr} can then be developed based on Eq. 3.1 ($R_{\text{nfield}} = R_{\text{ndr}} - GL$) and Eq. 5.4 as:

$$\text{Required } R_{\text{ndr}} = (Q_f + \gamma_p DD) / \phi_{\text{dyn}} + GL \quad (5.8)$$

This equation is consistent with Eqs. C10.7.3.7-1 and C10.7.3.7-2 presented in AASHTO LRFD (2012). Where both R_{ndr} and R_{nre} resistances are measured in the field (at BOR

conditions), the required R_{nre} can then be developed based on Eq. 3.2 ($R_{nfield} = R_{nre} - GL$) and Eq. 5.4 as:

$$\text{Required } R_{nre} = (Q_f + \gamma_p DD) / \phi_{dyn} + GL \quad (5.9)$$

Based on the site-specific setup considered in the design, the required R_{ndr} for BOR conditions can be estimated. The R_{ndr} and R_{nre} curves in the design chart can also be used to estimate the required R_{ndr} and R_{nre} resistances.

5.2 DETERMINATION OF THE MAXIMUM FACTORED AXIAL COMPRESSION LOAD (Q_{FMAX})

The maximum factored axial compression load that can be applied to the top of a pile at the strength limit, Q_{fmax} , can be obtained by addressing all the strength limit states for the compression resistances of that pile. $Q_{fmax-geotechnical}$ is defined as the maximum factored axial compression load that can be applied to the top of a pile based on the geotechnical resistance. $Q_{fmax-geotechnical}$ is determined from the Q_f vs. depth curve as the Q_f at L_{max} , so it meets both the geotechnical strength and drivability limit states. Q_{fmax} can be determined as the smaller of $Q_{fmax-structural}$ and $Q_{fmax-geotechnical}$.

The geotechnical strength and drivability limit states are expected to control Q_{fmax} ($Q_{fmax-geotechnical} < Q_{fmax-structural}$) in most cases, including:

- When using design methods to determine bearing resistances that have relatively small geotechnical resistance factors, such as static analysis methods, wave equation analysis, and dynamic formulas.
- When the structural resistance is very large, such as in pipe piles filled with concrete.

The structural limit state is expected to control Q_{fmax} ($Q_{fmax-structural} < Q_{fmax-geotechnical}$) in a few cases, including:

- When using design methods to determine bearing resistances that have relatively large geotechnical resistance factors, such as the static load test.
- For piles seated on top of very hard rocks.

5.3 SOLUTION TO THE LRFD DESIGN EXAMPLE

This section presents the final solution to the LRFD Design Example problem that is presented in Section 2.7 and Figure 2.6 and is solved step by step throughout this report. As described in Section 2.7, the complete solution to the LRFD Design Example requires:

I. Developing design charts for a 12x53 H-pile using the following four design methods to determine the pile bearing resistances and length:

1. β -method: a static analysis method with a resistance factor of 0.25 (AASHTO LRFD Table 10.5.5.2.3-1).
2. Wave equation analysis at end of driving (EOD) conditions with a resistance factor of 0.5 (AASHTO LRFD Table 10.5.5.2.3-1).
3. Wave equation analysis at beginning of restrrike (BOR) conditions with a resistance factor of 0.5 (AASHTO LRFD Table 10.5.5.2.3-1).
4. Based on fitting to the Iowa ASD procedure for wave equation analysis at EOD conditions.

II. Using the developed design charts to:

- Check the limit states for the following combinations of applied factored loads, Q_f , at the strength limit state, and minimum pile lengths, L_m : (Q_f, L_m) = (100 kips, 40 ft); (100 kips, 65 ft); (100 kips, 85 ft); and (300 kips, 65 ft) and identify the combinations that meet the limit states. Note that these combinations may not be realistic in an actual design, but were selected to demonstrate the design solutions for various design scenarios that may be encountered in an actual design.
- Determine the contract pile length and the required field bearing resistances (if needed) for the combinations of Q_f and L_m that meet the limit states. It is given that the contract pile length and required field bearing resistances are not controlled by the extreme event limit states for the axial compression resistances of a single pile.

As outlined in Section 2.2.5, the design chart can be developed in two major steps (see Figure 2.3):

Step 1 (Chapter 3). Determine the available nominal geotechnical bearing resistances at various depths using:

- a) The selected static analysis method (Section 3.1).
- b) The selected design method to determine the pile length in the design phase, either a static analysis method or a field method. These resistances could be the same as in Step 1a.
- c) Wave equation analysis (needed for the drivability analysis performed in Step 2b). These resistances could be the same as in Step 1b if wave equation analysis is selected to determine the pile bearing resistances and length in the design phase.

Step 2. Address the strength limit states for axial compression resistances of a single pile, using:

- a) The structural limit state, and determine $Q_{fmax-structural}$ (Section 4.1).
- b) Drivability analysis using wave equation analysis, and determine L_{max} (Section 4.2).

- c) The geotechnical strength limit state to develop the Q_f vs. depth curve (Section 5.1).
- d) All of the above limit states to determine Q_{fmax} (Section 5.2).

Finally, note that the factored DD load, γ_p DD, is estimated based on the static analysis as 8.4 kips (Section 3.2) and will be considered in developing all design charts.

5.3.1 Developing a Design Chart Using the β -Method

The β -method is the static analysis method selected to generate the bearing resistances needed in Steps 1a and 1b and determine the pile length. The design chart presented in Figure 5.1 is developed and used as follows (including steps detailed in previous chapters as noted):

- **Step 1a.** Generate the $R_n = R_{nstat}$ and R_{ndr} resistance vs. depth curves using the β -method (see Figure 3.1).
- **Step 1b.** Add the R_n resistance vs. depth curve obtained with the β -method (as in Step 1a, Figure 3.1) to the design chart (Figure 5.1).
- **Step 1c.** Generate the R_{ndr} resistance vs. depth curve using wave equation analysis (needed for the drivability analysis); see Figure 4.1.
- **Step 2a.** Determine that $Q_{fmax-structural} = 402$ kips (Section 4.1).
- **Step 2b.** Obtain $L_{max} = 80$ ft from the wave equation analysis at EOD conditions (Section 4.2).
- **Step 2c.** Using Eq. 5.5, generate a curve for $Q_f = 0.25R_{nstat} - 8.4$ (where 0.25 is the resistance factor for the β -method) at various depths and add it to the design chart (Figure 5.1).
- **Step 2d.** Obtain $Q_{fmax-geotechnical}$ from the Q_f vs. depth curve at $L_{max} = 80$ ft (see Figure 5.1) as 235 kips. This value is less than $Q_{fmax-structural}$, so $Q_{fmax} = Q_{fmax-geotechnical} = 235$ kips.

The design chart (Figure 5.1) indicates that the (Q_f, L_m) combinations where $L_m = 85$ ft (larger than the L_{max} of 80 ft) and $Q_f = 300$ kips (larger than the Q_{fmax} of 235 kips) are not acceptable. In such cases, the designer can increase the number of piles and/or consider larger piles that can be driven deeper and to higher resistances without damage. With the 12x53 H-pile, the smallest number of piles with the longest (deepest) lengths can be achieved by selecting an applied Q_f close to 235 kips.

Minimum pile lengths (L_m) of 40 ft and 65 ft are less than $L_{max} = 80$ ft, so these are acceptable. An applied Q_f of 100 kips meets the requirements for the drivability and structural limit states because it is smaller than Q_{fmax} . Therefore, the acceptable combinations of (Q_f, L_m) are (100 kips, 40 ft) and (100 kips, 65 ft). As demonstrated in the design chart (Figure 5.1):

- Determine the required pile length, L , for a given Q_f of 100 kips using the Q_f vs. depth curve as 56 ft. Use the R_{nstat} vs. depth curve and pile length of 56 ft to determine the required R_{nstat} as 433.6 kips.
- Alternately, the required R_{nstat} can be computed from Eq. 5.4 as $(100 + 8.4)/0.25 = 433.6$ kips. This resistance can also be used to determine the pile length, L , in the design chart using the R_{nstat} vs. depth curve as 56 ft.

With an L_m of 40 ft, the contract pile length is 56 ft (the larger of 40 ft and 56 ft), and with an L_m of 65 ft, the contract pile length is 65 ft (Table 5.1).

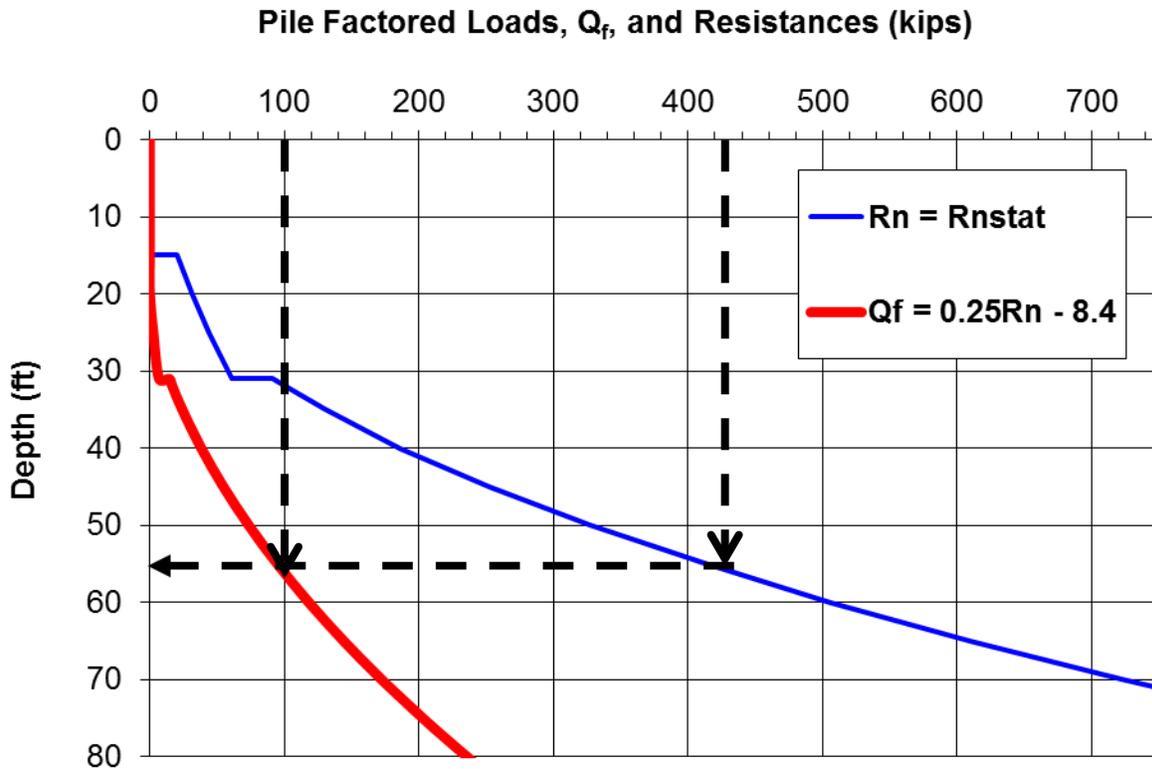


Figure 5.1. LRFD Design Example: B-Method Design Chart ($L_{max} = 80$ ft, $Q_{fmax} = 235$ kips)

If the bearing option is selected to evaluate drivability, the required R_{ndr} should be determined from the wave equation analysis predictions for R_{ndr} at the contract pile length (from Figure 4.1). For example, the R_{ndr} is 175 kips in Figure 4.1 at a contract pile length of 56 ft, so therefore a required R_{ndr} of 175 kips should be used to evaluate drivability using the bearing option.

Table 5.1. LRFD Design Example: Determination of Contract Pile Length with the β -Method.

Pile Length, L, Needed to Support $Q_f = 100$ kips (from β-Method) (ft)	L_m (ft)	Contract Pile Length (ft)
56	40	56
56	65	65

5.3.2. Developing a Design Chart Using Wave Equation Analysis at EOD Conditions

First, the β -method is selected to generate the static analysis bearing resistances (Step 1a). Wave equation analysis at EOD conditions is the method selected in the design to determine the pile length (Step 1b) and to perform drivability analysis (Step 1c). Since wave equation analysis at EOD conditions was selected to determine the pile length, restrikes will not be performed, and therefore R_{nre} resistances are not needed in the drivability analysis.

The design chart presented in Figure 5.2 is developed and used as follows (including steps detailed in previous chapters as noted):

- **Step 1a.** Generate the $R_n = R_{nstat}$ and R_{ndr} resistance vs. depth curves using the β -method (shown in Figure 3.1).
- **Step 1b.** Generate the $R_n = R_{nfield}$ and R_{ndr} resistance vs. depth curves using wave equation analysis (see Figure 3.2) and add them to the design chart (Figure 5.2).
- **Step 1c.** The R_{ndr} resistance vs. depth values from the wave equation analysis (needed for the drivability analysis) are the same as those obtained in Step 1b (Figure 4.1 or Figure 3.2).
- **Step 2a.** Determine that $Q_{fmax-structural} = 402$ kips (Section 4.1).
- **Step 2b.** Obtain $L_{max} = 80$ ft using wave equation analysis at EOD conditions (Section 4.2).
- **Step 2c.** Using Eq. 5.5, generate a curve for $Q_f = 0.5R_{nfield} - 8.4$ at various depths and add it to the design chart.
- **Step 2d.** Obtain $Q_{fmax-geotechnical}$ from the Q_f vs. depth curve at $L_{max} = 80$ ft (Figure 5.2) as 182.6 kips. This value is less than $Q_{fmax-structural}$, so $Q_{fmax} = Q_{fmax-geotechnical} = 182.6$ kips.

The design chart (Figure 5.2) indicates that the (Q_f, L_m) combinations where $L_m = 85$ ft (larger than the L_{max} of 80 ft) and applied $Q_f = 300$ kips (larger than the Q_{fmax} of 182.6 kips) are not acceptable. In such cases, the designer needs to increase the number of piles and/or consider larger piles that can be driven deeper and to higher resistances without damage.

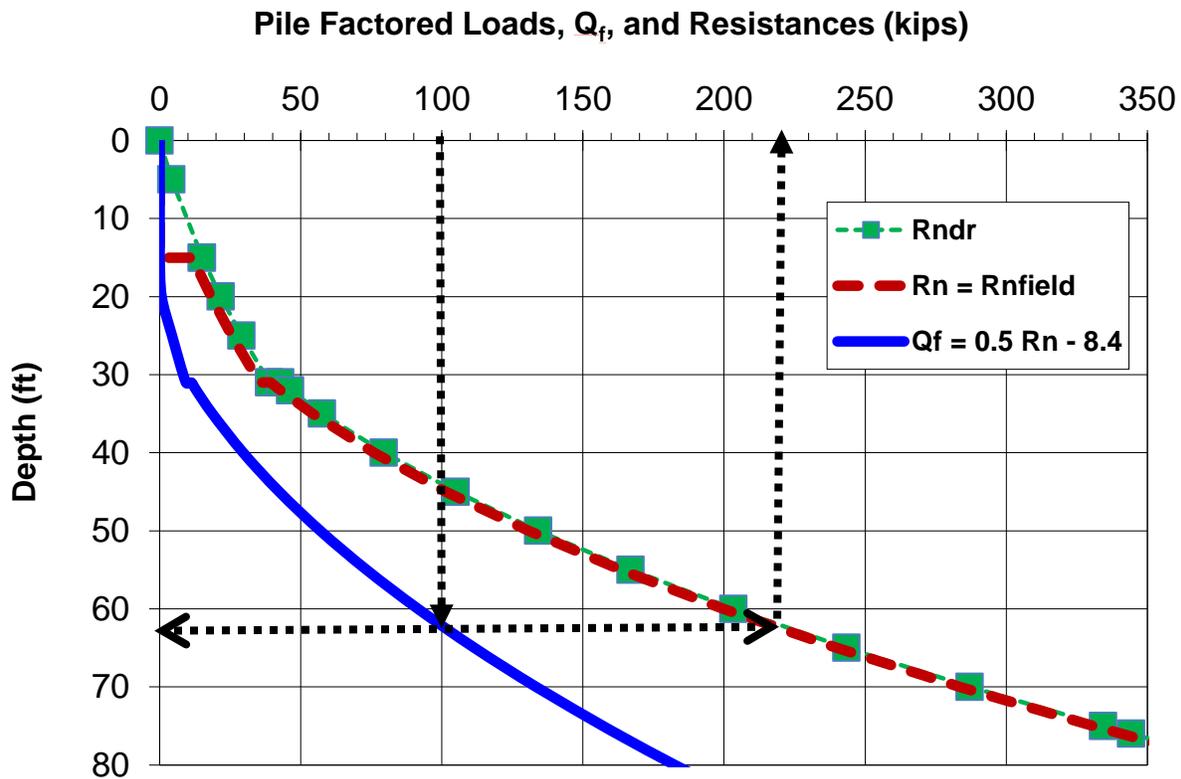


Figure 5.2. LRF Design Example: Design Chart for Wave Equation Analysis at EOD Conditions ($L_{max}= 80$ ft, $Q_{fmax}= 182.6$ kips)

Minimum pile lengths, L_m , of 40 ft and 65 ft meet the drivability limit state because they are smaller than the L_{max} of 80 ft. An applied factored load of $Q_f = 100$ kips meets the requirements for the structural and drivability limit states since it is smaller than the Q_{fmax} of 182.6 kips. As demonstrated in the design chart (Figure 5.2):

- Determine the required pile length, L , for a given Q_f of 100 kips using the Q_f vs. depth curve as 62 ft.
- Use the R_{ndr} vs. depth curve and pile length of 62 ft to determine the required R_{ndr} as 220 kips. Alternately, the required R_{ndr} can be computed using Eq. 5.8 as $(100 + 8.4)/0.5 + 3.5 = 220.3$ kips (see Table 3.2 for obtaining $GL = 3.5$ kips). The required R_{ndr} of 220.3 kips can also be used to estimate the pile length, L , from the design chart.

To account for uncertainties in the procedure suggested in this report to predict in the design the field pile geotechnical resistances, a conservative larger pile length, L , of 64 ft (larger than 62 ft) is selected to solve the LRF design example. With an L_m of 40 ft, the contract pile length (larger of L and L_m) is 64 ft, and with an L_m of 65 ft, the contract pile length is 65 ft.

If the bearing option is selected for evaluating drivability, the required R_{ndr} should be determined from the wave equation analysis predictions for R_{ndr} at the contract pile length (from Figure 4.1). Since wave equation analysis was selected in the design to determine the pile length, the required R_{ndr} calculated for the drivability analysis will be similar to the value used to determine the pile length as long as the contract pile length is not controlled by the minimum pile length, L_m . When the contract pile length is 65 ft and is controlled by L_m , the required R_{ndr} for drivability analysis is 244 kips (from Figure 4.1 at a depth of 65 ft), and this value is different and larger than the required R_{ndr} of 220.3 kips required to determine the pile length in the field.

5.3.3. Developing a Design Chart Using Wave Equation Analysis at BOR Conditions

First, the β -method is selected to generate the static analysis bearing resistances (Step 1a). Wave equation analysis at BOR conditions is selected to determine the pile length (Step 1b) and to perform drivability analysis (Step 1c).

The design chart presented in Figure 5.3 can be developed and used as follows (including steps detailed in previous chapters as noted):

- **Step 1a.** Generate the $R_n = R_{\text{nstat}}$, R_{nre} , and R_{ndr} resistance vs. depth curves using the β -method (see Figure 3.1).
- **Step 1b.** Generate the $R_n = R_{\text{nfield}}$, R_{nre} , and R_{ndr} resistance vs. depth curves using wave equation analysis (see Figure 3.2) and add them to the design chart (Figure 5.3).
- **Step 1c.** The R_{ndr} and R_{nre} resistance vs. depth curves obtained using wave equation analysis (needed for the drivability analysis) are the same as those obtained in Step 1b (Figure 4.1 or Figure 3.2).
- **Step 2a.** Determine that $Q_{\text{fmax-structural}} = 402$ kips (Section 4.1).
- **Step 2b.** Using the wave equation analysis at BOR conditions, determine that $L_{\text{max}} = 70$ ft (Section 4.2).
- **Step 2c.** Use Eq. 5.5 to generate a curve for $Q_f = 0.5R_{\text{nfield}} - 8.4$ at various depths and add it to the design chart (Figure 5.3).
- **Step 2d.** Obtain $Q_{\text{fmax-geotechnical}}$ from the Q_f vs. depth curve at $L_{\text{max}} = 70$ ft (Figure 5.3) as 206.4 kips. This value is less than $Q_{\text{fmax-structural}}$, so $Q_{\text{fmax}} = Q_{\text{fmax-geotechnical}} = 206.4$ kips.

Minimum pile lengths of 40 ft and 65 ft meet the drivability limit state because they are smaller than the L_{max} of 70 ft. An applied factored load of $Q_f = 100$ kips meets the requirements for the structural and drivability limit states since it is smaller than the Q_{fmax} of 206.4 kips. As demonstrated in the design chart (Figure 5.3):

- Use the Q_f vs. depth curve to determine the required pile length, L , for a Q_f of 100 kips as 52 ft.

- Use the R_{ndr} vs. depth curve and pile length (or depth from ground surface) of 52 ft to determine the required R_{ndr} as 145 kips.
- Use the R_{nre} vs. depth curve and pile length (or depth) of 52 ft to determine the required R_{nre} as 220.3 kips. Alternately, the required R_{nre} at BOR can be computed using Eq. 5.9 as $(100 + 8.4)/0.5 + 3.5 = 220.3$ kips (see Table 3.2 for obtaining $GL = 3.5$ kips). This resistance can be used in the design chart to estimate the corresponding pile length (52 ft) and required R_{ndr} (145 kips).

To account for uncertainties in the procedure suggested in this report to predict in the design the field pile geotechnical resistances, a conservative larger pile length of 54 ft (larger than 52 ft) is selected to solve the LRFD design example. With an L_m of 40 ft, the contract pile length is 54 ft, and with an L_m of 65 ft, the contract pile length is 65 ft.

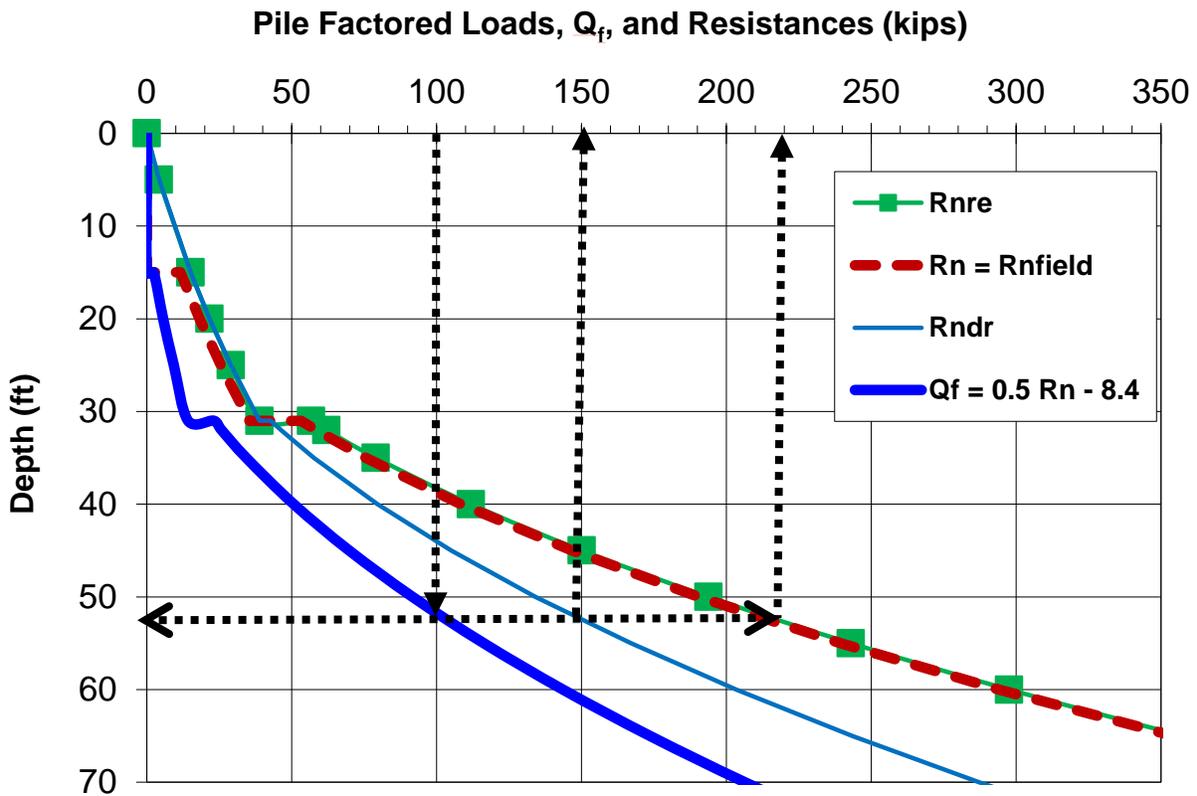


Figure 5.3. LRFD Design Example: Design Chart for Wave Equation Analysis at BOR Conditions ($L_{max} = 70$ ft, $Q_{fmax} = 206.4$ kips)

5.3.4 Benefits of Field Verification of Setup and Conducting Static Load Tests

Setup. The design charts for the wave equation analysis at EOD and BOR conditions (Figures 5.2 and 5.3) suggest that due to setup, the pile length needed to support a Q_f of 100 kips would be reduced by 10 ft (from 64 ft to 54 ft), and the load that the pile can support, Q_f , would be increased at any depth. This means that verification of site-specific setup at BOR conditions would allow for reduced pile length or fewer piles. However, the same contract pile length of 65 ft is obtained when the pile length is controlled by L_m at both EOD and BOR conditions. Hence, the benefits of setup can only be achieved if the contract pile length is not controlled by L_m .

Static Load Test. A static load test is the most economical design method because it:

- Has a large resistance factor, leading to high factored nominal bearing resistance.
- Can be used to confirm and reap the benefits of large site-specific setup without the need for restrike. This means smaller hammers can be used since the piles only need to be driven to EOD conditions, not to BOR conditions.

To demonstrate the advantages of the static load test, the LRFD Design Example is solved using this method as the design method to determine pile length. Since $\lambda_{BOR} = 1.0$ for the static load test and $\lambda_{stat} = 0.61$ for the β -method, α_{BOR} is estimated as 0.61 (0.61/1.0) and used to develop the R_{nfield} vs. depth curve as discussed in Chapter 3. Then, Eq. 5.5, with a resistance factor of 0.75 for the static load test, is used to generate the Q_f vs. depth curve using $Q_f = 0.75R_{nfield} - 8.4$. Since restrike is not needed with static load tests, all benefits of setup up to a depth of 80 ft can be assumed in the design without the need for verification at BOR conditions. The Q_f vs. depth curve developed using the static load test is presented in Figure 2.5 (Chapter 2). It shows $Q_f = 402$ kips (equal to $Q_{fmax-structural}$) at a depth of 77 ft and $Q_{fmax-geotechnical} = 438$ kips (greater than $Q_{fmax-structural}$) at a depth of 80 ft. Hence, in this case the structural resistance controls Q_{fmax} , and the pile only needs to be driven to a depth of 77 ft to obtain $Q_{fmax} = 402$ kips.

In the LRFD Design Example, $Q_{fmax-geotechnical}$ values are less than $Q_{fmax-structural}$ values using the β -method and using wave equation analysis at EOD and BOR conditions, and therefore $Q_{fmax} = Q_{fmax-geotechnical}$ for all three methods. This is not the case for the static load test, where $Q_{fmax} = Q_{fmax-structural}$. Figure 2.5 presents the Q_f vs. depth curves for various methods to determine pile length, and suggests that the factored axial compression loads, Q_f , that can be supported at various depths are largest with the static load test. In the final design, this would lead to either the smallest number of piles or the shortest pile lengths.

5.4 DEVELOPING A DESIGN CHART BASED ON FITTING TO ASD PRACTICES

The use of wave equation analysis to evaluate drivability can be waived where successful long-term practices have been consistently employed to drive piles without damage. This waiver assumes indirectly that a lack of pile damage during driving has been verified by observation or measurement. A maximum safe allowable design load, Q_{smax} , of $0.25A_s f_y$ is recommended in the AASHTO Standard Specifications for Highway Bridges (2002) for H-piles to keep the driving stresses within the recommended limits (to address the drivability limit state). The specifications recommend a higher value of $0.33 A_s f_y$ for H-piles if damage to the pile is unlikely and static or dynamic load tests are performed.

For a certain field analysis method with a specific safety factor (FS), some DOTs selected in their ASD platforms Q_{smax} values for their driven piles based on a conservative pile allowable structural capacity. It is assumed that Q_{smax} values chosen in this manner will meet both the structural and drivability limit states, and thus there is no need to perform wave equation analysis to evaluate drivability in the design phase. Abu-Hejleh et al. (2010) describes the use of calibration by fitting for development of resistance factors, ϕ , for axial compression resistance determination methods. With this calibration and using an average load factor, γ_{ave} , of 1.4, the resistance factor can be estimated as $\phi_{dyn} = 1.4/FS$, and the equivalent LRFD maximum factored compression load that can be applied to the top of a pile, Q_{fmax} , can be obtained from Q_{smax} as:

$$Q_{fmax} = 1.4Q_{smax} - \phi_{dyn}GL - \gamma_p DD \quad (5.10)$$

Note that the effect of downdrag loads and geotechnical resistance losses are not considered in the evaluation of Q_{smax} , but are considered in the evaluation of Q_{fmax} .

This calibration approach ensures that the pile quantities and lengths specified based on the LRFD design method do not differ from those determined using the ASD method. For the static load test, where $Q_{smax} = 0.33 A_s f_y$, $Q_{fmax} = 0.46 A_s f_y - \phi_{dyn}GL - \gamma_p DD$.

Based on the above, consider the following steps to develop a design chart for a field analysis method with a given safety factor based on fitting to ASD practices:

1. Determine the available bearing resistances at various depths using the selected static analysis method and field analysis method to determine pile length (Steps 1a and 1b in Figure 2.3), as discussed in Chapter 3. Note that resistances from the wave equation analysis are not needed because drivability analysis will not be performed.
2. Develop a resistance factor for the field analysis method using $\phi_{dyn} = 1.4/FS$

3. Estimate Q_{fmax} per Eq. 5.10.
4. Develop a Q_f vs. depth curve as $Q_f = \phi_{dyn}R_{nfield} - \gamma_p DD$
5. Use the developed Q_f vs. depth curve to estimate the L_{max} value that corresponds to the computed Q_{fmax} .

LRFD Design Example.

Problem. Based on years of successful designs, Iowa DOT has used an allowable design stress value of up to 9 ksi for H-piles ($Q_{smax} = 9A_s$) without the need to conduct drivability analysis during design. Iowa DOT used wave equation analysis at EOD conditions with a safety factor of 2 to determine the pile bearing resistances and length. This section demonstrates how to develop an LRFD design chart based on fitting to Iowa ASD design practices and use this chart to solve the LRFD Design Example.

Solution. The β -method is selected to generate the static analysis bearing resistances, and the wave equation analysis at EOD conditions is selected to determine the pile bearing resistances and length. The design chart presented in Figure 5.4 is developed as follows:

1. Generate $R_n = R_{nstat}$ and R_{ndr} resistance vs. depth curves using the β -method (see Figure 3.1). Then, generate $R_n = R_{nfield}$ and R_{ndr} resistance vs. depth curves using wave equation analysis at EOD conditions (see Figure 3.2) and add them to the design chart (Figure 5.4). GL for wave equation analysis at EOD conditions is 3.5 kips (see Table 3.2).
2. Based on calibration by fitting to Iowa ASD practices, the resistance factor for the wave equation analysis is developed as $1.4/2 = 0.7$, which is much larger than the 0.5 recommended by AASHTO LRFD for wave equation analysis.
3. Estimate Q_{fmax} :
 - Q_{smax} (kips) = $9A_s$
 - Q_{fmax} for H-piles can be estimated based on Eq. 5.10 as $12.6 \times 15.5 - 0.7 \times 3.5 - 8.4 = 184.5$ kips. This Q_{fmax} value is very close to the Q_{fmax} of 182.6 kips determined in Section 5.3.2 for wave equation analysis at EOD conditions.
4. Use Eq. 5.5 to generate a curve for $Q_f = 0.7R_{nfield} - 8.4$ at various depths and include it in the design chart (Figure 5.4). Note that a higher resistance factor of 0.7 is used to develop this curve (compared to the resistance factor of 0.5 used in Figure 5.2).
5. Use the Q_f vs. depth curve in Figure 5.4 to obtain $L_{max} = 69$ ft for a Q_{fmax} value of 184.5 kips.

The use of the developed design chart (Figure 5.4) is similar to that discussed in Section 5.3.2. The chart (Figure 5.4) shows that the pile length needed to support an applied Q_f of 100 kips is 54 ft (see the arrows in Figure 5.4). This length and L_{max} (69 ft) are smaller than the values

obtained in Section 5.3.2 ($L = 62$ ft and $L_{max} = 80$ ft) primarily because a smaller resistance factor (0.5) was considered in the Section 5.3.2 analysis.

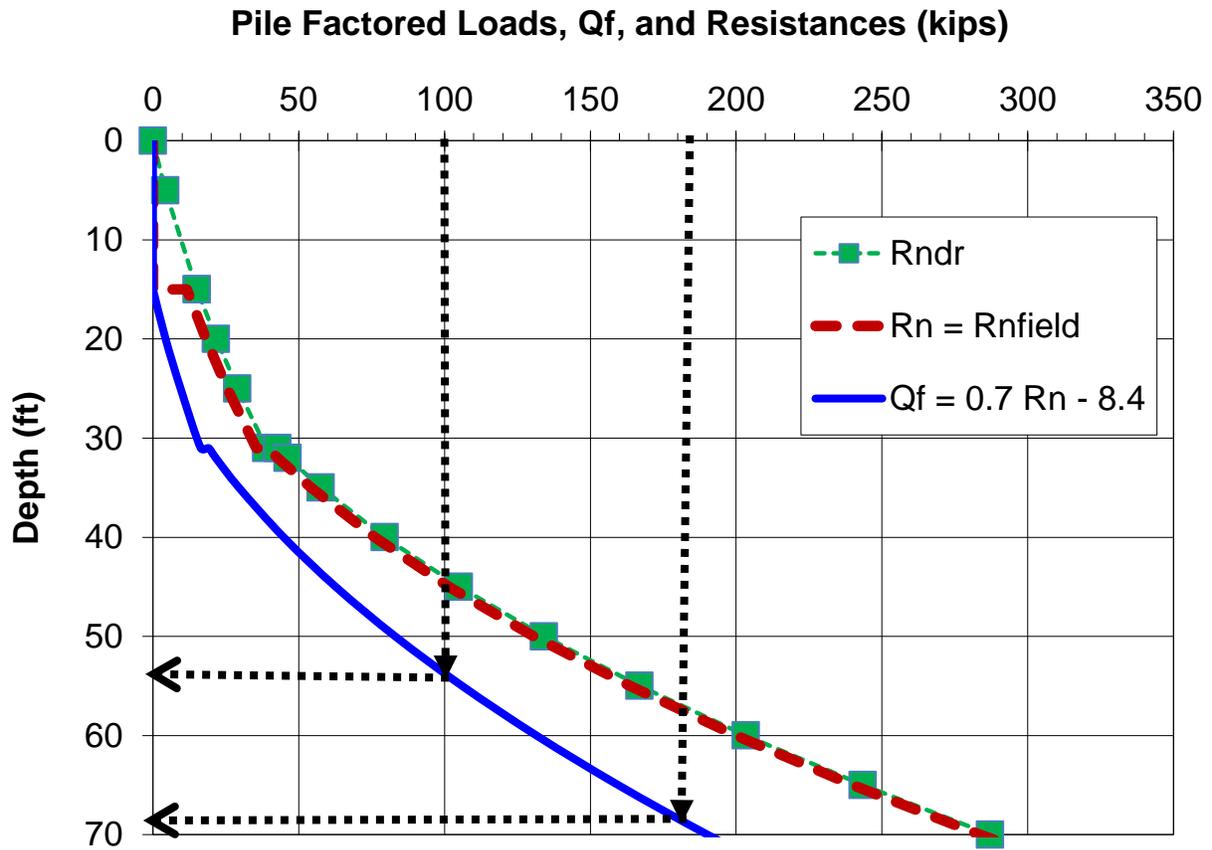


Figure 5.4. LRFD Design Example: Design Chart Based on Fitting to Iowa DOT ASD Design Practices Using Wave Equation Analysis at EOD Conditions

CHAPTER 6 CONSTRUCTION OF DRIVEN PILES

The design should be considered complete when all LRFD design limits and requirements for driven piles are met during construction, or when the piles are *safely* driven in the field to the lengths or field resistances required in the design. This chapter briefly describes how to ensure that all LRFD design limit states for driven piles are met in the field during construction, and the design and construction data that should be compiled by DOTs for future improvements to their local LRFD design methods.

Good construction references for driven piles are the AASHTO LRFD Bridge Construction Specifications (2010) and the FHWA manual Design and Construction of Driven Pile Foundations (Hannigan et al., 2006).

6.1 CONSTRUCTION PLAN CONTENTS

The construction plans provide the information needed during pile installation, including the method for approving the contractor's proposed driving system (see Section 6.2) and the design method selected to determine pile bearing resistance and length (either a static analysis method or a field method). Details provided in the plans include:

- **Static analysis methods.** If a static analysis method is selected to determine pile length, the construction plans should provide the contract pile length (L_c), which represents the length the piles need to be driven to in the field, and should provide the contractor with the basis to determine the pile length for production piles. This pile length may vary across the site to address site variability (Abu-Hejleh et al., 2010).
- **Field analysis methods.** If a field method is selected to determine the pile length, the construction plans should provide three pile lengths: the minimum length, L_m ; an estimate of the pile length needed to address the required bearing resistance (L); and the contract pile length (L_c), which should be used only to provide the contractor with a basis for bidding (not for ordering production piles). Additionally, the plans should list the required field bearing resistances: R_{ndr} at EOD conditions, as well as R_{nre} at BOR conditions if needed. These resistances are needed to determine the ordered pile length for the production piles in the field. If restrike at BOR conditions is required, restrike time and procedures should also be described. See AASHTO LRFD (2012) for recommendations on restrike time for different soil types and Hannigan et al. (2006) for the restrike procedure to obtain the BOR blow count.

In both cases, it is suggested that the plans provide L_{\max} and emphasize that this is an estimated value.

6.2 APPROVAL OF THE CONTRACTOR'S PROPOSED DRIVING SYSTEM

Before construction starts, it is necessary to evaluate the contractor's proposed driving system and determine whether it will be able to safely drive the piles to the required resistance or depth without damage. For this evaluation, Article 10.7.8 of AASHTO LRFD (2012) recommends performing wave equation analysis using the contractor's proposed driving system. This evaluation can be conducted using the drivability option or the bearing option as described in Chapters 4 and 5.

6.3 CONSTRUCTION CONTROL OF TEST AND PRODUCTION PILES

Test piles. AASHTO LRFD (2012) recommends driving test piles at several locations within the project site to check the performance of the contractor's proposed driving system. AASHTO LRFD indicates that the best approach to control driving stresses during pile installation is to conduct dynamic testing with signal matching on test piles to check hammer performance, and to verify and calibrate the wave equation analysis calculations. At a minimum, dynamic measurements to check the hammer performance should be considered.

The appropriate number, location, and depth of the test piles depends on site variability. Abu-Hejleh et al. (2010) provides recommendations for addressing project site variability using various design methods to determine pile length (static analysis methods, the field static load test, and field dynamic analysis methods).

- **Static analysis methods.** Ensure that the test piles can be safely driven to the contract pile length without damage. This defines the driving criteria for production piles.
- **Field analysis methods.** Test piles should be driven until both the required R_{ndr} and the minimum pile length (L_m) are achieved. For the BOR field methods (where the assumed site-specific setup should be verified), allow the driven test pile to set up for a sufficient amount of time (restrike time) and then restrike the pile or conduct a static load test to verify the higher required R_{nre} resistance. Note the following:
 - During driving and restrike, GL and site-specific setup can be measured in the field and used to refine the required R_{ndr} and R_{nre} . Consider dynamic testing with signal matching to measure the setup and the GL due to scour and downdrag.
 - Some DOTs drive test piles to a tip elevation established based on the contract

pile length and then wait for setup to occur before taking measurements of R_{nre} . In this case, it is not necessary to calculate the required R_{ndr} . Some DOTs drive test piles to 10 ft below the estimated tip elevation, determined based on the contract pile length, to verify the absence of any conditions that could affect a pile's long-term performance.

Next, analyze the test pile results to establish for production piles: (1) order length, and (2) end of driving (EOD) criteria that consists of two parts (Hannigan et al., 2006):

- Minimum blow counts (or penetration resistances) at given hammer/strokes needed to achieve the required R_{ndr} at EOD conditions.
- Minimum length (or penetration), L_m .

Production piles. In contrast to test piles, production piles are not required to be redriven to verify site-specific setup (higher resistance). Perform inspection and quality control for these piles as described by Hannigan et al. (2006). Proper construction control requires effective communication between the design and field engineers. Construction problems or deviation of pile quantities from the plan should be immediately discussed with the designer.

6.4 COMPILATION OF DESIGN AND CONSTRUCTION DATA FOR FUTURE IMPROVEMENTS

The FHWA manual on driven piles (Hannigan et al., 2006) lists setup factors for different soil types (up to 5.5) developed based on load tests. While these setup factors may be useful for preliminary analysis, it is important to develop local, site-specific setup factors. Accurate estimates of pile bearing resistances for the field analysis methods, including wave equation analysis, are needed for better estimation of the pile length, L , in the design and to perform more accurate drivability analysis.

Predicted resistance data from the static and dynamic analysis methods and measured resistance data from the static load tests are needed in the reliability calibration to improve the accuracy and develop resistance factors for the static and field analysis methods (Abu-Hejleh et al., 2010). These data should be compiled by State DOTs at their load test sites and can also be used to develop local setup factors and α_{BOR} and α_{EOD} median resistance factors as discussed in Section 3.3.

In addition, at sites with no load tests, State DOTs should compile design and construction data on their driven piles to facilitate future improvements to their local pile design practices. The resistances used in the design for the field analysis methods (including the wave equation

analysis method) should eventually be checked against field measurements of these resistances. As illustrated in Table 3.3 and discussed in Section 3.3, local setup factors and median resistance factors (α_{BOR} and α_{EOD}) can be obtained by compiling and analyzing the R_{nre} resistances obtained from the static analysis methods in the design phase, and the R_{nre} and R_{ndr} resistances measured in the field with dynamic analysis methods at BOR and EOD conditions.

To improve the accuracy of the wave equation analysis method:

- Determine local α_{BOR} and α_{EOD} factors that define the median resistance bias between the wave equation analysis and the selected static analysis method, as illustrated in Table 3.3 and discussed in Section 3.3.
- Compare the driving stresses predicted through wave equation analysis with those obtained through dynamic testing with signal matching or using a Pile Driving Analyzer.
- Compare the penetration resistances (number of blows per inch) and L_{max} values predicted through wave equation analysis with those measured in the field.

CHAPTER 7 SUMMARY

This report is intended to provide a technical resource for highway engineers responsible for the development of LRFD design specifications for driven piles based on the 2012 AASHTO LRFD Bridge Design Specifications. It addresses many of the issues and problems highway agencies face in implementing LRFD design for driven piles.

Pile length is defined in this report as pile penetration or depth from ground surface.

Chapter 2 of this report describes the AASHTO LRFD design limit states for driven piles, the design information obtained by addressing these limit states, and the overall design process needed to address them. This chapter defines the contract pile length, L_c , as the length needed to address all the LRFD design limit states for driven piles, or as the largest of (a) the pile length, L , needed to address the geotechnical strength limit state for compression resistance of a single pile; (b) the pile length, L_e , needed to address the geotechnical extreme event limit state for compression resistance of a single pile; and (c) the minimum pile length (or penetration), L_m , needed to address all other limit states listed in Article 10.7.6 of AASHTO LRFD.

In Chapters 3 to 5, the report describes in detail and with examples the design procedure required to address all the strength limit states for the axial compression resistance of a single pile: geotechnical, drivability, and structural. The design procedure used to address other LRFD design limit states is not discussed in this report.

Strength Limit States for Axial Compression Resistance of a Single Pile. The factored axial compression load acting on a single pile is obtained as the summation of the factored axial compression load applied to the top of the pile, Q_f , and the factored downdrag load. Q_{fmax} is defined as the maximum Q_f that can be met by all the strength limit states for compression resistance of a single pile (geotechnical, drivability, and structural). L_{max} is defined as the maximum length the pile can be safely driven to without damage.

- 1. Geotechnical strength limit state.** Chapter 3 describes the determination of pile bearing resistances using static analysis methods (e.g., the β -method) and field analysis methods (e.g., wave equation analysis). Using these resistances, addressing the geotechnical strength limit states as described in Chapter 5 generates:
 - A Q_f vs. depth curve that provides the pile lengths or depths, L , needed to support various factored axial compression loads applied to the top of the pile (Q_f).
 - With static analysis methods, the pile length, L , needed to be driven to in the field will be determined.

- With field analysis methods, two design outputs will be obtained:
 - The required field bearing resistance needed to determine pile length in the field. The strength limit state must be met in the field by driving the pile to a length or depth where the required field bearing resistance is achieved or exceeded.
 - An estimate of the pile length, L , needed to achieve the required field bearing resistance. This length, estimated in the design phase, may be different from the length determined in the field. Chapter 3 describes a new procedure to improve the agreement between the pile length estimated in the design, L , and the pile length determined in the field. In this procedure, the resistances for the field analysis method are predicted in the design phase using the resistances obtained from the selected static analysis method and the median resistance bias between the field analysis method and the static analysis method (see Table 3.2).

The estimated pile length, L , obtained with static or field analysis methods can be used to estimate the contract pile length, L_c , as described previously. For the static analysis methods, the contract pile length provides the basis for ordering production piles. For the field methods, the contract pile length is just an estimate, as the ordered pile length for production piles will be finalized in the field as the length needed to achieve the required bearing resistance and L_m .

For the field analysis methods, Chapter 5 discusses and demonstrates:

- The advantages of considering setup in LRFD design.
- The advantages of load tests over other design methods.

2. Structural strength limit state (Section 4.1). The structural strength limit state is addressed by ensuring that $Q_f \leq Q_{fmax}$.

3. Drivability analysis (Section 4.2). Wave equation analysis is employed to perform this analysis and determine L_{max} at the depth where the limiting conditions for driving stress and blow count are reached. Safe drivability is addressed in the design with all the applicable LRFD design limit states by keeping any estimated pile length (L , L_c , or L_m) less than or equal to L_{max} , or $L_c \leq L_{max}$.

$Q_{fmax-structural}$ is defined as the maximum factored axial compression load, Q_f , that can be applied to the top of a single pile based on the pile structural capacity. It is determined by addressing the structural strength limit state. $Q_{fmax-geotechnical}$ is defined as the maximum factored axial compression load that can be applied to the top of a pile based on the geotechnical resistance.

$Q_{\text{fmax-geotechnical}}$ is determined from the Q_f vs. depth curve as the Q_f at L_{max} , so it meets the both the geotechnical strength and drivability limit states. Q_{fmax} can be determined as the smaller of $Q_{\text{fmax-structural}}$ and $Q_{\text{fmax-geotechnical}}$.

Developing a Design Chart. The design results obtained from addressing the three strength limit states for the compression axial resistance of a single pile are summarized in a design chart that includes:

- Curves of nominal bearing resistances at various depths (R_n , R_{nre} , and/or R_{ndr}) up to L_{max} .
- A curve of pile factored loads (Q_f) vs. depth up to Q_{fmax} .

For a given pile type and size and a given design method for determining pile bearing resistances and length (a static or field analysis method), two major steps are needed to develop the design chart:

Step 1. Determine the available nominal bearing resistance at various depths using:

- a) The selected static analysis method (Section 3.2).
- b) The selected design method for determining pile length in the design phase, either a static analysis method (Section 3.2), or a field analysis method at BOR and/or EOD conditions (Section 3.3).
- c) Wave equation analysis (needed for the drivability analysis performed in Step 2b), which is a field analysis method (Section 3.3).

Step 2. Address all the strength limit states for the axial compression resistance of a single pile, using:

- a) The structural limit state, and determine $Q_{\text{fmax-structural}}$ (Section 4.1).
- b) Drivability analysis using wave equation analysis, and determine L_{max} (Section 4.2).
- c) The geotechnical strength limit state to develop the Q_f vs. depth curve and determine $Q_{\text{fmax-geotechnical}}$ (Section 5.1).
- d) All of the above limit states to determine Q_{fmax} (Section 5.2).

The report also discusses an approach to developing design charts based on fitting to ASD practices. In this approach, direct evaluations of the structural and drivability limit states are not needed.

Overall Design Process. Section 2.6 provides recommendations on developing an LRFD design process for driven piles based on the ASD design process presented by Hannigan et al. (2006). Initially, evaluate different candidate pile types and different design methods for determining pile bearing resistances and length, including the static load test. Then, select the most cost-

effective combination of pile type and design method. Finally, develop a design chart for this combination. Applications of this design chart are discussed next.

Comprehensive LRFD Design Example. This example problem is presented in Section 2.7 of this report. Chapters 3 to 5 provide a step-by-step solution to this example problem that demonstrates the development and application of design charts using both static and field analysis methods to determine pile bearing resistances and length. Four design charts are developed in Chapter 5 for the problem's 12x53 H-pile using the following four design methods:

1. β -method, a static analysis method with a resistance factor of 0.25.
2. Wave equation analysis at EOD conditions, a field analysis method with a resistance factor of 0.5.
3. Wave equation analysis at BOR conditions, with a resistance factor of 0.5.
4. Based on fitting to the Iowa DOT ASD procedure for wave equation analysis at EOD conditions.

As demonstrated in Chapter 5, the design charts provide a simple, flexible approach that foundation designers can use to optimize and finalize the LRFD design for a pile group by checking various limit states (e.g., $L_m \leq L_{max}$ and $Q_f \leq Q_{fmax}$) and obtaining the data needed in the construction plans, such as pile length and required field bearing resistance. For example, the design chart can be effectively used to evaluate various layouts for a pile group (number of piles, location, and contract pile length) and select the most cost-effective layout.

Finally, Chapter 6 describes how to ensure that all LRFD design limit states for driven piles are met in the field during construction, and identifies the design and construction data that should be compiled by State DOTs to facilitate future improvements to their local LRFD design methods.

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