Acceptance Procedures for Structural Foundations of Transportation Structures

FHWA Geotechnical Engineering Circular 015

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16. Abstract

The purpose of this document is to provide information about effective acceptance procedures for different types of deep foundation elements including driven piles, drilled shafts, micropiles, and Continuous Flight Auger (CFA) piles. This document is intended for transportation professionals involved with foundation acceptance, including geotechnical and structural design professionals, project and construction management professionals, construction inspection professionals, and agency administrators, all of whom play important roles in foundation acceptance processes.

The framework for acceptance of deep foundation elements revolves around a key component, which is documentation and communication of actual performance requirements for deep foundation elements in transportation applications. This document provides information about what should be collected and how it may be considered for foundation acceptance decisions.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards		0.765	m^3
		cubic meters NOTE: volumes		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit		5 (F-	°C
		32)/9	Celsius	
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

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	35.314	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
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inc h	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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CHAPTER 1
INTRODUCTION

Foundation acceptance is a crucial component of the design and construction process used to develop transportation infrastructure in the United States today. As considered in this circular, foundation acceptance refers to a process resulting in approval of payment to the constructor for installation of a deep foundation element. The process should involve the following actions by an owner agency, or entity acting on its behalf:

1. Establishment of measurable and achievable acceptance criteria that serve as assurance that a foundation element will fulfill all appropriate performance requirements, and
2. Documented evaluation of the constructed foundation element to demonstrate that the established acceptance criteria have been satisfied.

Foundation acceptance is the culmination of quality assurance (QA) efforts that, when appropriately implemented, provides the owner agency with confidence that a foundation element will fulfill all appropriate performance requirements. In some instances, the foundation acceptance process may include provisions for cost adjustments for foundation elements that do not strictly satisfy established acceptance criteria, but that are nevertheless judged to satisfy all appropriate performance requirements and which the owner agency agrees to accept.

The objective of this nonregulatory circular that does not create enforceable legal obligations is to educate transportation agencies, and those working on their behalf, about effective foundation acceptance procedures that may produce reliable foundation elements. The circular is intended for transportation professionals involved with foundation acceptance, including geotechnical and structural design professionals, project and construction management professionals, construction inspection professionals, and agency administrators, all of whom play important roles in foundation acceptance processes.

1.1 INFORMATION ABOUT THIS CIRCULAR

In many respects, foundation acceptance represents the final stage of quality assurance (QA) processes implemented by transportation agencies. While sometimes simple and straightforward, the process of foundation acceptance may be challenging. Some challenges arise because foundation acceptance may need input and action from numerous individuals involved in the design and construction process, which can lead to distributed responsibility. Effective foundation acceptance practices should include:

1. Clear communication and appreciation of performance requirements for deep foundation elements.
2. Understanding of the role of specific observations and collected information that contribute to foundation acceptance.
3. Clearly defined processes and objective criteria for foundation acceptance.

4. Clarity regarding the fundamental purpose of foundation acceptance and how it fits within the broader objectives of a project.

Foundation acceptance may be complicated by technical challenges that affect execution of acceptance processes. While the fundamental performance practices for different types of deep foundation elements are often similar, at least conceptually, the information and observations collected during construction vary significantly among the different types of deep foundation elements. For example, design, construction, and quality assurance methods for micropiles are considerably different than those for driven piles, which in turn are considerably different from those for drilled shafts and continuous flight auger (CFA) piles (a.k.a. augercast piles). It is important to understand the fundamental performance practices, the intended design of the foundation elements, as well as appropriate construction and inspection processes and procedures, and how those contribute to construction of an acceptable foundation element.

This circular provides a framework from which appropriate foundation acceptance decisions could be made, as well as information about applying the framework to different types of deep foundation elements. The document does not address shallow foundations. Information is provided about what foundation acceptance data should be collected and how it should be considered. Information about the actual conduct of inspection or quality assurance tests that contribute to foundation acceptation, and construction procedures appropriate for producing acceptable foundation elements is provided in other FHWA documents, some of which are referenced throughout this circular.

1.2 ORGANIZATION OF THE CIRCULAR

The circular is organized into seven chapters that address different aspects of foundation acceptance processes. Chapter 2 provides an overview of foundation acceptance considerations and describes the basic framework for foundation acceptance. Chapter 3 describes key concepts related to the role of inspection and testing in support of content in the remaining chapters. Content in both Chapters 2 and 3 is generally intended to apply to acceptance processes and decisions for all types of deep foundation elements.

Chapters 4 through 7 each address foundation acceptance for specific types of deep foundation elements. Content within each of these chapters is tailored to specific characteristics of the deep foundation elements, including construction techniques, inspection and quality assurance methods, and common performance practices. Chapter 4 provides information for acceptance of driven pile foundations while Chapter 5 provides information for drilled shaft foundations. Chapters 6 and 7 provide information for micropiles and CFA piles, respectively.

CHAPTER 2
FRAMEWORK FOR ACCEPTANCE OF DEEP FOUNDATION ELEMENTS

This chapter includes descriptions of the typical process for design, construction, quality assurance (QA), and quality control (QC) of deep foundation elements to provide readers with perspective regarding where each activity fits into producing foundations that satisfy the owner agency's performance requirements. Additionally, this chapter describes a general framework for evaluation and acceptance of deep foundation elements to provide readers with a high-level approach for evaluation and acceptance of structural foundations. The relationships, contributions, and responsibilities of participants in each activity vary among different forms of procurement (e.g., design-bid-build or design-build).

At the end of this chapter, readers should understand the general approach for evaluation and acceptance of structural foundations and have knowledge about what may be needed to conduct such evaluations. Specific details and inputs for the evaluations for specific deep foundation elements are provided in subsequent chapters of the manual.

2.1 DESIGN AND CONSTRUCTION PROCESSES FOR QUALITY DEEP FOUNDATION ELEMENTS

The overall objective is to construct deep foundations that can support the design force effects for the life of the structure across the anticipated range of ground conditions and with enough reserve strength to accommodate uncertainties. These objectives are achieved when construction and construction-related uncertainties are addressed during the design process, and when design and design-related uncertainties are accommodated during the construction process. Quality control (QC) performed by the constructor is an integral part of the construction plan, and quality assurance (QA) on behalf of the owner agency is achieved by thorough independent inspection, documentation, and verification. Participation of the responsible design professionals throughout construction and acceptance provides ongoing assessment of constructed deep foundations and timely acceptance of the work by the owner agency.

In Transportation Research Circular E-C037 (TRB, 2002), the Committee on Management of Quality Assurance (A2F03) describes QA as "All those planned and systematic actions necessary to provide confidence that a product or facility will perform satisfactorily in service… Within this broad context, QA involves continued evaluation of the activities of planning, design, development of plans and specifications, advertising and awarding of contracts, construction, and maintenance, and the interactions of these activities." Quality assurance in construction leads to acceptance (as illustrated in Figure 2-1 below) and is a part of the overall QA. TABLE 2-1 provides a comparison of QA and QC. Acceptance is the culmination of QA in construction, following the processes associated with planning, design, and construction and including activities associated with assurance that the design objectives are achieved during construction.

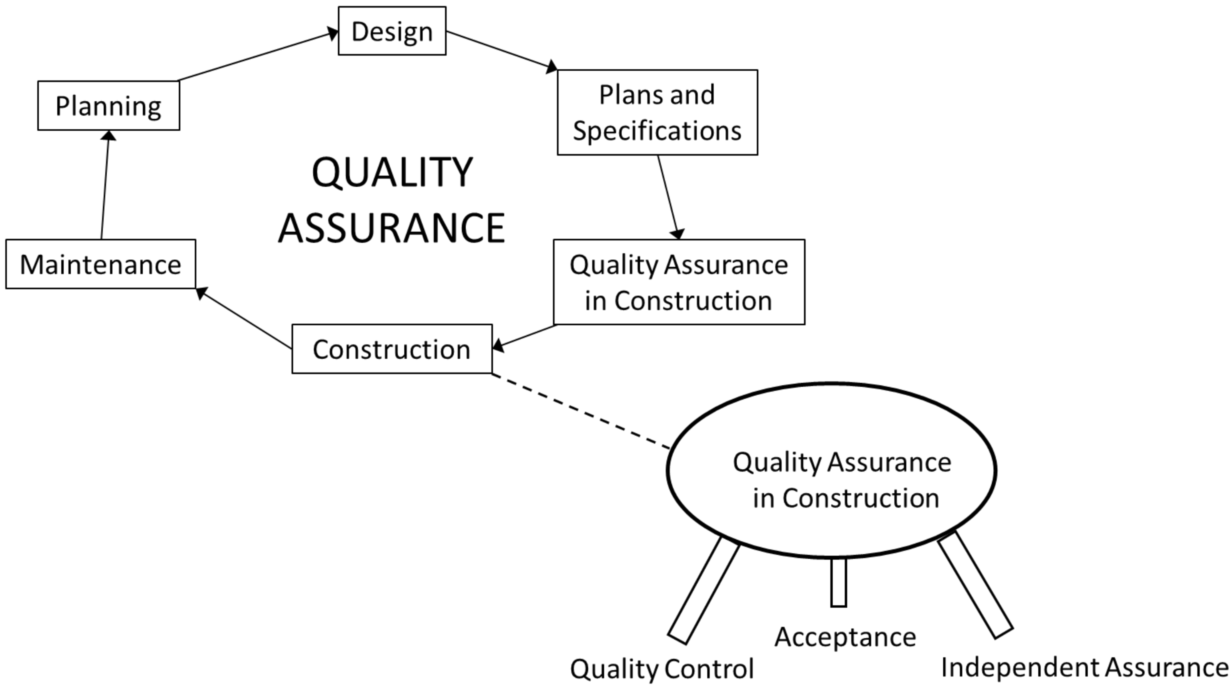

Figure 2-1 QA System Elements (adapted from E-C037)

TABLE 2-1 QA VERSUS QC (FROM E-C037)

Quality Assurance	Quality Control
Making sure the quality of a product is what it should be.	Making the quality of a product what it should be.
A highway agency responsibility.	A producer/contractor responsibility.
Includes QC.	A part of QA.
Doing the right things.	Doing things right.
Motivates good QC practices.	Motivated by QA and acceptance procedures.

The following sections of this chapter describe the factors that should be considered and included in each step of the process through design, construction, and acceptance of deep foundations. The general discussion will be provided in the context of design-bid-build project delivery, which remains the most common form of procurement for public transportation agencies. A brief discussion of different forms of project delivery is included as background.

2.2 PROJECT DELIVERY

Design-bid-build contracts are the most common form of procurement for public transportation agencies. However, design-build (D-B) procurement may be used in transportation projects, and other project delivery mechanisms such as Construction Manager or General Contractor (CMGC) contracts could re-align responsibilities relative to quality assurance and acceptance of deep foundations. Additionally, value-engineering (VE) or alternative technical concepts (ATC) may be incorporated into any of these as methods to optimize the project value.

2.2.1 Design-Bid-Build

Most transportation projects follow the traditional design-bid-build model in which the designer works directly for the owner agency, either as an employee or a design consultant. The contractor is then hired through a competitive bidding process in which the information used to prepare the bid is provided in the form of contract documents, possibly supplemented by informational meetings or site visits. The designer is responsible for providing a constructible design using ordinary means and methods in the foundation construction industry so that multiple bidders can compete to perform the work and provide the owner with a competitive fixed price for the work (although fixed unit prices may be used for work that involves variable quantities, such as pile lengths). In this model it is important that the designer understand how the foundations could be constructed and convey relevant information to bidders via the contract documents so that they can reasonably estimate costs, including contingencies for any risks and uncertainties that will be the responsibility of the contractor. The construction contractor is responsible for selecting the means and methods to construct the work in a way that satisfies the contract requirements as indicated in the plans and specifications.

There are two important concepts that influence risks and uncertainties in the design-bid-build process. The first is the "Differing Site Conditions" (DSC) clause from the Code of Federal Regulations 23 CFR 635.109, also sometimes referred to as "changed conditions" and described in FHWA Geotechnical Engineering Notebook Geotechnical Guideline No.15, Geotechnical "Differing Site Conditions" (FHWA, 1996). The DSC clause provides for an equitable adjustment to the contractor for conditions encountered that either differ materially from those indicated in the contract (Type I) or are unknown conditions of an unusual nature that differ materially from those ordinarily encountered and generally recognized as inherent in the work (Type II). Most agencies include DSC provisions in public works construction contracts and the Federal regulations cited above generally require the inclusion of DSC provisions in Federal highway projects. The purpose of these provisions is to provide the owner with competitive bidding for construction work without the need for contractors to include large contingency costs for unknown conditions that may or may not be encountered, are difficult or impossible to predict and price, and are not within the control of the bidder.

It is important to remember that a DSC in foundation construction typically represents a condition that was not revealed by the site characterization and/or is very unusual. DSC provisions simply provide a way for the commercial aspects of the work to proceed. A thorough site characterization can help reduce the potential that a DSC is encountered.

The second concept is that the design should be constructible using routine or normal construction practices used in the industry. The construction contractors can then price their bids competitively.

2.2.2 Design-Build

Design-Build (D-B) project delivery is often considered as an innovative approach to deliver large projects faster and more cost effectively by engaging a single entity known as the design-builder or design-build contractor. Since the responsible designer and constructor are part of the same D-B team, this type of procurement should foster collaboration between design and construction. Public-private partnerships, or P3 contracts, are a special form of design-build contract where the design-build contractor is paid through an entity that is responsible for project financing and long-term operation and maintenance of the facility.

D-B contracts could change the responsibilities for quality assurance and acceptance since the responsible designer is typically part of the D-B team. QA is typically performed by an independent entity engaged by the D-B team. The owner agency reviews the design and construction deliverables for compliance with contract requirements and determines acceptance of both the design and construction. Foundation acceptance decisions by the owner agency for D-B contracts may differ from traditional design-bid-build contracts in that acceptance also involves evaluation and acceptance of the foundation design itself since the D-B team is proposing a design for acceptance by the owner. The influence of major differences with D-B procurement compared to conventional design-bid-build on each part of the process of acceptance of deep foundations will be briefly described throughout the remaining sections of this chapter.

2.2.3 Construction Manager / General Contractor (CMGC)

CMGC procurement (sometimes also called “Construction Manager at Risk”) is a method often used to expedite project delivery by engaging a general contractor during the design process to work with designers to ensure constructability, identify risks, provide cost projections, and refine the project schedule. The construction phase then follows pending agreement between the owner and contractor on a negotiated price for the construction contract. The benefits of improved constructability in the design are derived from having a contractor involved and collaborating during the design process. CMGC procurement also allows potential VE or ATC ideas to be vetted during the design phase of the project.

2.2.4 Value Engineering and Alternative Technical Concepts

Some modifications to design and construction needs may occur with contractor proposals for VE alternates or ATC's. Both contract mechanisms could afford a contractor the opportunity to propose alternatives to the base design, which can offer the potential to save the owner cost or schedule time or reduce risks during construction for all parties. The owner can benefit from potential efficiencies proposed by a specific contractor who may have innovative ideas for construction or specialized equipment that may be advantageous. Owner acceptance of a VE or ATC proposal may potentially modify QA and acceptance.

2.3 DESIGN

Keys for successful completion of a quality deep foundation system begin during the design stage, from the start of site investigation through selection of foundation types, to completion of pre-construction design. Constructability and potential construction risks should be addressed as an integral part of design throughout this period. Project procurement using D-B and CMGC foster collaboration with the specific contractor that is to perform the work. With conventional design-bid-build contracting, the design team should take a more active role in understanding general construction capabilities and subsurface construction risks.

It is often helpful for a constructability review to be performed by knowledgeable persons independent of the design team so that potential risk items and constructability problems can be identified and addressed during the design phase of the project. The level of review may take on different forms depending upon the magnitude and complexity of the project.

2.3.1 Site Characterization

Site characterization provides important information on ground conditions for developing both a robust and reliable foundation design as well as a cost effective and reliable construction plan for foundation elements. Information on site characterization is provided in FHWA "Geotechnical Site Characterization, Geotechnical Engineering Circular No. 5 (GEC 5)" (Loehr, et al., 2016). Site characterization is also the first step in identifying and characterizing potential risks and uncertainties not only for foundation performance but also for construction of the foundations. Findings from site characterization should be documented in one or more engineering reports, which include all factual information obtained as well as interpretations of the information, a discussion of site geology, and an objective discussion of uncertainties and risks related to ground conditions that may impact foundation construction and performance. Examples of uncertainties and potential risks include stratigraphic variability, old fill or other potential obstructions, contaminated ground, uncertainties and variabilities in material properties, groundwater conditions, and notable geologic features such as solution cavities, boulders, artesian groundwater, faults or other features affecting rock strata, and cemented or unusually hard soil layers. An example subsurface profile illustrating stratigraphy is provided in Figure 2-2.

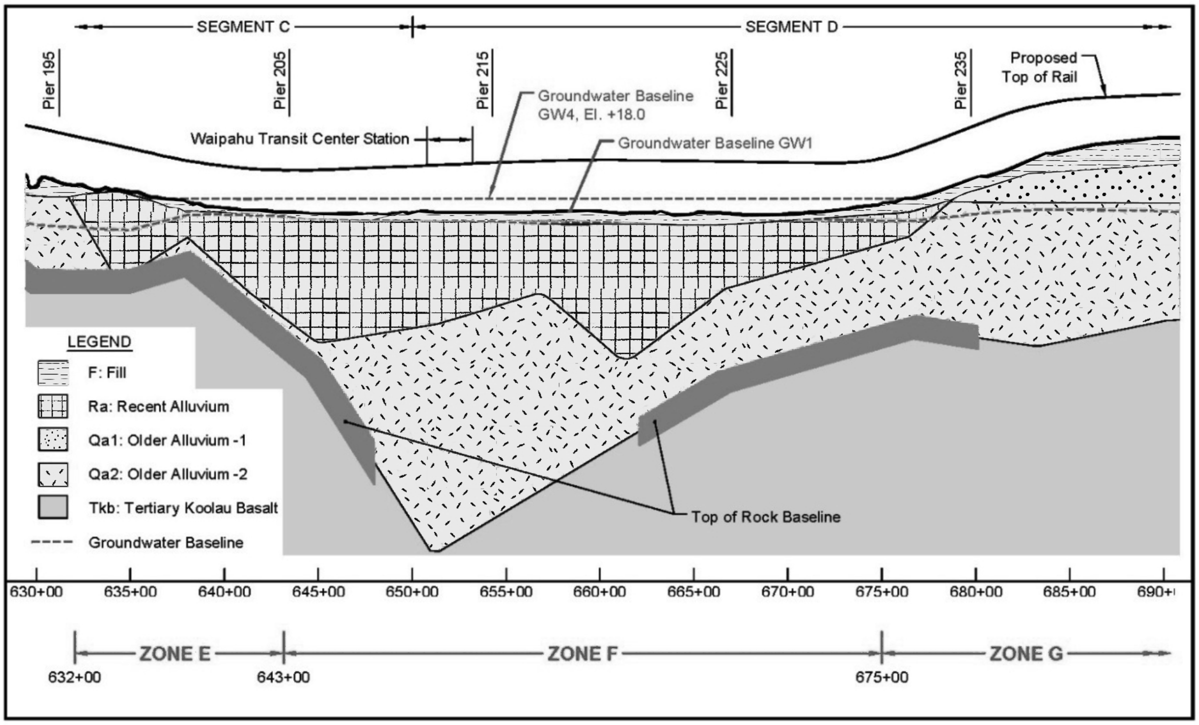

Figure 2-2 Example Soil and Rock Profile Illustrating Stratigraphy (from Drilled Shafts: Construction Procedures and Design Methods," Geotechnical Engineering Circular No. 10 (GEC 10) (from Brown, et al., 2018)

Although findings from site characterization are documented as a part of the design process, this information is also critical for subsequent planning of construction means and methods. Contractors use this information to prepare cost estimates for bidding and to develop installation plans that will satisfy the specifications and any other design requirements outlined on the contract documents. Items related to subsurface risks that are clearly identified in the reports of subsurface investigation can then be addressed, as appropriate through the contract. Site characterization reports should provide factual information that will facilitate accurate bidding.

For D-B projects, a limited pre-bid site characterization is typically performed, with final investigation and characterization being performed by the D-B contractor. However, thorough pre-bid site characterization provides valuable information that is necessary to prepare a preliminary design for estimating and planning construction work. Investment in thorough pre-bid site characterization may help to reduce risks and contingency costs in D-B proposals.

2.3.2 Foundation Design

Designers may consider aspects of acceptance during the process of foundation type selection and design, which are described in the geotechnical engineering circulars and other references for each specific deep foundation type. The foundation design and foundation type(s) selected should be adaptable to reasonable variations in subsurface conditions, as identified from site characterization. Design includes development of construction specifications that are appropriate for both the range of conditions anticipated and the design requirements. Some agencies have standard specifications for a range of foundation types, and designers can consider and address project-specific conditions with special provisions or plan notes. These special provisions and plan notes may form the initial acceptance criteria for use during construction, although final acceptance criteria may be developed as a part of a field-testing program. Field testing may be implemented prior to construction of production foundation elements for smaller projects, but for larger projects may sometimes be implemented in stages as construction advances.

The design may not be completed until acceptance criteria are established and construction completed because the design may need to be adjusted based upon the actual subsurface conditions revealed during construction. Acceptance criteria may form the basis for routine adjustments for variations, but unusually large variations in subsurface conditions can potentially trigger more substantial adjustments to the design. For example, drilled shaft excavation depths may be finalized in the field based on either an evaluation of pilot hole borings or the inspector's observation of excavated materials; the design includes the criteria for such determinations. Similarly, acceptance criteria for driven pile foundations are often developed during the test pile program based on dynamic or static load tests and correlations with the driving resistance. In this case, the design and specifications should convey requirements for the test pile program that are consistent with anticipated variations across the site and the target resistance factors used in design. The design aspects of quality assurance are illustrated in the flow chart in Figure 2-3, starting with the final step of design.

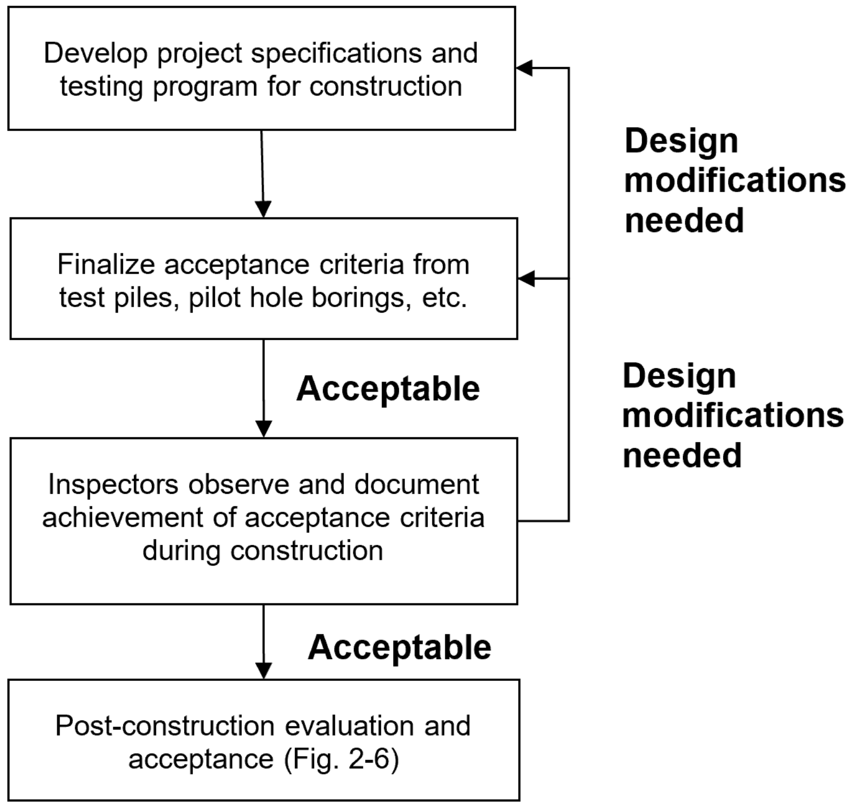

Figure 2-3 Design Aspects of Quality Assurance in Construction

Potential risks and uncertainties related to subsurface conditions should be carefully considered during foundation type selection since design and construction risks associated with different types of deep foundations vary. For example, risk associated with driving piles through a dense layer to achieve a minimum penetration might be reduced by designing open ended pipe piles rather than closed end piles (Figure 2-4 illustrates the driving of a steel pipe test pile). The potential impact of subsurface obstructions may present less of a potential risk for micropiles than for continuous flight auger (CFA) piles, and the costs and potential delays may offset the potential cost advantages of CFA piles unless efficient and effective contingency plans can be identified to address the risk. Another example is potential risks of solution cavities in rock for drilled shaft construction; such potential risks identified in design can be communicated through the contract documents prior to bidding, and specifications can be written with a plan for preconstruction pilot hole borings at each drilled shaft location and for use of temporary (or permanent) casing in mind.

Figure 2-4 Test Pile Installation to Develop Driving Criteria (photo by the authors)

Another area of consideration for constructability is the connection between foundations and the substructure. The constructability review for the pilecap and pile connection details, and for the column to drilled shaft connection should involve input from geotechnical and structural engineers as well as persons experienced in construction. For example, in some types of ground conditions, installation of piles within a cofferdam footing may pose challenges with respect to construction of the cofferdam, sheet pile installation, and the necessary seal for dewatering. Where column reinforcement extends into the drilled shaft reinforcement at the connection, rebar congestion could pose problems for tremie placed concrete. Ease of construction should be a consideration during design of these details to mitigate potential risks of problems during construction.

An effective assessment of subsurface risks with each foundation alternative should be part of the constructability review performed during design. Potential risk items can be addressed in specification provisions and plan notes to clearly alert the contractor to potential challenges that may be encountered during construction.

2.3.3 Communication of Design Information Needed for Acceptance

Construction documents should include content that describes design objectives and performance criteria. For example, minimum penetration of piling below scour elevations or minimum embedment of drilled shafts into rock or other well-defined bearing stratum can be cited on plan notes. Some demands or special requirements may be more appropriately outlined in project-specific specifications or special provisions. Construction drawings should include documentation of the demands for each foundation in a clear and concise manner, as this information facilitates eventual review and acceptance of deep foundation elements. For example, information may be included on plan notes documenting the target nominal resistance for each driven pile, including the anticipated resistance of the soil above the design scour elevation (that contributes to driving resistance, but not design axial resistance) and foundation embedment necessary to satisfy lateral or uplift demands.

2.4 CONSTRUCTION

Successful completion of a quality deep foundation system may be achieved when contractors understand the primary objectives of the foundation design, subsurface conditions, and geology and then use this understanding to develop a robust and reliable construction plan for foundation installation. A complete installation plan is appropriate for the ground conditions and adaptable to reasonable variations in subsurface conditions with contingencies for potential problems or potential risk items. Implementation of the construction plan should include a thorough quality control system to manage day to day work to install foundations that will satisfy the acceptance criteria.

2.4.1 Understand Objectives and Subsurface Conditions

A pre-bid site visit should usually be made to identify site constraints and conditions that may influence equipment selection and construction methods. The review of conditions might include specific items such as inspection of rock cores for a drilled shaft foundation or review of pile driving records from an earlier project at the site.

An understanding of specific foundation requirements related to the design objectives is important to developing an effective installation plan. For example, some driving aids might be limited to penetrating scourable overburden soils above the bearing strata, or the extension of drilled shaft casing into bedrock may require extension of the rock socket to maintain a minimum socket length.

2.4.2 Develop a Reliable Plan for Foundation Installation

With a good understanding of subsurface conditions and project requirements, the contractor can develop a robust and reliable construction plan for foundation installation. A good installation plan is complete and appropriate for the ground conditions present, and adaptable to reasonable variations in subsurface conditions with contingencies for potential problems or potential risk items. The plan should address contingencies for items in the contractor's control, such as equipment redundancy in the event of an inadvertent malfunction, and critical supply chain disruptions, such as concrete delivery or having adequate drill fluid volume. The installation plan should be developed prior to the start of any production foundation works and should be critically reviewed by the design and inspection team prior to commencing work. The installation plan should also address the quality control systems that the contractor will employ during construction to maintain consistent quality and identify any issues that may require adjustment as the work progresses. Appropriate QC systems should comply with the designer specified methods and integrate into the overall QA for construction.

There can be significant benefits in constructing demonstration foundation elements in advance of the start of production work. This pre-production work should allow the installation plan to be demonstrated to be effective and any adjustments or modifications to the plan be developed, agreed, and implemented prior to the start of production foundation construction. Installation methods may need to be adjusted for situations that were not identified in test installations or test piles. Flexibility in the plan and cooperation by the entire design and construction team aids in the construction of reliable foundations across a range of conditions on any given construction site.

2.4.3 Incorporate Quality Control During Construction

Quality control procedures may include measurement of performance parameters in a timely manner so that adjustments can be made during construction. Quality assurance may be enhanced by using the right QC tool for the application with clearly defined target metrics and good documentation of the measurements. Examples include simple checks on location, alignment and positioning of a foundation element, observation and measurement of concrete or grout properties prior to and during placement, along with casing and tremie pipe levels during placement of concrete or grout. For driven piles, the focus is often on observation of driving resistance with checks on hammer performance; periodic dynamic test measurements during production pile driving ensure consistency of driving resistance correlations. Quality control procedures should be defined in the installation plan, and sufficient to fully document the work. These observations and records are important components in the quality assurance plan.

In many cases, modern construction equipment includes automated monitoring of important quantities so that the operator can manage the equipment in real time to control quality. For example, some pile hammers may be equipped with instruments to record parameters related to hammer energy; inspectors also have access to various monitoring equipment to record pile driving measurements for quality assurance. Monitoring equipment for inspectors provides QC data including pile blow count, number of blows per minute, hammer stroke, and penetration. Hydraulic pressure sensors on drill rigs can provide information related to resistance required to advance the drill, which may be useful in identifying variations in the soil and rock formations. The photo in Figure 2-5 illustrates an example of automated monitoring for a CFA pile installation that can indicate to the operator the pressure and volume of concrete or grout pumped relative to the elevation of the tip of the augers. Records of this type are also very useful as a part of the quality assurance program.

Figure 2-5 Automated Monitoring During CFA Pile Construction (from FHWA GEC 8, Brown, et al, 2007)

2.5 INSPECTION AND QUALITY ASSURANCE

Acceptance of deep foundations relies primarily on field inspection and is dependent upon the observation, documentation, and communication of the work by on-site inspectors. Inspectors should verify that work is in conformance with the plans, specifications, and installation plan, and perform or observe measurements of various components of the work during construction. Records from these observations and measurements provide a factual, permanent record of the work performed on each deep foundation element and, as such, should be obtained and documented in a timely and accurate fashion. Monitoring instruments and equipment can also be used to measure factual data reducing potential areas of misunderstanding.

Communicating inspectors' observations with the contractor's representative on a daily basis may reduce potential risks. Inspectors' observations should be promptly communicated to the contractor so corrections or adjustments, if needed, may be initiated in a timely manner.

The inspection team serves as the link between design and construction to ensure that work is carried out in a manner consistent with the design requirements. Inspectors may identify the target tip elevation to satisfy the criteria set forth in design where ground conditions indicate, and inspection records provide the basis for such adjustments. Observations should be communicated to the responsible contracting officials and especially to the responsible engineer in a timely fashion when decisions are required that affect ongoing work.

When the responsible engineer is actively engaged in the project throughout construction, the ground conditions revealed during the work can be evaluated for consistency with those anticipated in design and any appropriate adjustments to the design made in a timely manner based upon the actual conditions as encountered. In routine work, the inspector may be given some authority to identify foundation tip elevations to satisfy the design criteria. However, where unusually complex or variable conditions may exist, or where specific foundations may be particularly critical, it is both important and appropriate to have a representative of the design engineer on site during construction. Timeliness of decision making is critical to the project work schedule, and foundation work is almost always a critical path item.

Besides the real-time observations and measurements of the inspector, supplemental measurements may be performed as a part of the quality assurance procedures. These might include restrike measurements or dynamic tests on driven piles, integrity tests performed on drilled shafts or CFA piles, and proof tests on micropiles or other deep foundation elements. Post-construction testing for integrity or axial resistance is supplemental to the inspection and serves as a verification of some aspect of the work; testing is not a substitute for proper inspection and construction documentation.

2.6 EVALUATION AND ACCEPTANCE

The final step for foundation acceptance should include review and evaluation of all collected records and measurements, and decision making for acceptance of a constructed foundation. A flow chart illustrating this process is provided in Figure 2-6. The responsible engineer should review and assess all inspection records including post-construction measurements and test data on a regular basis so that the work can be accepted efficiently, and any further evaluation or remediation needed prior to acceptance can be performed in a timely manner.

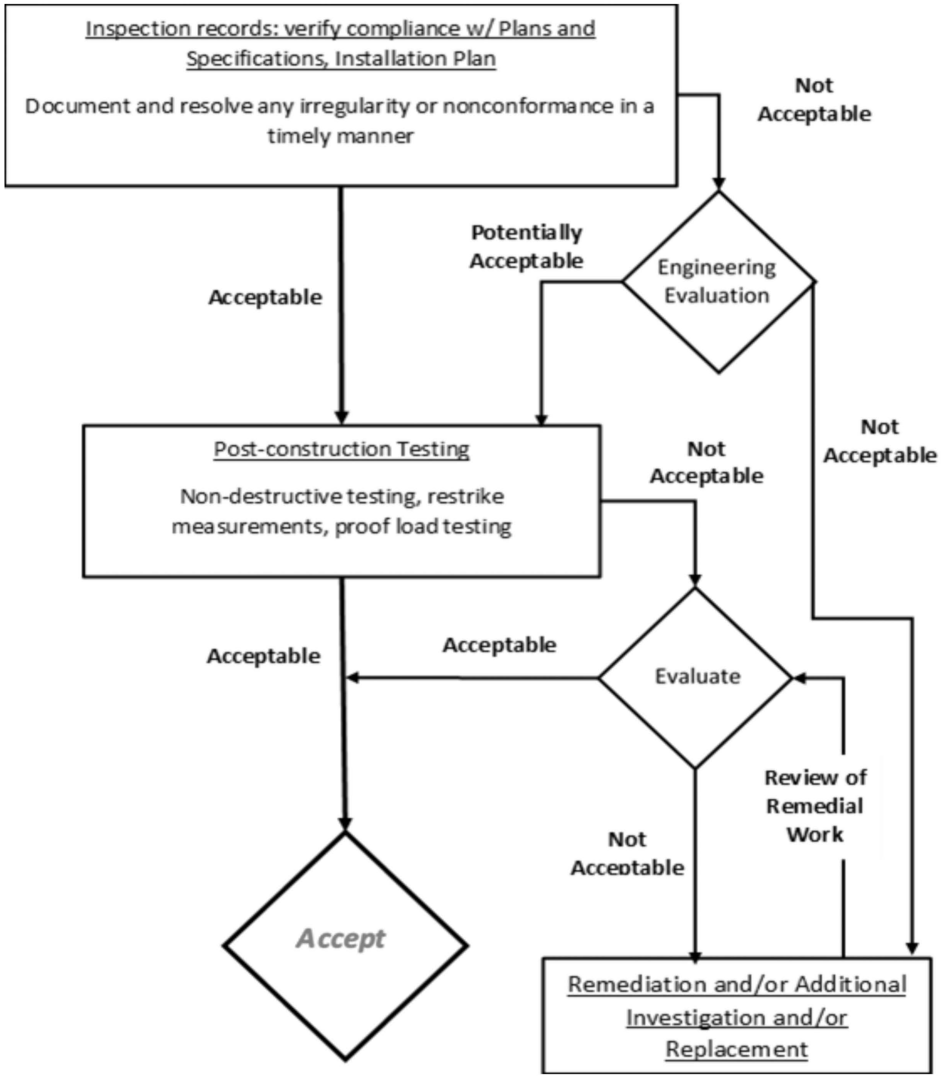

Figure 2-6 Flow Chart of Post-Construction Evaluation and Acceptance

2.6.1 Documentation for Review

The written documentation of work in inspection records provides a permanent record of the as-built foundations and should be a basis of quality assurance for each foundation element. Specific forms and details of the information recorded vary among agencies and different foundation types but these should be sufficient to confirm the as-built location, dimensions, elevations, and all details of the installation process to verify compliance with the specifications and the approved installation plan.

The engineer in responsible charge of the foundations, ideally the foundation design engineer, is best able to review the inspection records and provide a recommendation on acceptability in a timely manner. If inspection records are prepared as a well-organized package, and a system is established whereby the responsible engineer has access as soon as possible, this process can advance promptly to a timely review of any post-construction testing results.

Post-construction tests, such as non-destructive testing (NDT) on cast-in-place concrete foundations or confirmation restrike blows or dynamic tests on driven piling, are considered routine quality assurance tests used in transportation infrastructure projects. These measurements may provide an additional measure of quality assurance that can detect foundation problems that might not be readily apparent during routine inspection and thus form an additional check for the responsible engineer prior to acceptance. They may also provide verification or additional information about an unusual condition that was identified during construction and inspection.

For some types of foundations, there may be one additional inspection at the time that the connection between foundations and the structure is made. For example, the concrete surface of a drilled shaft may be subject to a final inspection during construction of the column to shaft connection. Any deep foundation may include the post-installation fabrication of a connection to a pile cap or footing. The inspection of this aspect of the work may be considered a part of the foundation acceptance or may be considered part of the inspection of the substructure work, depending on the circumstances of the project or agency policies.

Consistent terminology should be used with respect to evaluation of potential deficiencies in deep foundation elements. Nonregulatory industry terms generally used for drilled shaft foundations are included in FHWA "Drilled Shafts: Construction Procedures and Design Methods," Geotechnical Engineering Circular No. 10 (GEC 10)" (Brown, et al, 2018). Some of the terms that may be considered for general use are:

- ***Anomaly***: an anomaly is an irregularity in a measurement or observation that represents a deviation from the norm. This term is often used in reference to an anomalous pattern in an integrity test measurement, but it could also apply to something like an unusual observation of pile driving resistance such as an anomalous low blow count measurement or a measured reflected stress wave sooner than expected for a given pile length. An anomaly may or may not represent a defect or imperfection in the deep foundation.

- ***Imperfection***: an imperfection is some deviation in the constructed foundation element that is not intended and may or may not be detrimental to performance. Examples include a pocket of segregated concrete in a drilled shaft, or a crack in a driven concrete pile, or a micropile that is located out of the specified tolerance. An imperfection may or may not represent a deficiency in the constructed foundation element. Note that information from the DFI "Terminology and Evaluation Criteria of Crosshole Sonic Logging (CSL) as Applied to Deep Foundations" (DFI, 2018) suggest the use of the term "Flaw" as synonymous with this definition of "Imperfection".

- ***Deficiency***: a deficiency is an imperfection that rises to the level of rendering the foundation insufficient or inadequate to perform its intended function. Some type of remediation or replacement is likely needed. Note that the need for remediation may be affected by an evaluation of the entire foundation group rather than based on a single foundation element.

- ***Remediation or Repair***: the act or process of correcting a deficiency.

With complete and well-organized documentation of the construction inspection and any post-construction testing, the responsible engineer can assess the condition of the deep foundations for acceptance.

2.6.2 Post-construction Assessment

Post-construction assessments may be performed by the engineer in responsible charge of the foundations, which should be the foundation design engineer. Acceptance procedures are discussed in Section 2.6.5.

Problems or irregularities that occur during construction that can be identified by inspection can be resolved during construction by engaging the design professionals in a timely manner as described in Section 2.4. In the event that issues cannot be resolved satisfactorily, the construction team may potentially continue the work but post-construction assessment may determine that remedial work may be needed. For example, a temporary casing that has to remain in place due to unstable conditions or equipment malfunction that prevents its removal after concrete placement on a drilled shaft may present an issue that cannot be resolved immediately and may need subsequent evaluation. The engineer may evaluate a pile that is damaged during driving to determine the significance to the entire pile group foundation.

If there are unresolved issues during construction, or if inspection records indicate conformance with the requirements but the post-construction review or test records reveal significant anomalies, then further evaluation should be performed which may include additional investigation. To the extent possible and prior to an exhaustive destructive investigation, the assessment should characterize the nature, location, and extent of the potential defect or imperfection so that an evaluation of the effect on the foundation strength and serviceability can be performed. Often an anomaly in post-construction measurements can be correlated with some additional information from inspection records to provide more insight into the nature of any potential defect.

The time needed to perform the evaluation and investigation and the impact on the schedule is a consideration regarding the amount of effort in this work. For example, concrete coring in a drilled shaft that has anomalies in the NDT may represent a significant expenditure of time and money; it may be prudent to first perform an evaluation of the impact of a potential defect to determine if the potential problem rises to the level of a deficiency before undertaking an extensive investigation. For example, a small anomaly near the base of a drilled shaft may be determined to be relatively inconsequential if the structural demand at that location is very low. Even if a deficiency is identified, in some cases a remediation may be simple and efficient to perform, and a detailed investigation may not be justified. For example, deficient concrete near the top of a drilled shaft may be easier and less costly to remove than to investigate.

A detailed investigation may be needed for a potential defect with substantial impact on performance, or to verify the need for a costly potential remediation effort, or especially for a recurring problem that could represent a possible flaw in the foundation installation plan that requires correction or adjustment in the means and methods of subsequent work. In the latter circumstance it may be preferable to correct a small issue before it becomes a major one. Examples might be a recurrence of pile damage during driving or a recurring anomaly in NDT measurements on a drilled shaft at a depth coinciding with some operation during concrete placement.

The evaluation of the potential impact on performance should include an evaluation of both geotechnical strength and serviceability and structural strength for the controlling load cases (which may include extreme event loadings). Deficiencies identified during this evaluation may require the contractor to develop a remediation plan to address the deficiencies.

A finding of potential deficiencies by the responsible engineer should be communicated in a clear and timely manner to the contractor so that an effective plan can be developed and potential impacts on costs and schedule can be managed. Foundation demands for the repaired foundation should be included so that the contractor's engineer can develop a repair plan to restore the foundation to condition that is "fit for purpose", i.e., satisfies the design requirements. The contractor may elect to perform additional investigation to better define the potential defect and attempt to mitigate (or even eliminate) the magnitude of any remedial work needed. Representatives of the engineer and inspection team should participate in any additional investigation.

Problems that emerge during construction or assessment that affect the acceptance of the foundation may result in disagreements. Agencies should have a process for resolution of disputes, including claims for differing site conditions or other contractual issues.

2.6.3 Remediation

Development of a remediation plan may be the responsibility of the contractor, but this work needs input from, and communication with, the responsible engineer and the owner. In some circumstances, the contractor may retain a designer to help develop the remediation plan. When part of the remediation plan involves design work to evaluate the remediated foundation, the contractor could need information related to the foundation demands and the soil and rock characterization used for the original design. Additional investigation work may be performed to characterize the ground condition at the specific foundation location in more detail or for other purposes, for example, to design a ground improvement scheme. Sometimes a pile cap or even a pier column might need to be redesigned to accommodate a resized foundation. A replacement or supplemental foundation element may prove to be more efficient, reliable, and cost effective than attempting to repair a defective deep foundation element itself.

A deficient foundation is one that is not suitable for the purpose for which it was designed, and the remediation of a deficient foundation should have as a goal the repair of the foundation to a level that is fit for the required purpose. Deep foundation construction contains potential risks inherent in the work due to uncertainties in subsurface conditions, weather, and vulnerabilities to mechanical equipment and fallible human operators. A good design should tolerate minor imperfections.

Once a repair plan is designed and accepted by the owner and responsible engineer, the remediation work should be implemented with an appropriate plan for construction, quality control, inspection, quality assurance, and assessment so that the completed foundation can eventually move to acceptance.

2.6.4 Acceptance

After completion of the assessment of the construction and testing records by the responsible engineer and successful resolution of any outstanding issues, the engineer should document the acceptability of the foundation with a written record of the outcome of the evaluation process. This documentation by the responsible engineer could be referred to as a “Recommendation of Acceptance” letter. The documentation should include a reference to the construction records and conformance with the project requirements, the findings of the post-construction testing, resolution of any discrepancies or non-conformance issues, the records of any corrective actions taken, and documentation of analyses supporting the assessment process.

CHAPTER 3
ROLE OF INSPECTION AND TESTING FOR ACCEPTANCE OF STRUCTURAL FOUNDATIONS

This chapter addresses key characteristics of effective assessment and acceptance of deep foundation elements, emphasizing the importance of comprehensive consideration of available information rather than exclusive reliance on individual assessments. The chapter is organized according to different categories of assessment methods: (1) conventional construction observation and inspection techniques; (2) tests for assessing the integrity of constructed foundations; and (3) tests for evaluating foundation performance. This chapter also describes important reliability concepts for acceptance of structural foundations, and how different methods of assessment contribute to producing reliable foundation elements. Importantly, this chapter addresses the distinction between "design reliability" and "performance reliability" and explains how this distinction should be considered for acceptance of structural foundation elements.

3.1 DESIGN RELIABILITY VERSUS PERFORMANCE RELIABILITY

Foundations designed and constructed according to current AASHTO Bridge Design Specifications (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)), or State-specific design specifications, are intended to produce foundations that achieve acceptable reliability. Observations of the performance of constructed foundations strongly demonstrates that the actual reliability of constructed foundations is considerably greater than target values of reliability adopted for design (e.g., Barker, et al., 1991). This historical experience illustrates the difference between design reliability and the reliability of constructed elements, which is referred to in this document as "performance reliability". Design reliability represents the degree of confidence a designer has that foundations constructed according to a design will achieve the intended level of reliability. In contrast, performance reliability is more of an actuarial or empirical reliability describing how often acceptable performance is achieved.

Design reliability is sometimes lower than constructed reliability because of greater uncertainties and unknowns that are inherent to design. The act of construction, and the quality assurance (QA) activities associated with that construction, serve to reduce, or even eliminate some design uncertainties. For example, designers necessarily have to make assumptions or approximations of depth to bedrock, or depth of scour susceptible materials, to establish required design dimensions for deep foundation elements. Often times such assumptions are appropriately conservative, even with appropriate site characterization, to provide assurance that the structure will perform as needed. With appropriate quality assurance, many such uncertainties may be reduced or eliminated during construction. The net result of these observations may be that a constructed foundation that differs from specified tolerances may still reliably satisfy all performance requirements. The objective of acceptance is to approve and formally accept foundations that should fulfill their intended purpose despite virtually inevitable minor imperfections that may occur because of the nature of construction. In some cases, a robust design may be able to accommodate imperfections beyond specified tolerances.

While foundation acceptance may not rely on formal reliability analyses, understanding how different sources of information contribute to reliability can inform foundation acceptance decisions, particularly when integrating information from multiple sources. Methods for assessment can generally be categorized into three sources: (1) construction observation and inspection, (2) integrity testing, and (3) performance evaluation. The first method, construction observation and inspection, refers to collection of information during foundation installation by inspectors and other QA personnel. The second, integrity testing, refers to various tests used to evaluate the condition of constructed foundation elements. The third, performance evaluation, refers to various forms of testing or analysis that are intended to evaluate the performance of foundation elements as constructed. Each category of information is described in greater detail in the sections that follow. In subsequent chapters, specific techniques are described for various types of foundation elements.

3.2 CONSTRUCTION OBSERVATION AND INSPECTION

Construction observation and inspection refers to the practice of having an inspector on site during foundation installation to observe and document construction activities and events, so that conformance with plans, specifications, and approved installation plans can be effectively evaluated. Construction observation and inspection, and effective documentation of the work, are important components of civil engineering in general, and foundation engineering in particular. Construction observation and inspection should be conducted for every foundation element and should serve as a major component of acceptance of structural foundations. Three primary objectives of construction observation and inspection for foundations are involved in foundation acceptance: (1) verifying foundation elements are constructed according to plans, specifications, and approved installation plans; (2) documenting actual subsurface conditions and comparing them with subsurface conditions considered for design; and (3) identifying unforeseen conditions that may impact foundation performance.

The first objective, verification that foundation elements are constructed according to plans, specifications, and installation plans, is fundamentally similar to inspection of other construction activities (i.e., for above-ground structures), involving tasks such as verifying as-built locations and dimensions conform to plans and verifying construction materials conform to specifications. For foundations, examples of verification include verifying reinforcement characteristics for drilled shafts as illustrated in Figure 3.1, driven pile cross-sections (e.g., diameter and wall thickness for steel pipe piles), and the final depths of CFA piles. Such verification activities may confirm that as-built foundations satisfy plans and specifications and, in turn, provide some level of assurance that the constructed element will serve its intended purpose. Verification that construction conforms to approved installation plans is also important, and necessary to confirm that construction procedures do not negatively influence the performance of the foundation element. For example, it may be necessary to verify that the tremie pipe remains sufficiently embedded below the top of concrete during concrete placement for a drilled shaft. If as-built foundations do not conform to plans, specifications, or installation plans, any deviations should be noted by the inspector and documented in as-built records. The process of verifying foundation construction and documenting any deviations from plans, specifications, and installation plans should be a fundamental task of foundation acceptance.

The second objective of construction observation and inspection, documenting actual subsurface conditions and comparing them with subsurface conditions considered for design, is unique to underground construction. Foundation construction activities generally reveal information about subsurface materials to a greater extent than is possible from most site characterization programs. For instance, drilling activities associated with installation of drilled shafts, micropiles, and CFA piles can be used to create a log of subsurface conditions specific to the individual foundation element. Generally, such information is more specific than information available from design-phase investigations because design-phase site characterization typically involves using a limited number of boreholes (or CPT soundings, etc.) to infer conditions for many foundation elements. Although driven piles do not provide a visual record of foundation materials, pile driving resistance information provides an indirect assessment of ground conditions, akin to a log of SPT blow counts, for the specific foundation element.

Figure 3.1 Evaluation of steel reinforcement for a drilled shaft (photo by the authors).

Geotechnical engineers have long appreciated the value of subsurface information revealed during construction. The observational method (e.g., Terzaghi, et al., 1996) is an example of collecting and applying such information. In the observational method, geotechnical designs are developed using the most probable interpretation of subsurface conditions, rather than the most conservative interpretation. During construction, actual subsurface conditions are observed, and any deviations from the most probable interpretation are used to modify the design as necessary. The observational method is one framework for foundation acceptance—a framework focused on economy and the ability to modify designs during construction. Even for applications when the observational method is not explicitly applied, documentation of subsurface information during construction can provide assurance to the foundation engineer that the actual subsurface conditions are not detrimental to foundation performance. Documentation of subsurface information may therefore be a useful activity during construction observation and inspection.

The third objective of construction observation and inspection, identifying unforeseen conditions that may impact foundation performance, is closely related to the second objective. Whereas the second objective generally pertains to modest variations between conditions considered for design and construction conditions, the third objective pertains to unanticipated construction conditions that may be radically different from design conditions. Examples include encountering unanticipated voids or cavities during construction of drilled foundation elements or obstructions during pile driving. Identifying and responding to such occurrences is needed to effectively assess constructed foundations.

Some basic level of quality assurance is typically presumed during design. For example, designers appropriately assume that the constructed dimensions of the foundation will be verified to be consistent with those dictated in the plans and specifications. Acquisition and confirmation of such information is therefore needed for acceptance rather than a contribution to producing performance reliability that is greater than that considered for design. However, other aspects of observation and inspection may contribute to improving, or potentially reducing, the reliability of the constructed foundation. Examples of the latter may include encountering ground conditions during construction that are materially different than considered for design or having cast-in-place concrete achieve much greater compressive strength than considered for structural design of the foundation element. Both types of observations should be recorded and effectively communicated during construction so that the information can be appropriately considered for acceptance of the deep foundation element.

3.3 INTEGRITY TESTING OF FOUNDATION ELEMENTS

While construction observation and inspection are critical assessment activities that occur during construction, integrity testing refers to post-construction evaluations of foundation elements. Integrity test methods are commonly non-destructive tests but may include destructive tests such as coring of drilled shafts to observe concrete condition and measure concrete strength. The objective of integrity testing is to supplement construction observation and inspection to provide assurance that a constructed foundation element is sound. Common examples include using crosshole sonic logging (CSL) or thermal integrity profiling (TIP) to assure the presence of sound concrete within a drilled shaft, using sonic echo techniques to assure installation of a driven pile without damage, and using TIP to assure CFA diameter is relatively uniform. Integrity testing is generally best suited for assessment and evaluation of conditions that cannot be easily observed during construction. In each of these examples, the integrity test information may be a useful supplement to construction observation and inspection records that should improve the engineer's acceptance evaluation. In turn, construction observation and inspection records should inform the conduct and interpretation of integrity tests. Integrity testing should not be considered as the sole basis for acceptance of deep foundation elements.

Use of integrity test methods varies by foundation type and agency. For some foundation types, e.g., drilled shafts, many agencies require use of integrity test methods by specifications. For other types of foundations and other agencies, integrity test methods may be used on a project-specific basis via special provisions. Some agencies require integrity tests for all constructed foundation elements, while others may only require integrity tests for selected foundation elements or a selected percentage of foundation elements. When integrity testing is not required for all foundation elements, the foundation elements to be tested should be selected based on observation and inspection conducted for all elements. For example, observation of unusual pile driving resistance for driven piles or observation of a tremie breach during concrete placement for a drilled shaft should motivate conduct of integrity testing for a specific foundation element.

While integrity test methods may provide useful information for foundation acceptance, some perspective on the role of integrity testing is prudent. Integrity test methods are one tool in the foundation acceptance toolbox. Other tools including proper design for constructability, clear specifications, appropriate construction practices, and informed construction observation and inspection are methods to reduce foundation installation problems. Installation problems identified during integrity testing rather than during design or construction may be more challenging, consequential, and costly to remedy. It is also important to recognize that integrity testing methods themselves are indirect measures of integrity with limitations that one should consider alongside other information acquired as part of foundation acceptance decisions.

3.4 PERFORMANCE EVALUATION AND TESTING OF FOUNDATION ELEMENTS

A third source of information that may contribute to effective assessment of foundation elements is performance evaluation, which refers to use of analyses or tests to evaluate the performance of a constructed foundation element. One example of performance evaluation is static load testing, in which a foundation element is statically loaded in a manner consistent with anticipated loading from the structure to measure the performance of the element directly and demonstrate its ability to resist anticipated loads. Such an approach should be used for acceptance of ground anchors, wherein all constructed anchors are individually loaded to some proportion of the factored load to demonstrate acceptable performance. Alternative performance tests may include rapid load tests, high-strain dynamic tests, or even pile restrike tests to assess pile setup.

Load testing of all individual foundation elements may be impractical for deep foundations and, therefore, is seldom used as a direct means for acceptance, as is more routinely done for ground anchors. However, load testing can and does contribute to effective assessment and acceptance of deep foundation elements in an indirect manner. A common way that load testing contributes to assessment and acceptance is by contributing to the establishment of appropriate criteria for inspection and observation. Load testing is often used with demonstration elements (also called technique elements or method elements) constructed following design but prior to beginning production operations for a project. One or more demonstration elements may be constructed using construction methods and procedures proposed by the foundation contractor to demonstrate the effectiveness of the proposed foundation installation plan. If the demonstration elements are also load tested, such tests may serve both as a confirmation of the foundation design as well as confirmation that the contractors means and methods are sufficient to produce foundation elements that reliably satisfy performance demands. Load tested demonstration elements may also be used to refine acceptance criteria for subsequent production elements. For example, demonstration elements may be used to refine driving resistance criteria for driven piles or required grout pressures for micropiles.

Some form of load testing may also be occasionally used for some percentage of production foundation elements. Such tests are relatively uncommon with relatively high-capacity foundation elements like drilled shafts but are relatively common for foundation elements with lesser capacity. For example, proof testing of some percentage of micropiles is relatively common, as is high-strain dynamic testing of selected driven piles. Like load testing for demonstration elements, additional load tests for production elements serve as continuing evaluations to confirm the suitability of the foundation design and the contractor's means and methods. Load tests may also provide inherent indications of foundation integrity. Specific details regarding the role of load testing for specific foundation types is provided in subsequent chapters.

When load testing is performed, it is important that assessment of performance account for important design requirements and variations in ground conditions among individual foundation elements. For example, it is common to disregard resistance provided by scour susceptible materials for design of foundation elements to resist axial or lateral loads. However, such materials are often present when load tests are performed so it may be necessary to "correct" the observed response to account for resistance provided by the scour susceptible materials in order to appropriately assess whether the foundation satisfies performance demands. Such corrections are often facilitated by appropriately placed and monitored instrumentation, as well as interpretation analyses to characterize the available response for the design condition appropriately. Variations in ground conditions from the location of the tested elements to that of the foundation being assessed for acceptance also need careful consideration. Finally, it is important to recognize that load tests generally only assess one loading mechanism (e.g., axial or lateral loading) and that other loading mechanisms or combinations should also be appropriately considered. For example, an axial load test for a foundation element that is controlled by lateral loading considerations may provide limited benefit since the resistance component tested is not controlling the design. The axial test may contribute knowledge regarding the likelihood for the foundation to resist some lateral load, but it should be combined with some analysis to adequately assess acceptance.

In rare cases when element-specific load tests are performed, acceptance evaluations may be straightforward when performance information is available. In fact, some projects may specify acceptance criteria as part of the load test program. For example, a driven pile may be deemed acceptable if it deflects less than 0.25 inch upon application of the design load, or if application of the design load does not cause the load-deflection curve to cross the Davisson Offset Limit. It is also important to appropriately consider the reliability of different methods for load testing. Static load testing should not be considered equivalent to high-strain dynamic testing, or pile restrike testing, for example.

Finally, it is also important to recognize that performance evaluation may be accomplished by performing analyses to demonstrate that a foundation element has the desired reliability. Such analyses are commonly similar to analyses performed for the original design, but considering additional information acquired from construction inspection and observation to describe the "as-constructed" condition of the foundation element. For example, such analyses might take advantage of more favorable ground conditions or structural capacity in excess of that required by design (e.g., from documented concrete strength in excess of that required in plans and specifications, additional steel reinforcement in excess of minimum requirements, or pipe pile wall thickness in excess of that required by design) to assess the foundation element for acceptance.

3.5 INTEGRATION OF ASSESSMENT METHODS FOR ACCEPTANCE

Information from the foundation assessment should be used to evaluate the foundation element and make an acceptance decision. The acceptance process is described generally in Chapter 2, and for specific foundation types in Chapters 4 through 7. All assessments should include construction observation and inspection information. Many assessments include integrity testing information; in some circumstances, the integrity testing information may be collected in response to concerns that arise from evaluation of construction observation and inspection information. Some assessments may include performance evaluation through load test information.

Evaluation of assessment information is completed in the context of the performance requirements for the foundation element. Imperfections may be considered in light of how the potential defect may affect loading demands or durability requirements. Consideration of the loading demands is generally location specific:

- What is the design axial load, bending moment, and shear force at the depth of concern?
- How would the imperfection affect foundation performance in light of the load demands?
- Does the imperfection rise to the level of being a deficiency that requires remediation?

The loading evaluations may benefit from formal engineering analysis and calculations that build upon the design analyses. Evaluation of durability requirements may also be location specific. For instance, imperfections in concrete within a drilled shaft reinforcing cage may be less of a durability concern than similarly sized imperfections in concrete outside the cage since the concrete outside the cage is critical for durability.

When evaluation of the available assessment information is not sufficient to produce an acceptance decision, it may be beneficial to gather additional information. The additional information should be useful for evaluating potential concerns. For example, if pile driving logs indicate potential damage during driving, integrity test methods to evaluate pile condition would be helpful. If post-construction review of construction information suggests as-built micropile bond length was shorter than the design value, proof load test information would be helpful. In contrast, if concrete volume logs and slump flow information suggest drilled shaft concrete may not have passed through the reinforcing cage to fill the shaft, crosshole sonic logging information will not be useful (because it does not test concrete outside the reinforcing cage).

Finally, if the evaluation process concludes a foundation element is unacceptable, it may be necessary to develop a remediation plan. The remediation plan should include methods for assessment and evaluation of the remediation for final acceptance of the foundation. Alternatively, it may be decided to supplement or replace the defective element. Additional information regarding acceptance evaluations and remediation is included in subsequent chapters.

CHAPTER 4
ASSESSMENT AND ACCEPTANCE OF DRIVEN PILE FOUNDATIONS

This chapter describes how the framework for evaluation and acceptance in Chapter 2 applies to driven pile foundations and addresses special considerations for driven piles. The chapter includes descriptions of the typical process for design, construction, QA, and QC of driven pile foundations to provide readers with appropriate perspective regarding where each activity “fits” into producing foundations that reliably satisfy performance requirements. More extensive and detailed information on design and construction of driven pile foundations, including details regarding verification testing and other components of quality assurance, is provided in FHWA “Design and Construction of Driven Pile Foundations,” Geotechnical Engineering Circular No. 12 (GEC 12)” (Hanigan, et al, 2016). At the end of the chapter, readers should understand the approach for evaluation and acceptance of driven pile foundations and have knowledge about what is needed to conduct such evaluations. An applied example is included to demonstrate implementation of the general framework outlined in Chapter 2 for driven pile foundations.

4.1 DESIGN

Construction of driven pile foundations may be influenced by performance demands related to axial resistance and verification during construction that the required axial resistance has been achieved. In some circumstances, design may also call for embedment into a soil layer with enough strength to provide needed uplift or lateral resistance or to minimize long-term settlement of the foundation.

The axial resistance mobilized during pile installation during construction may be affected by numerous factors, including:

- side resistance along the length of the pile at the time of driving, which differs from the long-term side resistance after setup has occurred and after installation of other nearby piles;
- tip resistance at the pile toe at the time of driving, which can also vary from the long-term tip resistance;
- side resistance of soil layers that may be lost due to post-construction scour or liquefaction and that may not contribute to the necessary axial resistance for some strength limit state load combinations;
- use of driving aids such as predrilling or jetting that affect ground conditions at the pile location, and the use of a driving shoe or other variations in pile wall thickness that can affect the side resistance; and
- the sequence of driving piles within a group, which can affect the relative density of the soil, the horizontal stresses in situ, and the behavior and resistance of previously driven piles.

As a result of the many factors affecting the axial resistance mobilized during pile driving, design of driven pile foundations may include testing during or following pile installation, and resistance factors allowed in design by the AASHTO Bridge Design Specifications (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)), and some State agency guidelines are influenced by the scale of the testing program. Although static load tests may occasionally be included in a test pile program, current practice typically relies on interpretation of high strain dynamic test measurements as a means of quality assurance.

Three important components of design of driven pile foundations for constructability are:

1. thorough site characterization to identify potential risks related to pile driving,
2. Selection of pile types to achieve the performance demands without damage to the pile during installation, and
3. Documenting and communicating with the contractor the demands and potential risks associated with pile installation.

4.1.1 Site Characterization

For driven pile foundations, a thorough site characterization program is potentially important for selecting the most appropriate pile type, reliably estimating production pile lengths, identifying pile installation risks, and mitigating uncertainties related to pile driving operations. Potential risks and uncertainties include possible obstructions or hard driving layers above the minimum penetration depth that may require the use of driving aids such as predrilling or jetting.

Variability in the stratigraphy at the site can result in large variations in pile length so it is important that stratigraphy be established prior to production pile driving. For some projects, a supplemental investigation may be performed after the basic design is completed in order to fill gaps in information and more reliably estimate pile lengths. Although pile length may be finalized in the field during production, reliable pile length estimates are important for constructability. Some pile types are difficult or expensive to splice. Excessively long piles may require cutoff, which wastes money and can impact equipment selection by the contractor if very long piles must be picked and set.

Site characterization information is also required to size the pile hammer, select the cushions and other components of the pile driving equipment, evaluate the need for driving aids, and estimate costs for bidding the project. Misleading or incomplete information may potentially lead to a poor design, damaged piles, or other construction difficulties.

Where temporary works such as excavation shoring, cofferdams, or work trestles are needed, site characterization should be performed to provide information necessary for contractors to prepare a design of these features and estimate costs. Information on shallow soils and groundwater conditions that may have little importance for the performance of the permanent foundations can be very important for design of temporary works during construction.

For design-build project delivery, the contractor team may select pile type and estimates pile lengths based on the pre-bid information available, including bid contingencies for potential risks and uncertainty in estimated costs. By reducing uncertainty related to geotechnical issues, potential risk contingencies may be reduced and the owner could benefit from competitive bid prices and reduced potential risk of unanticipated additional costs.

4.1.2 Driven Pile Design

Besides the obvious design considerations affecting driven pile type selection, constructability and quality assurance for acceptance are essential components of the pile selection process. A thorough vetting of the construction challenges and potential risks associated with each pile type should be considered with respect to final pile type selection during design.

Large prestressed or post-tensioned concrete piles have benefits in marine environments but require significant planning of the installation process to mitigate potential risks of pile damage during handling and driving. Design-phase drivability analyses are especially important for projects utilizing concrete piles. Design of concrete piles should include provisions for pile length variations in case unanticipated splices or build-ups of concrete piles are needed, and designers should consider the potential need for replacement or supplemental piles in the event of a damaged pile during construction.

Steel H or pipe piles can also be damaged when driving to bear on rock or hard bearing strata or through layers containing cobbles and boulders, and drivability analyses are important to establish wall thickness suitable for the anticipated driving stresses. Selection of appropriately thickened bottom sections or driving shoes during design of piles driven in the aforementioned hard driving conditions can help mitigate installation damage and improve quality assurance. Closed end pipe piles have potential drivability concerns relative to the large displacement, and the bottom plate should have enough structural strength to withstand the anticipated driving forces during installation. Large diameter open-ended steel pipe piles appear to be enjoying increased use for transportation structures in North America due to the resilience, high capacity (both axial and flexural), and benefits in seismic environments, but these piles have some unique challenges for understanding the development of axial resistance and test pile measurements. Information on special considerations for design and installation of large diameter pipe piles is provided by NCHRP Synthesis 478 (Brown and Thompson, 2015) and FHWA-HRT-20-011 (Petek, et al, 2020).

The plan for a field pile testing program provides an opportunity for evaluation of installation challenges prior to the start of production pile driving. The scope and extent of pre-production testing varies with the size of the project and the magnitude of the uncertainties related to pile installation and performance. Pre-production tests provide the opportunity to evaluate long term setup and incorporate the anticipated setup into the driving criteria used for production piles. The need for and extent of driving aids such as predrilling or jetting may be identified with pre-production test piles. For simple projects with low risks (for example, H-piles driven to bedrock in an area with a history of successful performance), there may be no need for pre-production testing, and verification tests may be limited to a few restrike measurements on production piles. A useful reference on the use of test piles to develop pile driving criteria is provided by NCHRP Synthesis 418 (Brown and Thompson, 2011).

For large projects, it may be appropriate to perform design-phase testing of alternative pile types in order to evaluate potential risks; such testing is more successful when tailored to the specific issues that are most important to the design. For example, the San Francisco – Oakland East Bay Bridge project utilized design-phase drivability tests on large diameter steel pipe piles to evaluate setup that would occur during the time required for splicing and the effect that setup would have on subsequent drivability. The Tappan Zee Bridge project included static load tests performed on long friction piles during the bidding phase of this design-build project. The Roosevelt Bridge project in South Florida incorporated lateral load tests on driven concrete piles to evaluate the effect of jetting on lateral performance.

4.1.3 Pile Caps and Connections

Design of pile caps and pile-to-structure connections, and construction details associated with these connections, are an important part of design for constructability. Temporary works required to construct the pile cap may be a significant challenge for projects with tight working spaces, conflicts with utilities or other nearby structures, or over-water construction. Dewatering of footing excavations may also be a significant and costly challenge for situations such as contaminated sites, artesian groundwater conditions, or where cofferdams must be constructed in deep water.

Cofferdam construction presents its own challenge for installation of sheet piling, construction of a seal, and dewatering. Details of these temporary works are often left to the contractor, but design should be completed with consideration of the need for construction of these temporary items. In deep water, waterline footings in lieu of footings below mudline may reduce costs and risks associated with cofferdams.

Where pile bents can be employed, the elimination of pile caps offers the potential for cost savings and ease of construction over water or in congested sites. Since the pile itself forms the column from the ground surface to the pier cap, the connection of the pile to the pier cap is an important item. The top of the pile can be damaged during installation and so this connection should be designed with flexibility to accommodate this risk. For prestressed concrete piles, the top portion of a pile may sometimes incorporate additional reinforcement for this connection; however, if the pile achieves refusal during driving at a higher tip elevation than anticipated, the additional reinforcement can end up in the cutoff zone. A detail of this type should therefore include allowance for variability or an alternative contingency plan.

4.1.4 Communication of Design Information Needed for Acceptance

In order to achieve the needed quality and acceptance of driven piles, contract documents should clearly convey the requirements needed to achieve acceptance. These may include, but are not limited to:

- pile type and size at each pile location;
- the nominal driving resistance needed for each pile, which includes the anticipated additional resistance provided by upper soil layers that may be unsuitable for load support due to either poor soil characteristics or future loss of load support by scour or liquefaction;
- minimum pile penetration at each pile location (referenced as minimum tip elevation in some agency practices);
- estimated tip elevations;
- material strength requirements and the process for verification;
- specifications on tolerance items (location, alignment);
- requirements for tip reinforcement, pile splicing, buildups, cutoffs;
- any details related to the pile cap connection that affect pile installation;
- any limitations on pile installation equipment such as hammers or driving aids;
- methodology for establishing pile driving criteria, including criteria for requiring verification restrikes; and
- the type and minimum number of construction control tests to be performed, consistent with the resistance factors used for foundation design.

Initial pile driving criteria are typically based on design and drivability analyses. Final pile driving criteria for production piling may be modified based on test pile measurements at the beginning of pile driving operations and as construction advances. The methodology used for developing final driving criteria should be transparent and clearly communicated to all participants in the project (e.g., constructors, inspectors, construction managers) so that the process can be understood and documented throughout the project. This does not mean that the methodology cannot be changed if conditions warrant. FHWA GEC 12 (Hanigan, et al, 2016) provides a detailed discussion and examples of pile driving criteria.

4.2 CONSTRUCTION

Constructors should understand the basic objectives of the pile design, and the general nature of subsurface conditions and how those conditions might impact their ability to drive the piles successfully. They should use this understanding to develop a robust construction plan with pile driving equipment that is suitable for the conditions of the project, adaptable to reasonable variations in subsurface conditions, and with contingencies for potential problems or potential risk items. Finally, implementation of the construction plan should include a thorough quality control system to manage the day-to-day work to install foundations that will satisfy the acceptance criteria.

4.2.1 Installation Plan

The installation plan for driven pile foundations should demonstrate an understanding of the project requirements for acceptance of the foundations and should include details of the operations and equipment to be used to achieve these requirements. The plan should be complete and appropriate to cover the range of anticipated ground conditions, and adaptable to reasonable variations in subsurface conditions with contingencies for potential problems or risk items. The installation plan should be developed prior to the start of any test pile program and production foundation works. It should be critically reviewed by the design and inspection teams prior to commencing driving operations so that all parties understand and agree as to how the work will be performed. The installation plan should also address the quality control systems that the contractor will employ during construction to maintain consistent quality and identify any issues that may require adjustment as the work progresses.

The installation plan for driven pile foundations should include a drivability analysis with the proposed pile driving system that will demonstrate that the required nominal resistance can be achieved within a typical driving resistance of 3 to 10 blows per inch (bpi), and without overstressing the piles. This analysis is generally conducted using wave equation modeling software, which requires certain assumptions related to the behavior of the soil and driving equipment during driving (e.g., soil quake and damping values, soil setup, distribution of side and tip resistance, hammer efficiency, cushion material properties, etc.). It is important to understand that uncertainty always exists relative to the assumptions used in the analysis so evaluation of the results for a range of the most important parameters should be included.

Measurements on test piles during or in advance of production pile installation should be used to adjust the installation plan as necessary, and any such adjustments should be documented in a timely manner as the project advances. Modifications to installation procedures may occur in conjunction with changes to pile driving criteria used for acceptance.

Inclusion of pre-production indicator or test piles before beginning production work is a useful tool on larger projects, as this work allows the installation plan to be demonstrated to be effective, and any adjustments or modifications to the plan to be developed, agreed upon, and implemented prior to the start of production foundation work. Indicator piles may be production piles driven at locations along the alignment to help more reliably identify production pile lengths prior to ordering, which may be particularly helpful for precast concrete piles; indicator piles may also be used as test piles. Pre-production test programs allow development of pile driving criteria prior to the start of production pile installation, which enhances the efficiency and reliability of this work. Additionally, restrike measurements with high strain dynamic load tests or rapid or static load tests after setup has occurred allow more reliable incorporation of setup into the driving criteria, which improves efficiency of construction and can save both time and money. In addition to information provided in FHWA GEC 12 (Hanigan, et al, 2016), useful information on development of production driving criteria from test pile information are provided in

NCHRP Synthesis 418 (Brown and Thompson, 2011) and specifically on large diameter pipe piles in NCHRP Synthesis 478 (Brown and Thompson, 2015) and FHWA-HRT-20-011 (Petek, et al, 2020).

4.2.2 Quality Control During Construction

Quality control procedures for driven pile installation should be included in the installation plan and should address items such as:

- checks on location, alignment, and position of the pile;
- maintaining proper alignment of the hammer, driving helmet, cushion, and pile during impact;
- maintain the template and pile guiding system, such as rollers, to minimize binding during driving of battered piles'
- maintaining the hammer in good working order with regular checks on driving energy; some modern hammers may be equipped with instruments to record ram velocity just before impact or other parameters related to hammer energy; and
- maintenance of pile cushions in good working order with changeout of cushions as per applicable specification requirements.

Documentation of observations and records related to quality control checks, as described in Section 4.3, should be a component of the quality assurance plan.

4.3 INSPECTION AND QUALITY ASSURANCE

Acceptance of driven piles should rely on the observations, documentation, and communication of work by on-site inspectors. GEC 12 (Hanigan, et al, 2016) describes the various activities needed for the inspector to perform these duties and includes useful checklists of tasks and items to be reviewed, as well as example forms. Specific details vary with pile and hammer type, agency requirements, and project delivery methods.

Inspectors should first understand the project, which should be based on a review of the foundation design report, project plans and specifications, an understanding of anticipated subsurface conditions, and a review with the responsible designer of the design objectives and any special potential risks or concerns related to the planned construction. The preconstruction review should also include a clear understanding of the contractor's installation plan, and the inspectors should be included in any preconstruction meetings related to the piling.

In general, items to be inspected could be grouped as:

- piles prior to installation.
- work related to compliance with the approved installation plan.

- pile driving equipment, both before and during operation.
- test or indicator pile installation and load testing.
- production pile driving and documenting driving operations.

In general, the inspector should be the person in the field who verifies that the pile has been installed to satisfy the driving criteria and determines when pile driving may stop. There may be additional criteria to be satisfied if the requirements include restrike measurements. In some cases, the contractor may have the option to continue driving beyond the depth at which the criteria are first achieved, for example to avoid the need for a cutoff by driving the pile a few more feet. If the pile is installed to near full length without achieving the driving criteria, there may be options for restriking the pile to achieve acceptable driving resistance after setup. A pile that meets practical refusal prior to reaching the minimum depth of penetration may trigger the option to use jetting as a driving aid. All these options should be clearly defined and understood by the parties prior to the start of construction.

The inspector should inform the responsible design engineer in a timely manner of any piles that fail to achieve the required driving criteria. A pile that does not achieve the required driving criteria needs assessment by the responsible design engineer, who should recommend how construction is to proceed.

The engineer should be informed if the inspector observes any unusual conditions that may indicate potential problems. Unusual driving conditions could be signs of a broken pile. Other examples that may require action include the observation of visual damage, improper cutoff, problems during concrete placement in a pipe pile, or indications that a pile has heaved or moved out of position as a result of driving nearby piles. Finally, any preparation of the top of the pile such as cutoff, buildup, or connection detail to pile cap should be inspected and documented. FHWA GEC 12 (Hanigan, et al, 2016) includes a list of common pile installation problems and possible solutions.

If good and timely communication is maintained between the inspector and the design engineer, potential issues that might impact acceptance can be handled more efficiently and effectively, and the post-construction evaluation and acceptance of driven pile foundations can go more smoothly.

4.4 EVALUATION AND ACCEPTANCE

This section reviews the applicable assessment methods and documentation needed for acceptance of driven pile foundations. As mentioned in the previous section, much of the evaluation needed for acceptance of driven piles happens during construction based on achievement of the driving criteria and documentation by the inspector.

4.4.1 Assessment Methods and Documentation

Generally, driven piles are assessed based on achieving the driving criteria during production pile driving, as documented on the pile driving logs. These logs should reference the appropriate driving criteria document since the criteria may change with location or equipment used and as the project progresses. The logs should therefore note all items that are specifically relevant to the driving criteria, such as the hammer and cushion used, the fuel setting and stroke of the hammer or other measurement indicative of hammer energy, the depth corresponding to the minimum penetration requirement, elevations of the reference point used for depth measurement, pile number and location, and other information related to pile installation. Agencies may have standard forms for this purpose, tailored to agency-specific specifications and payment methods. Example pile driving logs and other record keeping forms are provided in FHWA GEC 12 (Hanigan, et al, 2016).

Several other aspects of quality assurance may be assessed during the inspection phase and prior to installation, such as the mill certification documentation on steel piles and pile shoes, welds or splices; verification of materials and fabrication of precast concrete piles; visual verification of compliance with pile handling and placement prior to installation; driving splices; and other specific characteristics related to pile materials and integrity. These inspection checks should be documented and records maintained to record the quality assurance of the pile from fabrication to final placement (cradle to grave).

Assessment of axial resistance, pile integrity, hammer performance, and suitable driving criteria is enhanced with the use of dynamic measurements. Dynamic measurements are most often performed as a part of high strain dynamic load testing (HSDLT) to provide measurement of hammer energy imparted to the pile and the pile response during testing. These measurements provide immediate information that allow an interpretation of the approximate static axial resistance of the pile for each blow, as well as the structural integrity of the pile. For selected blows, signal matching analysis can subsequently be performed to develop a more refined interpretation of soil resistance. The benefits and limitations of HSDLT are described more completely in FHWA GEC 12 (Hanigan, et al, 2016). HSDLTs should be performed by trained and experienced specialists and the results described in a technical report that documents the measurements and the basis for the interpretations that are made from them.

Test piles (which may include indicator piles) should be properly identified and installed in advance of production piles within the corresponding portion of the project, and any revisions to the production pile installation criteria should be noted in the inspection records and on production logs moving forward.

The quality assurance and assessment plan may call for periodic proof tests, for example dynamic tests on one pile per pier or no less than two percent of production piles installed. On some projects, this requirement may be satisfied by driving and testing the indicator piles prior to the start of production pile driving; in such cases, however, additional dynamic testing should be performed on production piles when driving operations extend over a period of several months after driving the initial test piles, to check hammer efficiency and the delivered energy.

Post-installation measurements and inspections cited in the previous section should also be documented for final assessment. Final documentation should include any post-installation field testing that may be required, including verification restrike measurements or post-installation integrity tests or evaluations. Low strain integrity tests (conducted using a small hammer) can be used for assessment where questions of pile integrity may arise, although this type of testing is not common for driven piles since high strain testing can generally be employed. Finally, the documentation should include resolution of any non-compliance issues or identification of such issues for post-construction assessment. A flow chart in Figure 4-1 describes key components of the process for driven piles (from GEC 12, (Hanigan, et al, 2016)).

4.4.2 Assessment

Following the general flow chart outlined in Chapter 2, post-construction assessment by the responsible engineer should largely be a review of inspection documents highlighted in the previous section, plus a review of any post-construction testing and inspection that might be needed.

Where verification restrikes might be employed on, for example, one pile per bent or one pile per footing, there is a need for some process to identify which pile should be restruck and doing so in a timely manner. The logic behind this selection can vary according to the specific project characteristics. Often the pile selected might be one that had the lowest end-of-initial-drive resistance or had exhibited some other unusual behavior during initial driving. For piles relying primarily upon end bearing, a selected pile might be one of the first piles driven to ensure that the pile has not been “unseated” by the installation of subsequent piles. Another reason to restrike one of the first piles installed is to maximize the amount of setup time prior to restrike.

Verification restrikes might also include dynamic measurements for verification of performance of a pile as a high strain dynamic load test (HSDLT). These measurements provide a more reliable check on the axial resistance than a simple verification of driving resistance without such measurements and provide an opportunity for evaluation of hammer performance and to conduct an integrity assessment of the pile itself.

If a pile or piles with insufficient axial resistance are identified while driving operations are still in progress, corrective measures may call for consultation with the responsible engineer. One corrective measure may be to splice and drive the pile(s) deeper to achieve greater axial resistance; the splice may need to be designed to provide suitable flexural strength if located in a zone of high bending and may be subject to driving stresses. If splicing and additional driving is not feasible, such as for a broken pile, then installing additional piles (or installing other piles to achieve higher resistance) may be considered.

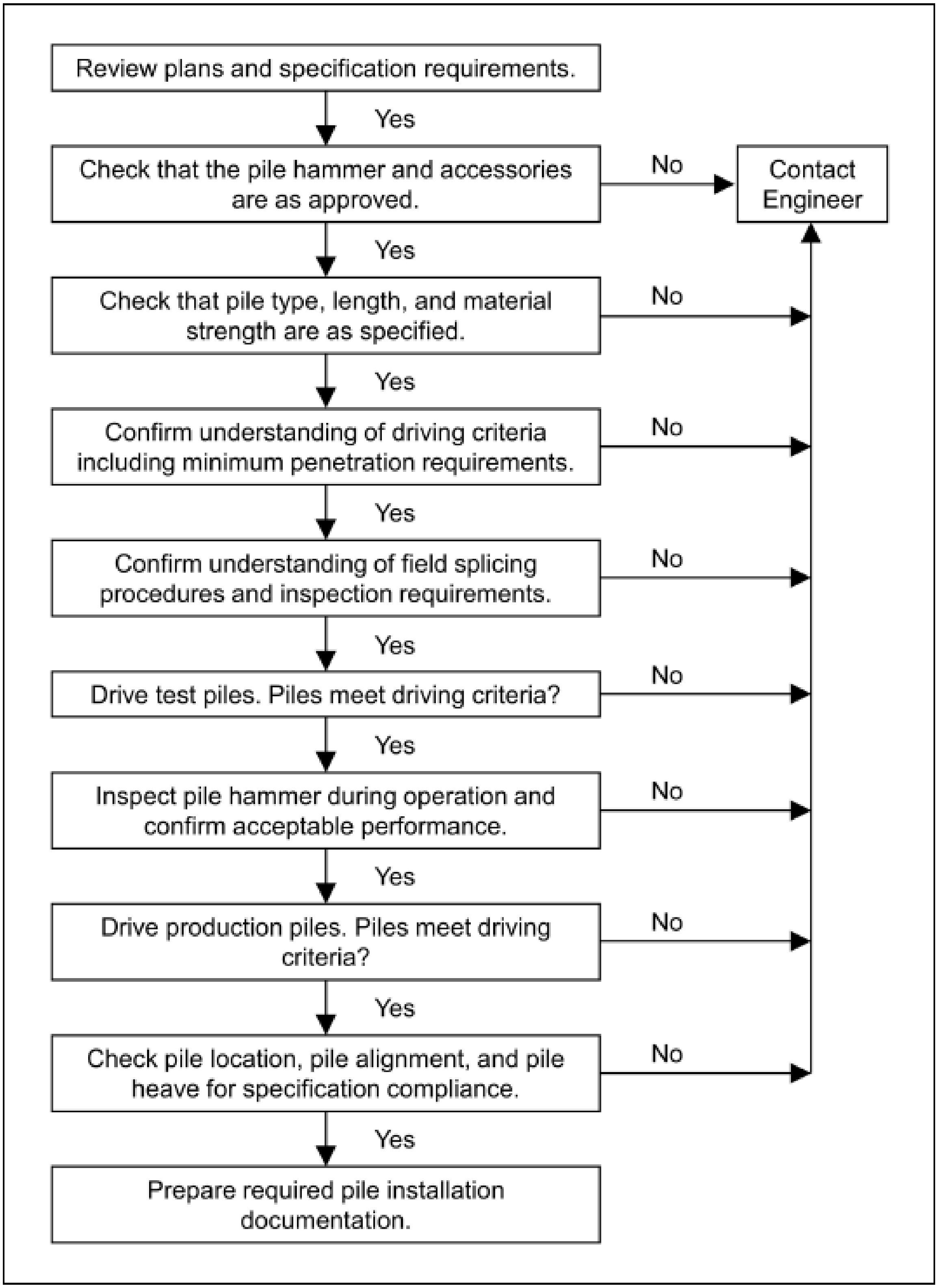

Figure 4-1 Key components of the pile installation process (from FHWA GEC 12 (Hannigan, et al., 2016)

With a complete inspection record of all of the piles in a foundation, along with the appropriate level of post-construction verification on selected piles where applicable, the responsible engineer has the information available to evaluate the installation of the piles for the foundation as an entire entity and assess the foundation for acceptance. Where any irregularities or unusual circumstances are identified, the responsible engineer should be able to evaluate them in a context relative to the overall foundation demands. For example, driven pile foundations often incorporate a large degree of redundancy that may be tolerant of minor irregularities. Although all piles in a group are typically driven to the same criteria based on the pile with the highest demand, the actual demand on some piles is often slightly lower and may allow acceptance of a pile that may not have achieved the required criteria during initial installation. Restrike verification of setup may be considered for all the piles based on the setup measurement of a single pile in the group. So, the evaluation process may offer an opportunity to achieve acceptance based on appropriate engineering principles applied to the entire group rather than on an individual per pile basis.

Where the evaluation cannot determine whether the foundation is acceptable, remedial work may be required such as splicing or adding additional piles, as discussed above. However, acceptance could still be achieved based on additional proof testing for verification of axial resistance and enhanced quality assurance. Consider that Table 10.5.5.2.3-1 of the AASHTO Bridge Design Specifications (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)) allows for the designer to choose to use a higher resistance factor on driven pile foundations where 100 percent dynamic testing has been employed. When the original design is based, for example, on a resistance factor of 0.65, proof tests performed on all piles in a given foundation would allow the use of a resistance factor of 0.75. Therefore, for a given factored load per pile, the target nominal resistance needed with the higher resistance factor is thereby reduced as a result of the enhanced reliability associated with 100 percent proof testing. As an example, consider a group of piles designed for a factored load demand of 300 kips per pile with a resistance factor of 0.65. The target nominal resistance is 300/0.65 = 462 kips per pile. By performing dynamic testing on all piles, the target nominal resistance would be reduced to 300/0.75 = 400 kips per pile. If the dynamic tests can demonstrate that 400 kips per pile has been achieved, then additional piles or splicing might be avoided, and the piles accepted.

The responsible engineer should document the results of the post-construction assessment and any engineering evaluation or other resolution of anomalies, questions, irregularities, or non-conformance issues.

4.4.3 Remediation

In some cases, the evaluation identifies that a deficiency exists or is likely to exist, and remediation work may be necessary. Table 18-7 in FHWA GEC 12 (Hanigan, et al, 2016) lists some common pile installation problems and possible solutions. Examples might include a broken or badly out of position pile, a pile encountering refusal above minimum penetration requirements, or a pile that, for whatever reason, cannot achieve the needed axial resistance.

Some common solutions involve the installation of additional piles, which may need structural modification of the pile cap or pier cap and therefore call for coordination with the responsible engineer for the substructure. Modification of the pile group configuration also affects the distribution of load within the piles in the group.

Because of the cascading effect of changes to the pile group layout, designers and the contractor should communicate and coordinate the development of the remediation plan.

Implementation of the remediation plan should include inspection, quality assurance, and documentation so that the assessment process can achieve acceptance after the work is completed.

4.4.4 Acceptance

Completion of the assessment should include documentation of the records used in the process, such as:

- the post-construction testing and a report of the outcome of the evaluation (with documentation of any analyses performed),
- resolution of any discrepancies or non-conformance issues, and
- the records of any remediation or corrective actions taken.

For design-build project delivery, the responsible engineer who performs the assessment (see Chapter 2) may be part of the design-build team and the owner's representatives may review the foundation certification package for acceptance. For conventional bid-build projects, this documentation may be provided by the agency's engineering staff or consultant. The letter or documentation may recommend acceptance by the owner and should be signed and stamped by the appropriate design professional.

The acceptance documentation should typically address the following items for driven piles:

- the specific piles addressed by the documentation are clearly identified;
- the piles have been installed in the proper location and within specified tolerances;
- the piles have been installed to the minimum penetration length, and therefore satisfy the requirements for lateral stability and uplift resistance;
- the inspector's logs of the production piles have been reviewed and indicate that the piles have been installed to satisfy the driving criteria;
- test piles, if any, demonstrated that the driving criteria achieves the required axial resistance;
- no pile damage is indicated either visually or from measurements; and

- any potential deficiencies have been addressed and any necessary remedial work has been successfully completed.

Note that the list cited above does not address the preparation at the top of the pile for the connection to the pile cap or pier cap or footing, as this item is most commonly associated with substructure construction activity after the piles are accepted.

4.5 POTENTIAL ISSUES IN DRIVEN PILE ASSESSMENT

As described in this chapter, assessment of as-built driven pile foundations is based largely on observations made and recorded by inspection personnel during the installation process, supplemented by dynamic measurements and other types of load testing. Some common issues that may be encountered in the assessment and acceptance process include, but are not limited to, the following.

- Pile installation

Requirements for pile driving can lead to difficulties during installation, as described in section 4.1. For example, a pile design that requires very high nominal resistance can result in driving stresses near the limit of the structural capacity of the pile with increased potential for damage during driving.

- Quality control procedures

Quality control of pile driving operations should be an integral part of quality assurance, and inadequate quality control can lead to unreliable measurements of driving resistance, broken or damaged piles, piles out of position or alignment, and other problems requiring remediation. FHWA GEC 12 (Hanigan, et al, 2016) describes potential pitfalls associated with pile installation equipment and procedures.

- Inspection and documentation

Inspection and the thorough documentation of the construction activity are important for the overall assessment and acceptance process. Because of the reliance on observations of driving resistance during installation, much of the work of assessment for pile acceptance occurs concurrently with construction. The process should involve ongoing full-time inspection by personnel with training and experience, and timely communication with the responsible engineer.

- Interpretation of dynamic measurements and/or load test information

High strain dynamic testing greatly benefits from well-trained and skillful operators who can successfully interpret axial resistance from measurements, particularly for piles such as large diameter open ended piles where dynamic and static behavior may differ due to soil plugging and other effects.

CHAPTER 5
ASSESSMENT AND ACCEPTANCE OF DRILLED SHAFT FOUNDATIONS

Drilled shafts are a widely used structural foundation type for transportation infrastructure. Each drilled shaft is a reinforced concrete element constructed in a stabilized excavation to allow controlled placement of steel reinforcement and concrete. Acceptance of a drilled shaft foundation may include verification that the excavation remains stable throughout the entire construction process and that the steel and concrete are placed in conformance with the plans and specifications and consistent with procedures used at successful demonstration shafts. Assessment and acceptance of each drilled shaft is a significant aspect of bridge construction (or other transportation structures) and one with important consequences for project costs, schedule, and ultimately the reliability of the finished structure. Proper assessment and acceptance should be a coordinated effort on the part of the owner, structure design engineer, geotechnical or foundation engineer, drilled shaft and general contractors, and field inspection personnel.

The approach for acceptance of drilled shafts follows the general principles and concepts discussed in Chapters 2 and 3. In addition, FHWA GEC 10 (Brown et al., 2018) provides comprehensive information regarding drilled shaft design and construction. Some of the content of this chapter is adapted from FHWA GEC 10 (Brown et al., 2018) but with a specific focus on drilled shaft assessment and acceptance.

Section 5.1 summarizes factors that provide a basis for the design of drilled shafts, including the subsurface investigation, loading demands for typical drilled shaft applications, and materials considerations. Section 5.2 provides an overview of construction inspection requirements and other information that provide a basis for assessment, such as demonstration shafts and load testing. Where applicable, reference is made to other FHWA documents that provide more specific details. Section 5.3 describes the drilled shaft acceptance process, following the general framework described in Chapter 2 and supplemented in Chapter 3. Remaining sections describe potential corrective actions (Section 5.4), and additional information related to acceptance of drilled shafts (Section 5.5).

5.1 DESIGN AND PERFORMANCE CONSIDERATIONS

The ultimate objective of assessment and acceptance procedures is to ensure that each as-built foundation can meet the performance demands for which it was designed. This section provides a brief background on the factors considered by engineers when designing drilled shafts to meet project performance demands. Each of these topics is addressed in greater detail in FHWA GEC 10 (Brown et al., 2018).

5.1.1 Site Characterization

Knowledge of ground conditions is fundamental to every aspect of drilled shaft design and construction, including the inspection and acceptance process. The subsurface stratigraphy and engineering properties of the soil and rock, in combination with factors associated with the structure being supported, are the basis of foundation type selection and final design of drilled shafts. As noted in Chapter 2, contractors rely heavily on the subsurface information made available to them to develop drilled shaft installation plans. Both contractors and designers rely on the subsurface investigation to identify and allocate potential risks associated with the ground conditions. Site characterization is, therefore, an important source of information for both *design* and *construction* of deep foundations.

Table 2-2 of FHWA GEC 10 (Brown et al., 2018) provides a summary of subsurface information that is directly relevant to drilled shaft construction. Several aspects of the subsurface investigation that are of particular importance to drilled shafts are:

Groundwater Conditions. Accurate information regarding the location and characteristics of the groundwater table(s) is critical to drilled shaft construction. Groundwater conditions may inform the installation method needed to make a stable excavation in the ground (e.g., dry, wet, casing, combined). The location of the water table and the presence of artesian conditions may determine the level of positive head inside the excavation needed to offset the formational water pressures. Excavation stability typically requires a positive head (i.e., higher fluid pressure inside the excavation than in the surrounding ground) so that seepage pressures act against the sidewalls and base of the excavation, not inward. For a contractor to develop an appropriate installation plan and accurately estimate the cost of drilling fluid and casing, the geotechnical report and boring logs should present as much information as possible on groundwater. Features such as perched water tables, confined aquifers that might be artesian, or groundwater elevations that may fluctuate seasonally should be identified and discussed as appropriate. If not sufficiently characterized prior to construction, groundwater conditions may pose a potential risk to drilled shaft installation.

Characterization of Rock. Drilled shafts bearing on or socketed into rock pose special challenges for construction. Rock can exhibit a wide range of characteristics affecting its geotechnical resistance and also affecting the contractor's ability to excavate the rock. Given its variability and uncertainties, designers often make conservative assumptions regarding rock strength and its geotechnical resistance. A contractor should make accurate estimates of what it takes to excavate the rock. Rock strength, hardness, degree of weathering, fracturing, or other factors should be considered with respect to drillability.

Figure 5-1 Rock core showing wide range in rock mass characteristics – photo by authors.

Some designers assume the base of the shaft will bear on relatively sound or intact rock and that measures will be taken during construction to verify that assumption. It is important for both the designer and contractor to have a common understanding of what constitutes adequate bearing conditions in rock and what measures will be taken to install the shaft tip at the proper elevation. Exploratory drilling conducted at the shaft location prior to construction should include rock coring to a depth that is sufficient to determine that rock is not a cobble or boulder ("floater"), evaluate rock quality, and identify the presence of solution cavities or zones of decomposed rock. Boring logs should include clear indications of the depth to acceptable bedrock.

If coring into rock is not done prior to construction, it may be necessary to core pilot holes within and below the rock socket for each drilled shaft during construction to confirm rock quality. In some cases, only the depth to top-of-rock needs to be established and this can be accomplished using probe holes (drill only, no sampling) made prior to drilled shaft installation. In other cases, for example karst, coring or probe holes beneath the tip of the excavated shaft may be required to verify the presence of suitable rock and absence of cavities or soft materials. FHWA GEC 10 (Brown et al., 2018) provides additional examples of geologic conditions involving challenging rock conditions and how these challenges can be addressed through appropriate application of site investigation tools.

5.1.2 Load Demands on Drilled Shafts

A widely used application of drilled shafts in the transportation industry is for bridge foundations. The limit states to be evaluated for a particular bridge or other structure are determined by the structural designer, typically in accordance with the AASHTO Bridge Design Specifications (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)) . A structural model of the proposed bridge is typically developed and analyzed under the load combination corresponding to the limit state being evaluated (see Table 3.4.1-1, AASHTO Bridge Design Specifications (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v))). Loads used in the analysis are factored. Foundation supports may be modeled as springs or using an assumed "depth of fixity." Force reactions at the supports computed by the structural analysis are taken as the factored values of axial, lateral, and moment demand acting on the drilled shafts. These factored demands are then applied to the top of the shaft to analyze foundation response and determine whether the trial design satisfies the design criteria for each applicable limit state.

Drilled shafts may also be used in transportation applications where the load demands are generated by earth pressures. Examples include retaining walls, bridge abutments, and landslide stabilization systems. Wall applications include using drilled shafts as foundations for conventional retaining walls or as the retaining structure itself. When used as wall elements, drilled shafts may be installed with some overlap between adjacent shafts (secant piles) or immediately adjacent to one another (tangent piles), or with some amount of clear spacing between shafts (soldier piles). Drilled shaft walls can be cantilevered or, if necessary, can be anchored using prestressed tieback anchors.

Section 3.11 of AASHTO Bridge Design Specifications (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)) provides an approach for calculating lateral earth pressures (EH) for retaining structures. Depending on the specific application, this may require calculation of active, passive, or at-rest earth pressures, or, in the case of an anchored wall, apparent earth pressures (AEP). Lateral earth pressures resulting from surcharge loads applied near the wall will also apply in most situations. Where applicable, groundwater pressure is also considered.

Drilled shafts have been used effectively by transportation agencies for stabilization of landslides. As in wall applications, the shafts could be installed as secant or tangent piles and could either be cantilevered or used in combination with tieback anchors. The shafts could also be on some specified spacing and connected structurally using a cap beam or walers. Multiple rows of drilled shafts with space between the rows have also been used for this purpose. Earth pressures acting on drilled shafts used for slide stabilization are not addressed directly in the AASHTO design code. The FHWA publication "Design, Analysis, and Testing of Laterally Loaded Deep Foundations that Support Transportation Facilities", GEC 9 (Parkes et al., 2018) provides information about establishing the load demands on drilled shafts used for slide stabilization. The approach described in FHWA GEC 9 (Parkes et al., 2018) may be useful to establish the drilled shaft loads as a function of the landslide driving and resisting forces, which are calculated using limit equilibrium slope stability software, and the selected target factor of safety for the slope. FHWA GEC 9 (Parkes et al., 2018) also summarizes published case histories on the use of drilled shafts for slide stabilization, some of which describe the methods used to establish the load demands needed to stabilize the slope.

5.1.3 Material Requirements

The materials comprising a completed drilled shaft, and which provide its structural strength and stiffness, are *steel* and *concrete* . Steel reinforcement is provided in many cases in the form of a rebar cage. However, a structural steel section, such as a wide-flange beam, could also be embedded in the concrete, which is common in earth retention applications. When permanent casing is specified, its contribution to the structural strength and stiffness of the drilled shaft can be incorporated. Some agencies do not use the contribution of the permanent casing to structural strength, for example where the casing is primarily intended to facilitate installation of the shaft through water or soft soils. Where the casing is relied upon structurally, the potential for long-term corrosion should be addressed by decreasing the wall thickness used in analyses.

The properties of concrete important to drilled shafts may be placed into two categories: (1) properties of the hardened concrete in the completed shaft, and (2) properties of the fresh concrete that affect its ability to be placed properly. Note that these are not entirely independent; properties of the hardened concrete may be affected by the handling and placement of the fresh concrete.

Useful information on properties and handling of fresh concrete for drilled shaft construction include:

- "Evaluation of Tremie Concrete for Deep Foundations" (Boeckmann et al., 2020)
- "Guide to Tremie Concrete for Deep Foundations" (EFFC/DFI, 2018)

Some important properties of fresh concrete for drilled shaft construction are:

- *Workability*, or the ability of the fluid concrete to flow, is important for successful drilled shaft construction. Concrete must flow readily through the tremie and the rebar cage to fill the shaft excavation and exert fluid pressure against the sides of the borehole.
- *Retention of workability*: as a general rule, concrete should remain workable for a period of two hours greater than the anticipated time to complete concrete placement and remove the temporary casing, if necessary.
- *Passing ability* refers to the ability of fresh concrete to pass through the reinforcement without being blocked. Passing ability needs high workability but also depends on the aggregate size and gradation, and the size of the openings between bars comprising the reinforcement cage. FHWA GEC 10 (Brown et al., 2018) and the AASHTO Bridge Construction Specifications (AASHTO, 2017b) (23 CFR 625.4(d)(1)(v)) recommend clear spacing between bars of at least five inches or five times the maximum aggregate size, whichever is greater.
- *Stability* describes a concrete mixture's resistance to segregation, bleeding, and filtration.

Other materials may be employed as part of the contractor's means and methods of installation but may not be incorporated into the final product. These include drilling fluids and temporary casing that is removed during or immediately following concrete placement.

Material properties are relevant to assessment and acceptance of drilled shafts. Final acceptance should document that the concrete strength of the as-built shaft meets the specified design strength. It should also verify that the steel reinforcement and permanent casing, if used, have been certified by the steel supplier to have the specified properties (*e.g.*, grade of steel), and be of the required dimensions. Materials used for construction only, such as drilling fluids, should be documented to verify that the drilled shaft installation was performed in conformance with the specifications. If non-destructive testing yields anomalous readings, the responsible engineer should review the inspection records to determine if the installation, including the properties of materials (such as drilling fluids) and properties of the fresh concrete during placement, were in conformance with the specifications and approved drilled shaft installation plan.

Secondary components of a drilled shaft (i.e., non-structural) may include items such as steel or plastic access tubes for integrity testing, temperature sensors (wires) for thermal integrity testing, and spacing devices for centering the rebar cage. The engineering properties of these features may not be critical to drilled shaft design; however, each one has an important function for the purpose of quality assurance or quality control and a role in the assessment and acceptance process.

5.2 DRILLED SHAFT INSPECTION

In accordance with the framework presented in Chapter 2, effective assessment of any deep foundation element is based in part on thorough construction observation and inspection. Drilled shaft installation may be assessed by verifying that each shaft has been installed consistent with the contract documents and the drilled shaft installation plan including, if applicable, procedures used for installation of demonstration or load test shafts. Inspection may also identify unanticipated conditions encountered during construction that might affect the performance or structural integrity of the as-built shaft. Written documentation of the work needs to provide a record of the work performed for each drill shaft installation. These records, in combination with integrity testing, can provide a basis for acceptance of as-built drilled shafts.

The following resources, which do not impose legal requirements at the Federal level, provide additional information about inspection of drilled shaft construction.

- FHWA GEC 10 (Brown et al., 2018)
- National Highway Institute Drilled Shaft Foundation Inspection (NHI, 2002)
- ADSC-DFI Drilled Shaft Inspector's Manual,2nd Edition, 2004 (ADSC and DFI, 2004)

These documents discuss some common activities involved in drilled shaft inspection, including:

- meetings during pre-construction and construction with the inspector, designer, geotechnical engineer, resident engineer, and contractor, as appropriate;
- review of subsurface conditions, including soil and rock types and groundwater elevations, as anticipated based on boring logs and available geotechnical reports;
- review of contract documents including drawings, specifications, special provisions, and payment provisions applicable to drilled shafts;
- review of the Drilled Shaft Installation Plan, especially information related to procedures and equipment to be used;
- review of the drilled shaft installation criteria and tolerances; and
- preparation and completion of documentation of inspection and installation procedures.

Subjects that should be observed, considered, tested, and documented during construction are described in the resource documents referenced above and listed here in approximate chronological order:

- Prior to construction, inspection of contractor’s tools and equipment;
- Inspection of demonstration or load-test drilled shafts, if applicable;
- Inspection during shaft excavation and cleanout, including properties and handling of drilling fluids;
- Casing inspection and installation;
- Inspection of rebar cage and cage installation;
- Observation and documentation of concrete placement; and
- Integrity testing, final survey of location and tolerances, and documentation of pay items during post-installation/completion.

Each transportation agency may have standard forms for documenting drilled shaft construction and inspection. Non-binding recommendations about the items that should be included in drilled shaft inspection forms is provided in Appendix E of FHWA GEC 10 (Brown et al., 2018) which also includes an inspection checklist and sample inspection forms for illustration.

5.2.1 Drilled Shaft Installation Plan

The Drilled Shaft Installation Plan is an important factor in the construction, inspection, assessment, and acceptance process. This plan documents the equipment and procedures used by the contractor to carry out drilled shaft construction in compliance with the drawings and specifications. The plan should be prepared by the contractor and submitted to the owner and foundation design engineer in advance of initiating drilled shaft construction. This allows the owner and foundation design engineer to confirm the contractor's proposed equipment and procedures and identify proposed practices that may influence the nominal resistances or serviceability performance characteristics of the completed drilled shafts. After receiving review comments, the contractor may revise and re-submit the installation plan. Drilled shaft construction should not proceed until the installation plan is accepted.

Specific items that should be included in a Drilled Shaft Installation Plan are outlined in Appendix D of GEC 10. During the course of work, the installation plan should be updated and resubmitted to the owner and foundation design engineer for review whenever there is a significant modification to the drilled shaft installation equipment or procedures. Field personnel should always be provided with the most recent version of the plan to ensure that work is performed as intended and that assessment/acceptance is based on the current installation plan.

5.2.2 Demonstration and Test Shafts

An effective quality control and quality assurance tool for drilled shaft construction is to install one or more full-size demonstration shafts (also referred to as "technique shafts", "method shafts", or "trial shafts") prior to installation of production shafts. The primary purpose is for the contractor to demonstrate that the means and methods described in their installation plan will result in a successful installation. This enables the contractor, if necessary, to revise their means and methods (and installation plan) based on the actual conditions encountered. If warranted, revisions may be made to the project specifications or the inspection procedures. For example, the means and methods for achieving and verifying base cleanliness sometimes are determined on the basis of observations made during demonstration shaft installation.

To be most effective, demonstration shaft installation should reproduce as closely as possible all conditions anticipated for production shaft installation, starting with the excavation method (dry, casing, slurry), rebar cage and concrete placement, and post-construction integrity testing if applicable. It is equally important for inspectors to observe the demonstration shaft installation(s) and to carry out a full inspection just as they would for a production shaft. The demonstration shaft installation, including inspection, is a full dress-rehearsal of production shaft installation. The reference documents and list of inspection activities above provide in-depth information on inspection procedures. The means and methods of construction and the inspection procedures used to document them may be finalized on the basis of observations made during demonstration shaft installation.

If drilled shaft load testing is part of the project, each test shaft installation can be considered a demonstration shaft. On many projects, the load tested shaft(s) serve the dual purpose of being a demonstration and test shaft. Detailed treatment of drilled shaft load testing is given in Chapter 13 of FHWA GEC 10 (Brown et al., 2018).

The contractor’s equipment and methods used in a more effective demonstration shaft should be consistent with those described in the approved installation plan, prior to production shaft installation. Applicable State-based specifications may impose requirements regarding demonstration shaft conformance with the approved installation plan. Consistency of conformance requirements between demonstration and production shaft installation provides the owner, foundation design engineer, and inspectors a basis for assessment and acceptance of each production drilled shaft based on installation of a demonstration shaft that itself met the specifications and installation plan.

5.2.3 Additional Inspection Considerations

When an inspector observes construction procedures that are not in accordance with the specifications or the accepted installation plan, some agencies use a separate form denoted as a ‘Non-Conformance Report’ (NCR) or similar title to document the non-conforming work. Project specifications should clearly define the procedure to resolve the non-conforming work reported in an NCR for the subject drilled shaft and, if applicable, for revising the installation methods to avoid the non-conforming practices on subsequent installations. Failure to resolve non-conforming work or practices can be used as a basis for non-acceptance of a drilled shaft.

In addition to formal inspection forms, it may be helpful for each inspector to maintain a daily report to record information and construction activities that are not entered on the shaft inspection forms. Examples of such information include weather conditions, equipment and work force on site, equipment maintenance or repair work performed, work delays, and any other information documenting that day’s activities.

Finally, effective assessment may be aided by having all records collected, organized, and maintained in a central file in accordance with document control procedures established for the project. Copies of the complete drilled shaft installation records should be distributed to the resident engineer, and the foundation design engineer or project geotechnical engineer promptly for review and evaluation.

5.3 EVALUATIONS FOR ACCEPTANCE

Figure 5-2 is a graphical representation of the assessment and acceptance process for drilled shafts. As outlined in Chapter 2 and depicted in Figure 5-2, assessment is based largely on two categories of information: (1) construction observation and inspection, and (2) integrity testing. Each of these is described in the following sections. If load testing is part of the project, installation of the test shaft(s) and the test results provide a third category of information that can be used as a basis for assessment and acceptance.

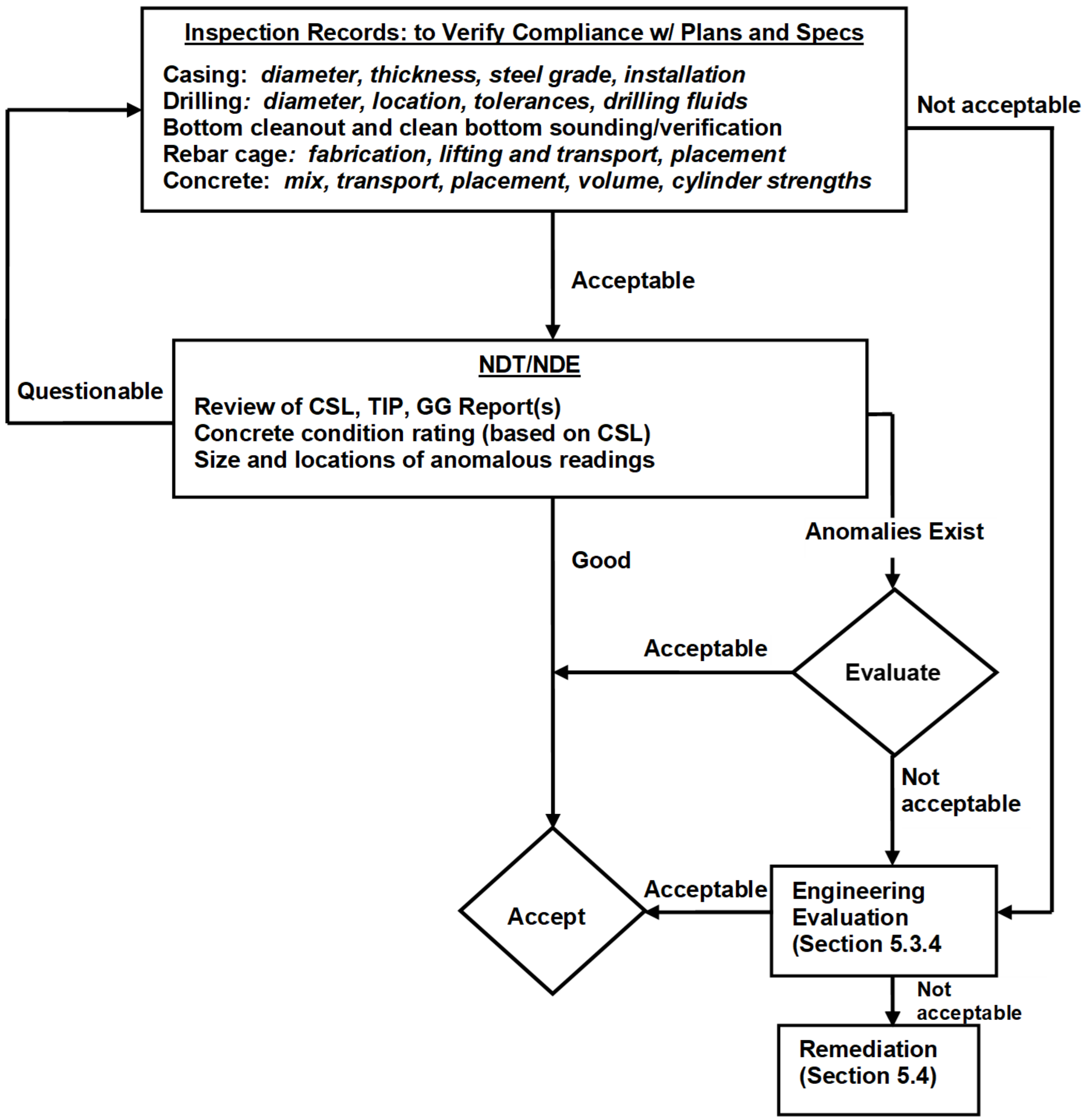

Figure 5-2 Drilled Shaft Assessment and Acceptance Process.

5.3.1 Evaluation of Installation Records

Complete written documentation of the work performed during drilled shaft installation is used to provide a permanent record of the as-built shafts and is the primary basis of quality assurance for each drilled shaft on the project. The specific forms and their contents can vary between agencies and projects, but should include records documenting casing inspection, installation, and removal (where applicable); logs of the excavation; properties and handling of drilling fluids; base cleanout; reinforcing cage inspection and installation; concrete testing and placement; NCRs; and post-construction integrity testing. An important consideration is whether the information provided in the completed forms is sufficient to confirm the as-built location, dimensions, and elevations of each drilled shaft and that the installation process is sufficiently documented to verify compliance with the drilled shaft construction specifications and the approved installation plan.

The engineer in responsible charge of the drilled shaft foundation, typically the foundation design engineer, should review the inspection records and integrity test results (discussed in Section 5.3.2) and provide an acceptance decision in a timely manner. When subsequent construction of columns, piers or other structural elements is contingent upon acceptance of the drilled shafts, inspection records should be prepared as an organized package and provided to the responsible engineer along with the associated integrity test report as soon as possible. The responsible engineer should review and provide the acceptance decision promptly to avoid delays.

In cases where review of the inspection records and integrity test data may not meet established criteria, an engineering evaluation should occur. That evaluation may result in acceptance or further action may be needed. Engineering evaluations and corrective measures are covered in subsequent sections of this chapter.

5.3.2 Evaluation of Integrity Testing

Integrity testing methods currently in use for drilled shafts supporting transportation infrastructure are:

- Crosshole Sonic Logging (CSL) ASTM D 6760
- Thermal Integrity Profiling (TIP) ASTM D 7949
- Gamma-Gamma Logging (GGL) Caltrans Test 233

Descriptions of each test method, including the basic principles and underlying physics, along with advantages and limitations, are given in FHWA GEC 10 (Brown et al., 2018). Each of the methods is considered to be a routine quality assurance test for drilled shafts used in transportation infrastructure, although their use is often determined by owner policy or local practice. Integrity testing methods based on measurements of stress wave propagation (e.g., sonic echo) are also available but may not be used as a routine quality assurance tool for drilled shafts in transportation applications.

One approach that has been used by many transportation agencies in the United States is to require at least one of the tests listed above on all drilled shafts constructed using methods that involve tremie placement of concrete under slurry or water and on all load test and demonstration shafts. The philosophy is that tremie placement of concrete under slurry or water is more challenging and makes direct visual inspection difficult or impossible, thus creating greater uncertainty about concrete integrity. The risk associated with this higher level of uncertainty is addressed, in part, by post-construction integrity tests. At least one of the integrity test methods is also used for drilled shafts constructed by the dry method or with casing if there is concern regarding stability of the shaft excavation or any condition that poses a challenge to successful concrete placement (for example, a congested rebar cage). Another approach is for all drilled shafts to be installed with access tubes, but to perform CSL or GGL tests only when a question arises about concrete integrity in response to some observation or incident during construction.

After construction, inspection records should be reviewed by the responsible engineer for compliance with the specifications as indicated in the first box of Figure 5-2. The integrity test results should be reviewed by the responsible engineer for the presence of anomalies. If the inspection records and integrity test results are satisfactory and no anomalous readings are obtained, the drilled shaft can be approved.

Concrete condition ratings are presented in Table 5-1. The ratings are based on two parameters, velocity reduction (VR) expressed as a percentage and magnitude of energy reduction in the received signal. Table 5-2 presents a rating system that considers readings from TIP and GGL measurements.

If integrity tests indicate an anomaly characterized as Q in Table 5-1 or Class C according to Table 5-2, the inspection records should be reviewed carefully, particularly if the values are near the upper end of the limit. A potential imperfection or deficiency would be indicated if the Q or Class C reading corresponds to an observation during construction that would also indicate a potential problem. For example, if the Q or Class C reading occurs at a depth where inspection records indicate there was an interruption in the concrete pour, there is sufficient reason to suspect deficient concrete, and further investigation may be warranted.

When any of the three methods yields results falling into category P/D in Table 5-1 or Class C of Table 5-2, further consideration of potential imperfections or deficiencies may be warranted. If CSL was the primary testing method, application of tomography is typically the next step. Engineering judgment should be applied carefully before deciding whether concrete coring is needed; coring should not automatically be the next step. For anomalous zones limited to small areas of the shaft or non-critical locations the engineer may determine that the potential risk posed by a minor imperfection does not warrant the cost and effort of concrete coring. If further evaluation leads to the conclusion that coring is not warranted, the engineer's rationale for accepting the drilled shaft with anomalous integrity test results should be documented in writing and made part of the permanent record.

TABLE 5-1 CONCRETE CONDITION RATING CRITERIA FOR CSL (ADAPTED FROM FHWA GEC 10, BROWN, ET AL. 2018)

Velocity Reduction, VR (%)	Signal Distortion/Strength	Concrete Rating	Indicated Conditions
0 – 10	none/normal energy reduction ≤ 6 dB	Good (G)	Acceptable quality concrete
10 – 20	minor/lower energy reduction 6.1 to 9 dB	Questionable (Q)	Minor contamination, intrusion, or questionable quality concrete
> 20	severe/much lower energy reduction > 9 dB	Poor/defect (P/D)	contamination, intrusion, and/or poor quality concrete
No signal	None	No Signal (NS)	Intrusion or severe defect; could also be caused by tube debonding
≈60	severe/much lower energy reduction ≥ 12 dB	Water (W)	water intrusion or water-filled gravel intrusion with few or no fines

TABLE 5-2 ANOMALOUS READINGS BY INTEGRITY TEST METHOD.

Integrity Test Method	Parameter Measured	Class A Acceptable	Class C Abnormal
TIP	Radius Reduction, R_r (%)	≤ 6%	> 6%
	Local Cover (in)	≥ 3 in	< 3 in
GGL	Standard Deviations below Mean	< 3	> 3

5.3.3 Evaluation of Concrete Coring

One of the available tools for further evaluating concrete quality is to execute a program of drilling and coring. Core sampling provides direct visual examination of concrete and the opportunity to conduct strength tests on as-placed concrete. However, drilling and coring are time-consuming and expensive. Coring also has limitations that may preclude the visual verification that is needed or desired in every case, as described below.

In some cases, it may not be necessary to core the entire length of the shaft, and it may be more economical to blind drill competent sections of the shaft since drilling is much faster than coring. An effective way to employ a coring program is to limit core sampling to a zone extending from a few feet above to a few feet below the target zones in the shaft where concrete quality is questionable. In zones that are not cored, the quality of concrete can sometimes be inferred from the drilling rate. Drilling alone may also reveal imperfections or deficiencies; for example, a soil-filled cavity may be indicated by an abrupt drop in the drill for a significant distance.

Coring in the target zone can provide both qualitative and quantitative information on the integrity and quality of drilled shaft concrete. Visual observation of core samples is useful in identifying voids, weak cementation, fractures, soil or slurry intrusions, and other potential flaws or deficiencies. Reduced core sample recovery or loss of water return may also indicate potentially deficient concrete. Intact core samples can be tested for compressive strength. For coring to be effective, high quality cores should be retrieved. Cores should be recovered utilizing double or triple barrel coring techniques. Ideally, core diameters for strength tests should be a minimum of four to five times the maximum aggregate size. For mix designs with ½ inch maximum aggregate, NX core which provides a 2.15-inch diameter core sample may be sufficient, but for concrete with maximum aggregate size in the range of ¾ inch to 1 inch, a 4-inch diameter core should be obtained for strength testing.

Figure 5-3 illustrates features observed in concrete core that serve the purpose of either verifying concrete quality at the cored location, or that reveal potential imperfections or deficiencies. Part (a) shows concrete core in a shaft that exhibited CSL anomalies with velocity reductions in the 15 to 20 percent range. Coring showed continuous, integral concrete over the entire cored depth. Compression tests on core sample exhibited strengths well in excess of the 5,000 psi design value. No further action was taken. Part (b) shows core at the base of a shaft obtained in response to questions raised about base cleanout effectiveness; the core at this location showed high quality concrete in direct contact with the supporting rock, and no further measures were deemed necessary. Part (c) shows a core sample taken from near the top of a drilled shaft that exhibited an excessive amount of bleed following completion of the pour. This sample shows poor cementation and the presence of bleed channels. The solution was to chip down the top of the shaft until acceptable concrete was verified and re-pour the top portion of the shaft. Part (d) of the figure shows core near the tip of a shaft where difficulties with the tremie pipe resulted in the initial discharge of concrete several feet above the base under wet conditions. Poor recovery and weak concrete observed in the core resulted in remediation by hydrodemolition followed by grouting.

The ability of a concrete core hole to precisely penetrate the target zone of potentially questionable concrete can be limited by the reinforcing steel, integrity test access tubes, and the potential for horizontal drift of the core hole. For example, if the target zone is identified by a CSL anomaly which is limited to the space between two access tubes or by anomalous GGL readings in the vicinity of a single tube, coring may have limited ability to target these zones. Jones and Wu (2005) indicate that core holes should be located a minimum of 6 inches away from steel reinforcing and steel access tubes to reduce the risk of interference while drilling. At least several inches of horizontal drift can be expected in core holes (and in the drilled shaft as well), and it is not uncommon for the core hole to run out the side of the drilled shaft or to encounter one or more bars of the reinforcing steel, particularly for deep core holes. It is highly recommended that the personnel operating the coring equipment are experienced in coring of drilled shafts.

Considering its advantages and limitations, drilling and coring may be most effective for identifying and characterizing potential imperfections or deficiencies of relatively large size. If the excavation has collapsed during concrete placement and if concrete is absent in a section of the shaft, the deficiency will almost always be detected. Pulling the tremie pipe out of tremie concrete can also result in an imperfection or deficiency that can be readily detected. However, smaller imperfections or deficiencies can easily be missed. The reverse can also be true; coring may reveal an imperfection that is thought to be severe but in fact is insignificant. For example, coring can reveal weak concrete or sand locally at the base of a rock socket, but sound rock and a good contact could exist across most of the socket.

(a) Continuous high quality core

(b) High quality core; base in contact with rock

(c) Core exhibiting poor cementation

(d) Deficient zone of weak concrete

Figure 5-3 Examples of Features Observed in Concrete Core – photos by the authors.

Referring to Figure 5-2, when a potential or actual imperfection has been identified by any of the assessment methods discussed above (inspection, integrity testing, or coring), an engineering evaluation should be the next step toward determining whether the shaft can be accepted as-built or if a remediation process should be initiated. This should involve the following steps:

1. Gather all available construction records, QA/QC records, integrity test results, and first-person accounts of the sequence of construction events for the shaft in question.
2. Perform structural, geotechnical, and corrosion (if applicable) engineering analyses that explicitly consider the actual or potential imperfections to determine

if the as-built shaft meets the performance requirements. If the as-built shaft is determined to be adequate, no further corrective action is necessary.

Assessment of the as-built conditions including potential imperfections should take advantage of all available information, such as expected concrete and reinforcing steel strength based on laboratory tests and mill certifications, load test results, actual stratigraphy at the drilled shaft location, and refined estimates of structural demands on the drilled shaft in question and at the depth in question. This information should be considered regardless of whether it was available at the time of the original design. Several examples follow.

Considerations in cases where the geotechnical strength may be in question may include:

- Evaluate the *actual* demands on the specific shaft in question. For simplicity during design, often all of the shafts in a group or within a section of the project are designed for the largest load demand anticipated for any shaft in the group; the specific shaft in question may be subject to an actual load demand that is somewhat less.
- Evaluate the specific geotechnical conditions at the location of the shaft. This may require additional geotechnical exploration if a boring at the specific shaft location is not available. For example, it may be found that the soil or rock conditions at the shaft in question may be more (or less) favorable than the general simplified conditions used to establish tip elevations. If so, it may be possible to justify an increase in the estimated axial resistance in some portion of the shaft to compensate for a deficiency elsewhere (such as a stuck temporary casing, for instance).
- Consider performing a proof test of the shaft in question. In some cases, an evaluation of geotechnical strength could include a proof test using a rapid load test, dynamic load test, or even a static load test.

Structural strength evaluation involves an assessment of the nature, location, and extent of the structural imperfection and the potential impact on structural performance. Structural considerations are generally dominated by flexural strength demands. A *p-y* computer model of the shaft under the actual load demands and ground conditions for the specific shaft in question can be used to determine the flexural demand at the location of the structural imperfection. Often, the bending moment demand is small in the deeper portions of the shaft and may allow shafts with minor imperfections in the lower sections of the shaft to be acceptable.

If deficient concrete is within a portion of the shaft that includes permanent (construction) casing, the shaft can be re-analyzed considering the contribution of the casing. Sometimes the composite section consisting of steel casing with weak or deficient concrete has sufficient strength to meet the loading demands and costly, time-consuming repairs can be avoided without sacrificing structural performance.

Evaluation of the structural strength of a drilled shaft cross-section with low strength concrete or a soil inclusion over a portion of the section should be based on a conservative assessment of the character and extent of the imperfection from integrity testing, coring, or other techniques. Exposed reinforcement may be discounted because of possible buckling of the bars or future corrosion. Structural evaluation of the strength of an imperfect cross-section calls for engineering judgment and analyses that may be beyond the scope of routine design work. However, tools for performing rigorous section analysis of reinforced concrete members with explicit modeling of deficient concrete zones are widely available and may be warranted.

Figure 5-4 is a graphical representation of the steps that may be taken to address a drilled shaft with anomalies or imperfections, based on an assessment of the anomalies or imperfections by engineering analysis, as described above. If the anomalies or imperfections are determined to rise to level of deficiencies so that remediation is needed, corrective actions are designed to address the geotechnical or structural deficiencies determined to be present.

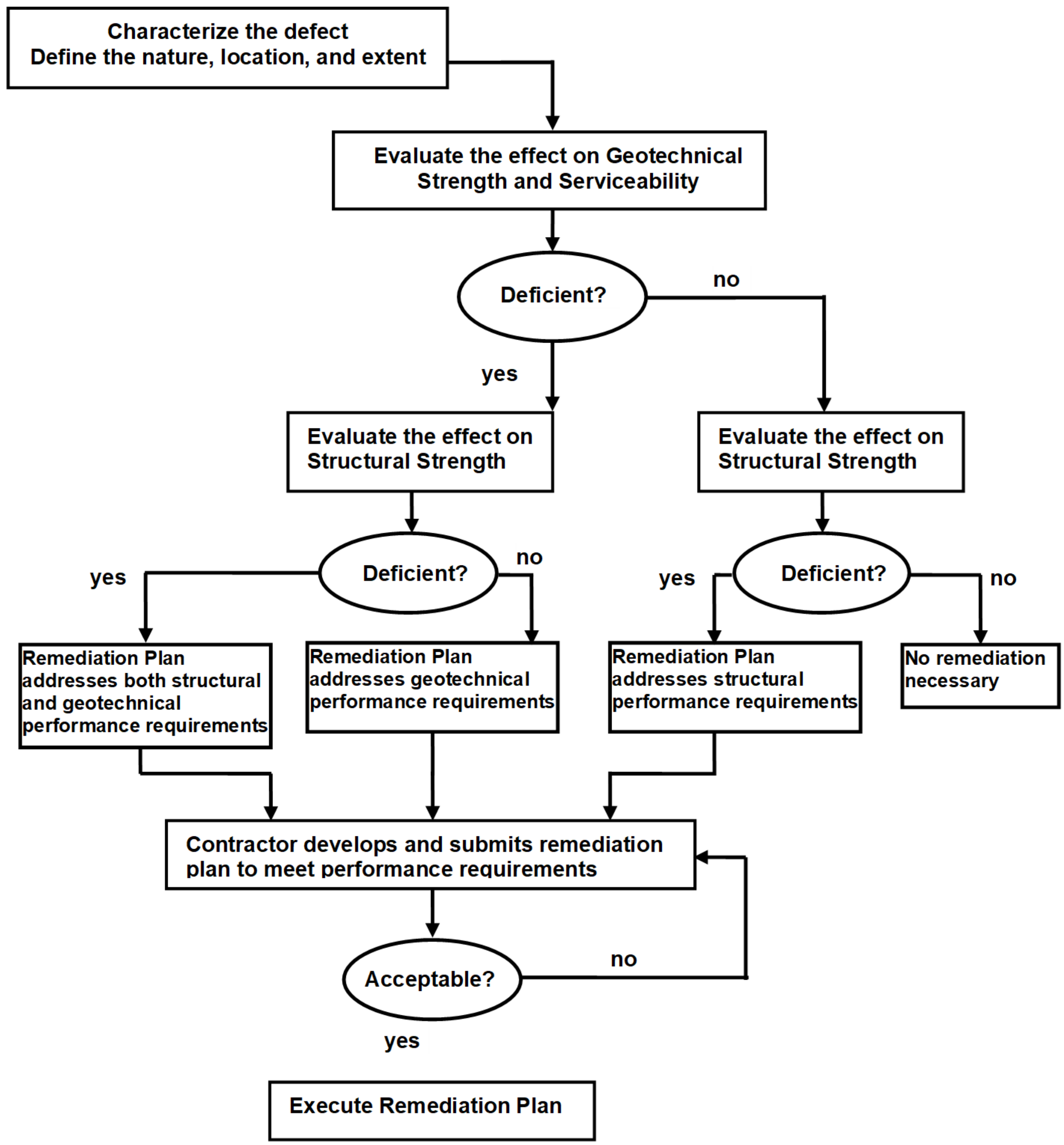

Figure 5-4 Assessment by Engineering Analysis and Remediation Process (Adapted from FHWA GEC 10, Brown et al., 2018).

5.4 CORRECTIVE ACTIONS AND REMEDIAL MEASURES

If an as-built drilled shaft is determined to have a deficiency, corrective actions should be taken to improve or replace the foundation so that it will satisfy the applicable performance demands. This section describes types of potential deficiencies that can affect the structural or geotechnical resistance of drilled shafts, corrective actions, and methods for assessment and acceptance of the corrective actions.

5.4.1 Types of Deficiencies in Drilled Shafts

Deficiencies may be broadly categorized as those that significantly affect the structural or geotechnical resistance of the drilled shaft. Examples of structural deficiencies include poor quality concrete due to segregation, entrapment of sediments or laitance, mixing with soil or slurry, or poor passing ability; necking of the shaft cross-section due to soil intrusion or ground squeezing; or damage or misalignment of reinforcing steel. Structural deficiencies are typically identified initially through integrity tests or based on concrete cylinder break test results. Misalignment of the drilled shaft in terms of verticality or horizontal position may also constitute a structural deficiency due to the inability of the as-built shaft to resist additional structural demands resulting from the misalignment, or because of corrosion concerns.

Geotechnical deficiencies may be those that compromise the geotechnical resistance of the as-built drilled shaft relative to the performance demands, and often involve unintentional, significant disturbance of the ground surrounding or beneath the shaft. Examples include loss of resistance due to caving of the shaft or basal heave as a result of improper support fluid management or encountering significantly poorer subsurface conditions than anticipated for design. Caving or basal heave are examples of phenomena that may lead to geotechnical and structural deficiencies – ground disturbance reduces the geotechnical resistance while soil intrusion compromises the concrete performance. Inadequate bottom cleaning may reduce the base resistance of the drilled shaft and cause sediments to mix with the concrete.

Because ground conditions are not directly measured by integrity tests such as CSL or GGL, the occurrence of geotechnical deficiencies is typically only discovered by direct observation during construction. For this reason, detailed record keeping and full-time observation by qualified representatives of the design engineer are important components for drilled shaft construction. Logs should include drill tooling types and advancement rates, casing elevations and advancement rates, details of support fluids including elevations and slurry QA and QC test results, and a description of the excavated material so that stratigraphy at the drilled shaft location may be inferred. Records documenting the methods used for cleaning the base and the results of base inspection by weighted tape, mini-SID, or other devices should provide valuable information for assessing the possibility of deficiencies.

Detailed records of the concrete pouring operation should also be maintained, including actual versus theoretical concrete volume placement curves, tremie pipe tip elevation during the pour versus the elevation of the rising concrete surface, and documentation of proper use of a “pig” or other device used to separate concrete from drilling fluids during initiation of the pour. Other records may include concrete QA and QC test results and survey reports to verify proper reinforcing cage positioning both before and after the pour. Because the first step in assessing a potentially deficient drilled shaft may be to determine what happened and how the sequence of events resulted in the potential deficiency, having detailed construction records is useful. Gaps in information or unclear records may increase the cost and schedule delays of corrective actions.

5.4.2 Corrective Actions

A variety of potential corrective and remedial methods are available for restoring a deficient drilled shaft to a condition that satisfies the performance criteria. Considering that every project has unique criteria and potential deficiencies may vary widely in severity, location in the shaft, etc., there is no single standardized repair method applicable to all cases. However, the various approaches summarized below may be used successfully. Chapter 17 of FHWA GEC 10 (Brown et al., 2018) provides more in-depth discussion and case history examples of each of the following approaches.

5.4.2.1 Supplemental Foundations

Examples of supplemental foundations include constructing two drilled shafts in line with the deficient shaft and connecting the new “sister shafts” with a grade beam or pile cap. Other applications include the use of micropiles extending through the cap or footing, which itself may need to be enlarged. Micropiles have also been extended through the base of a deficient shaft to develop additional resistance in underlying geomaterials. Supplemental foundations will likely require revisions to the structural analysis and design of the substructure, including distribution of force effects to the individual foundation elements, connections and development length, and modified foundation stiffness.

When constructing supplemental foundations, the construction procedures that resulted in deficiencies in the original drilled shaft should not be repeated, so as to avoid similar deficiencies in the new foundation elements. The project team should work collaboratively to identify the probable cause of the deficiencies and develop a new work plan with modified construction procedures. Detailed records should be made and retained during construction and inspection.

Supplemental foundations are sometimes not given the consideration that may be warranted. The potential need for substructure re-design is sometimes cited as a reason for eliminating supplemental foundations as a feasible option. Re-design of elements other than the foundations may require the time and resources of personnel other than the contractor, including potentially the owner’s engineer. However, there can be a high degree of uncertainty about the cost and impact on the schedule when undertaking repairs or structural enhancement of existing drilled shafts with deficiencies, especially for large-diameter or deep drilled shafts. Additionally, the techniques for repair or enhancement may be non-standard and specialized, while the means and methods used for supplemental foundations are usually those already being used on the project, and the equipment is likely to be on site and available. Before eliminating supplemental foundations, all of the factors noted above should be considered.

5.4.2.2 Excavate and Replace

Mechanical excavation of deficient concrete followed by replacement may be a feasible repair method for structural deficiencies that are relatively shallow and therefore accessible from the surface. Poor quality concrete in the top of a large diameter shaft may be removed manually with impact tools. If the upper portion of the soil around the shaft can be excavated and a dry working environment secured, hand methods may be used to chip away deficient concrete from the outside of the shaft, and the upper portion of the shaft can be re-cast within a form. Concrete inside the reinforcing cage can be excavated using drilled shaft equipment with rock drilling tools such as rock augers and core barrels. The excavated core within the reinforcing cage can be re-poured, with the remaining outer shell acting as the form.

5.4.2.3 Structural Enhancement

This approach refers to adding structural steel through the zone of deficient concrete, either to transfer axial load through the deficient zone to a competent zone below (i.e., a structural bridge), or to provide enhanced flexural resistance in the deficient zone, or both. In some cases, this can be accomplished by placing additional reinforcing bars in cored holes large enough to accommodate the bars and then grouting the added bars into place. Another approach is to excavate the deficient concrete inside the existing rebar cage and replace it with new concrete with reinforcement sufficient to meet the original flexural strength of the as-designed cross-section. This may result in a higher amount of steel or higher-strength steel reinforcement in the smaller-diameter replacement section. For example, Figure 5-5 shows a cage consisting of fourteen Grade 75, No. 28 bars of 3.5-inch diameter that were placed in a 48-inch diameter hole excavated inside a 96-inch diameter drilled shaft. The hole was then filled with 8 ksi grout. The combination of high-strength grout and high-strength reinforcement provided axial and flexural resistance equivalent to that of the as-designed 96-inch diameter shaft. A section of steel pipe grouted into the cored center of the shaft also provides a means to obtain structural strength equivalent to that of the as-designed section.

Figure 5-5 Reinforcing cage with Grade 75 threaded bars used for structural enhancement of a drilled shaft in which deficient concrete had been removed from inside the reinforcing cage.

5.4.2.4 Grouting

Grouting offers a means to treat a deficient area directly to improve or restore the structural or geotechnical strength. For example, a deficiency at the base of a shaft caused by trapped material or segregated aggregate can sometimes be treated by *base grouting*. Existing access tubes for nondestructive testing, or cored holes are needed for grout placement and return flow. *Permeation grouting* may be a feasible option where the presence of segregated aggregate has been confirmed by coring and water flushing. *Jet grouting* around the outside perimeter of a drilled shaft has been used to repair deficient concrete on the outside of the rebar cage, and to restore geotechnical resistance. These types of grouting are typically performed by specialty contractors and experienced personnel that should work with the drilled shaft contractor and the project engineers. FHWA GEC 10 (Brown et al., 2018) presents several case histories of grouting as a repair method.

5.4.2.5 Hydrodemolition with Replacement Grouting

Deficient concrete can sometimes be removed by hydrodemolition, which involves using a downhole device that provides a high-pressure jet of water capable of cutting away the deficient concrete (demolition) while leaving competent concrete and steel reinforcement in place. The jetting device can be lowered to the target zone either through existing CSL or GGL access tubes, or via holes cored from the surface. Return flow of the jet water and cuttings should be provided through the other access tubes or cored holes. Skill and experience on the part of the operator are key to the successful use of this method. If the pressure is too high, it is possible to demolish competent concrete and cut steel reinforcing bars. If concrete is removed all the way to the outer perimeter of the shaft, the soil or rock can also be removed. In soil, this can result in rapid removal (mining) of the surrounding ground and cause more harm than good.

Following hydrodemolition, the resulting void is filled with replacement grout. If specified, the hydrodemolished void can be inspected using a downhole camera to ensure removal of deficient concrete prior to placement of grout. It is also possible, but not always necessary, to core the repaired zone to verify that the deficient concrete has been replaced with grout as intended. If CSL or GGL tubes remain intact, integrity tests can be performed to assess the effectiveness of the remediation. Chapter 17 of FHWA GEC 10 (Brown et al., 2018) provides a case history example of drilled shaft repair by hydrodemolition and grouting.

5.4.2.6 Extension of the Drilled Shaft

Where deficient concrete is found to exist at or near the base of a drilled shaft and the volume of deficient material is more than can be removed effectively by hydrodemolition, it may be feasible to extend the drilled shaft to a deeper tip elevation. This is accomplished by removal of the concrete, typically using a rock drilling tool or core barrel, from inside the rebar cage and then extending the excavation to the depth required to provide side and base resistance equivalent to the resistance lost as a result of the deficiency.

A limitation of coring concrete from the inside of an existing drilled shaft is that the vertical alignment of most shafts is not perfect, posing a risk of the drilling tools hitting and damaging the rebar cage. The deeper the excavated center, the greater the risk of hitting the cage. In particular, where shafts transition from overburden soil to a rock socket, there is typically a horizontal offset in the alignment, and it becomes difficult to maintain clearance between the hole being excavated and the rebar cage.

5.4.2.7 Standardized Repair Procedures

Some agencies that utilize drilled shafts extensively have developed standardized repair procedures. The advantage of having a standard procedure in place is that it may provide contractors and the agency with a clear path to shaft acceptance when deficiencies occur. For example, Caltrans (2019) outlines a repair hierarchy for drilled shafts that are rejected on the basis of anomalies or known deficiencies. The following three levels of repair are described:

1. Standard CIDH (Cast-in-Drilled Hole) Pile Anomaly Mitigation Plan A - Simple Repair

Caltrans's simple repair consists of excavation of soils and then removal and replacement of deficient concrete. This repair may be implemented under the following conditions:

- The anomaly is within 5 feet of the top of the shaft;
- There are no other repairs in the same shaft; and
- The repair area can be made completely visible.

2. Standard CIDH Pile Anomaly Mitigation Plan B – Grouting Repairs
   Caltrans's standard plan describes the steps required for replacement and permeation grouting, including hydrodemolition if needed. While the plan described is generic, the intent is to expedite acceptance of typical mitigation plans by providing a template for formal submission to Caltrans. The mitigation plan can be made job-specific by attaching a cover letter that addresses the specific site conditions and contract requirements.

3. CIDH Pile Non-Standard Mitigation
   For a drilled shaft which cannot be repaired by simple repair or grouting, non-standard repair methods identified by Caltrans include structural bridging and replacement/supplemental shafts. Under the Caltrans procedure, these types of repairs require the contractor to submit a Repair Plan, normally stamped by a California licensed Professional Engineer, prepared in accordance with guidelines provided in Chapter 9 of the Caltrans *Foundation Manual* (Caltrans, 2019).

5.4.3 Assessment and Acceptance of Corrective Actions

A decision to proceed with one of the corrective actions described above involves a determination that the as-built drilled shaft is not sufficient to meet the performance demands for which it was designed (see Figure 5-4). Engineering analysis of the shaft with the proposed repair should demonstrate that the repaired shaft will meet the performance criteria. Final acceptance may be contingent upon verifying that the repair is carried out in accordance with the accepted remediation plan. The underlying principle is the same as for initial construction of the drilled shaft: the contractor submits and obtains approval of an installation (repair) plan, and independent field observation/inspection should verify that the repair operation conforms to the approved drawings and applicable specifications.

As shown in Figure 5-4, the contractor should prepare and submit the remediation plan. The plan should include a step-by-step description of the repair procedure with sufficient detail for the engineer in charge and construction personnel to assess the suitability and appropriateness of the procedure. Plan drawings showing the repaired shaft with all relevant views, details, and notes should be provided. Any relevant specifications or special provisions should be cited. Any materials to be utilized, such as grout, high-strength steel bars, steel structural sections, should be compatible with the drilled shaft design. The plan should include engineering analysis that demonstrates the ability of the repaired shaft to meet the geotechnical and structural performance demands.

Conversely, the engineer should evaluate the contractor's remediation plan in a timely manner and to provide meaningful feedback. Deadlines for response from both the contractor and owner may be included in the project drilled shaft specifications. When evaluating a contractor's remediation plan, the engineer performing the review should have sufficient knowledge and experience in drilled shaft design and construction to make meaningful judgments on the feasibility of the repair scheme and to assess the engineering analysis provided to support the repair. If the engineer in charge has limited experience in drilled shaft engineering, in-house or outside experts should be engaged in the process.

Once the remediation plan is approved, the contractor should perform the repair in conformance with the procedures, plan drawings, and specifications included in the approved plan. When the repair has been completed, inspection records, including any post-repair verification testing such as CSL testing or concrete coring, should be submitted to show that the repair was carried out in accordance with the approved plan and that the drilled shaft can be accepted.

5.5 POTENTIAL ISSUES IN DRILLED SHAFT ASSESSMENT

As described in this chapter, assessment of as-built drilled shaft foundations is based largely on three sources of information: (1) observations made and recorded by inspection personnel during the installation process, (2) post construction integrity testing, and (3) load testing (if included). These sources of information should be complementary. Each has potential strengths as an assessment tool, and each has potential limitations. Some of these limitations are discussed below.

- Thorough inspection and documentation

Inspection is an important part of the overall assessment and acceptance process. Failure to implement a thorough inspection process as described in Section 5.3 and other references may deprive the agency of its ability to determine whether the drilled shaft was installed in accordance with plans and specifications. Thorough inspection requires sufficient personnel with training and experience. Insufficient or incomplete documentation does not allow effective interpretation of anomalies identified by non-destructive testing and makes it difficult for an agency to accept the work.

- Post-Construction Integrity Tests in Acceptance

Each integrity testing method has advantages that allow some aspect of the as-built drilled shaft concrete integrity to be assessed. However, no integrity test is capable of establishing every aspect of the drilled shaft integrity. Integrity tests should not be relied upon exclusively as a basis of acceptance.

Identification of anomalies by integrity test measurements should not automatically be interpreted as a deficiency. As described above and discussed in greater detail in FHWA GEC 10 (Brown et al., 2018), there can be multiple reasons for anomalous readings. Only when further evaluation has established the location, nature, and extent of a deficiency can rational decisions be made about acceptance or the need for remediation. Anomalous integrity test readings should not be taken as indicative of a 'void' in a drilled shaft.

- Remediation Compatible with Performance

Often it is not practically possible, nor necessary, to require that the redesigned/repaired shaft provide resistance equal to or greater than the as-designed shaft, rather than satisfying the actual performance demands. As described in Section 5.4.4, in performing engineering evaluation of a drilled shaft for acceptance, with or without remediation, all available information should be considered, even if it was not available for the original design (e.g., load tests, actual concrete strength, revised load demands, etc.).

A final point worth considering is the degree to which factors related to design and specifications can contribute to the likelihood of having anomalies and deficiencies in drilled shafts. FHWA GEC 10 (Brown et al., 2018) provides information about design of drilled shafts for constructability. However, designs in use may not consider these "best practices" as enforceable regulatory standards, which may create certain risks. For example, rebar cages with clear spacing between bars that do not meet the suggested minimum of 5 inches may create a risk of insufficient concrete passing ability and may result in poor or deficient concrete around the outside of the cage. Designs that lead to drilled shafts having dimensions larger than actually required may increase the risk of construction difficulties that may negatively impact the acceptance process. For example, some designers disregard base resistance in rock-socketed drilled shafts. The resulting design may include a much deeper rock socket compared to a design that accounts for base resistance. The increased depth can have the unintended consequence of increasing the likelihood of construction difficulties (e.g., caving rock, difficulties excavating very strong rock, concrete placement issues, etc.) that increase the likelihood of deficiencies and repairs. While the designer may think of disregarding base resistance as a way of reducing design risk by increasing the shaft length (i.e., the design is more "conservative"), the designer may be unintentionally creating additional risk to construction and final acceptance.

CHAPTER 6
EVALUATION AND ACCEPTANCE OF MICROPILE FOUNDATIONS

This chapter describes evaluation and acceptance techniques for micropile foundations. The chapter begins with a discussion of the unique characteristics of micropiles before presenting information pertaining to evaluation and acceptance during design, construction, and inspection. Evaluation and acceptance procedures are discussed, with an emphasis on load testing, which may be more common for micropiles than other foundation types. The chapter closes with a discussion of common mistakes during micropile evaluation and acceptance.

6.1 UNIQUE ASPECTS AND APPLICATIONS OF MICROPILES

Micropiles are small-diameter (typically less than 12 in.) drilled and grouted deep foundation elements constructed of grout and steel reinforcement, and typically also including permanent steel casing. As summarized in Table 6-1, Article 10.9.1 of the AASHTO Bridge Design Specifications (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)) classifies five types of micropiles according to construction technique. An example micropile (Type B, C, or D) is detailed in Figure 6-1. Micropile Types A through D typically include an upper-cased section, a lower section without casing (the “bond length”), and a center steel reinforcing bar through both sections. Axial geotechnical resistance is typically assumed to develop solely from the grout-to-ground bond strength in the bonded length of the micropile. Type E micropiles (“hollow bar” micropiles) are installed by drilling with grout injection through continuous-thread hollow-core steel bars so that drilling and grouting are completed in a single pass. Type E micropiles have not been routinely used in Federally funded highway work.

TABLE 6-1 MICROPILE TYPES DEFINED BY AASHTO Bridge Design Specifications (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)).

Micropile Type	Description
A	Grout placed under gravity only.
B	Grout injected under pressure while a temporary casing or auger is withdrawn.
C	Primary grouting under gravity, followed by pressure grouting approximately 20 minutes after primary grouting.
D	Primary grouting under gravity, followed by pressure grouting through a grout pipe after the primary grout has hardened.
E	Drilling with grout injection through continuous-thread hollow-core steel bar with sacrificial bit.

Because of their small cross-sectional area, micropile resistance may be governed by structural rather than geotechnical considerations. Accordingly, micropiles typically include a much greater percentage of steel reinforcement, up to half of the cross-sectional area, compared to other deep foundation types. Also, the geotechnical resistance of micropiles is sensitive to construction technique. Because of the variability of geotechnical resistance, micropiles are typically load tested to verify resistance. Load tests are an important component of evaluation and acceptance for micropile foundations.

Another unique aspect of micropiles is that they are typically installed by specialty contractors. To encourage specialty contractors to develop innovative and cost-saving installations, and because of the sensitivity of micropile resistance to construction techniques, specifications for micropile drilling and grouting are typically performance-based. With the performance-based approach, the owner typically defines geometric constraints and loading demands, and the contractor specifies the micropile design, number of micropiles, and construction process. Prequalification of micropile contractors typically accompanies use of performance-based specifications. Specifications for other aspects of the micropile construction (e.g., structural details) may be prescriptive.

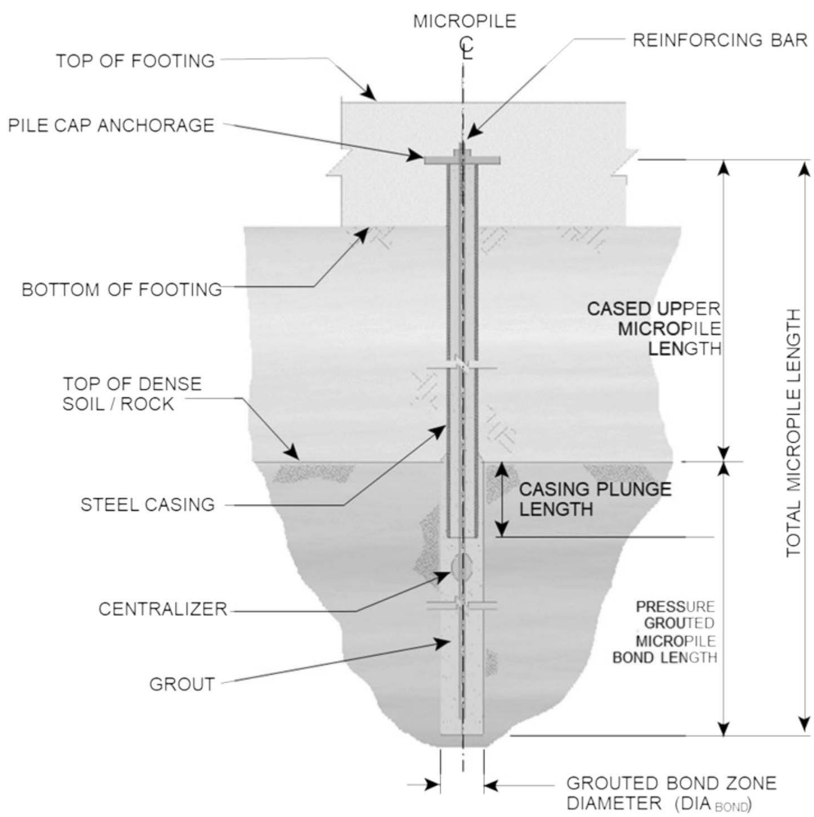

Figure 6-1 Example micropile detail from FHWA NHI-05-039 (Sabatini, et al., 2005).

Some common applications of micropiles are described below. These applications are more typically used for micropiles than other foundation types. The descriptions focus on loading demands associated with the applications.

Underpinning or Enhancement of Existing Foundations

Micropiles are typically installed to improve existing foundations, in some cases to remediate performance problems and in others to increase capacity for new loading. The situation is typical for bridge replacement projects involving foundation reuse, the topic of FHWA-HIF-18-055 (Agrawal, et al., 2018). As for the case of micropiles for new foundations, load demands on micropiles for underpinning and enhancement applications are project specific. An additional consideration for design of micropiles for underpinning or enhancement applications is the interaction between new micropiles and existing foundation elements. Existing foundation elements are typically driven piles or drilled shafts; either foundation type is typically much stiffer than a micropile for both axial and lateral loading. Stiffness differences should be considered in any analysis of the pile cap retrofit, requiring structural models that do not assume a rigid cap. Design for underpinning should also consider load transfer from the existing foundation to the micropiles, either by preloading the micropiles or through passive load transfer resulting from foundation displacements, as determined by an evaluation of the structure's tolerance to displacements. If the micropile is to be preloaded, evaluation of preload should be part of the foundation acceptance evaluation.

Seismic Retrofit

A specific application of micropiles to increase capacity for new loading is seismic retrofit projects. In addition to the possible benefits of micropiles for retrofits—equipment access in tight sites, ability to drill through obstructions, installation through existing footings, etc.—micropiles typically have similar capacity in tension and compression. This characteristic can lead to efficiency in seismic retrofit designs (Bruce and Chu, 1995). In addition to tensile and compressive load demands, lateral force demands are also often placed on seismic retrofit micropiles. As for underpinning and enhancement applications, analysis of interaction between the new micropiles and existing foundation is important for design of the pile cap. The pile cap design could include new micropiles through an existing footing, or new micropiles tied into an existing footing through expansion of the footing. Details of the structural connection between micropiles and footings are discussed in Section 6.2.3.

Micropiles for Slope Stabilization

Another application for micropiles is for slope stabilization. Such applications typically involve installation of the micropiles in an "A-wall" configuration as shown in the example of Figure 6-2 (Gómez, et al., 2013). With the A-wall configuration, micropiles are installed with successive micropiles alternating between inclined upslope and inclined downslope, and all micropiles are installed through a common capping beam. Ground anchors are typically incorporated in the stabilization schemes.

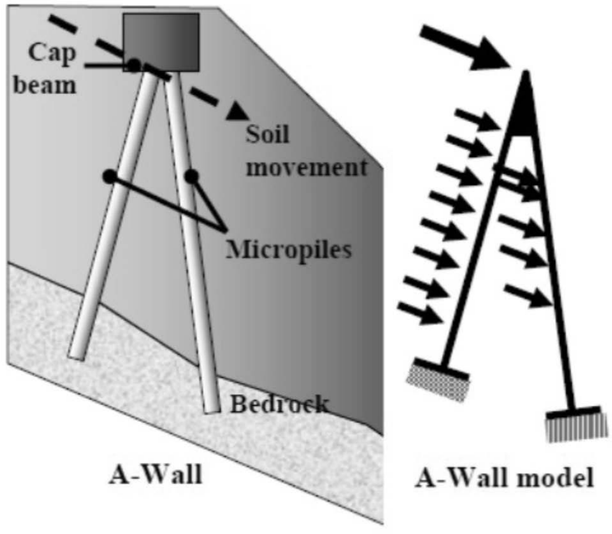

Figure 6-2 Schematic representation of micropiles installed in "A-wall" configuration for slope stabilization (from Gómez et al., 2013).

Loading demands on micropiles for slope stabilization are typically derived from slope stability analyses, which are used to determine the magnitude of stabilizing forces required to bring the slope to an acceptable factor of safety against instability. Micropiles are passive members, needing ground deformation to engage the micropiles and mobilize forces (as opposed to active elements like ground anchors, which are preloaded). As a result, there may be uncertainty in the loading demands on micropiles for slope stabilization. Loehr and Brown (2008) developed a procedure for designing micropiles for slope stabilization. Unlike the 2005 FHWA method described in FHWA-NHI-05-039 (Sabatini et al., 2005), the method by Loehr and Brown is displacement-based, so it may satisfy compatibility and facilitate evaluations of serviceability, which may control design.

6.2 DESIGN

Micropiles are typically used in situations where other foundation types are infeasible. In the transportation sector, such situations could include foundations for sites with space limitations related to environmental restrictions, overhead constraints or site congestion, foundations through karstic geology, foundations through boulders, supplemental foundations to increase capacity for existing foundations for seismic retrofit or foundation reuse, and slope stabilization applications. This section discusses design-phase considerations pertaining to site characterization, durability, micropile-cap connections, and material requirements. Constructability should be considered throughout the design process, especially in light of the challenges associated with micropile installation.

6.2.1 Site Characterization

Effective site characterization facilitates effective micropile design and reduces potential risks associated with micropile installation. Micropiles are typically installed in difficult ground conditions, such as karstic limestone or boulders. An objective of site characterization programs for micropile foundations is to identify potential risks associated with difficult installation conditions, and to characterize the severity, prevalence, and likelihood of the identified risks. Satisfying this objective may entail a more robust site characterization program than would be employed for a typical foundation project. Information revealed during the site characterization, including factual outcomes, geological and engineering interpretations, and potential construction risks, should be identified so that all parties, including inspectors and contractors, are informed of the site conditions.

6.2.2 Durability: Corrosion Considerations

The durability of micropiles protects the reinforcing steel against corrosion. FHWA-NHI-05-039 (Sabatini, et al. 2005) provides specific information about evaluating corrosion potential, which can be severe for sites with extreme pH, low resistivity, and high concentrations of sulfates or chlorides. That research suggests assuming aggressive ground conditions if tests are not performed to assess corrosion potential.

FHWA-NHI-05-039 (Sabatini, et al. 2005) also includes information about corrosion protection measures. For reinforcing steel bars within the micropile, a protection measure is ensuring grout cover surrounding the reinforcing steel by use of centralizing devices. In aggressive ground conditions, additional measures, including epoxy coating, galvanized coating, or, for maximum protection, encapsulation in sheathing, may be considered. Corrosion protective measures for the steel casing on the outside of the micropile may not be practical, so a common practice in aggressive ground conditions is to include additional sacrificial thickness for compressive loading and not to consider the additional thickness for resisting tensile loading. Additional details of corrosion protection measures are provided in FHWA-NHI-05-039 (Sabatini, et al. 2005) and in the nonbinding industry guide specification from the Joint Micropile Committee of the Deep Foundations Institute and ADSC: The International Association of Foundation Drilling (2004).

6.2.3 Structural Connection of Micropile to Footing or Other Member

The structural connection at the top of the micropile is an important component for transferring load to the micropile. Sabatini, et al., 2005 provides information on seven different types of connections. The connections can vary based on the footing type (new footing, existing footing, extension of existing footing), the type of loading to be transferred to the micropile (compressive and/or tensile), and the magnitude of loading. Sabatini, et al., 2005 suggests load testing some connections to verify bond strengths between casing and grout and between grout and existing concrete.

6.2.4 Materials

Micropiles consist of steel reinforcement and grout. For typical micropile designs, the reinforcing steel within the micropile is assumed to carry most, if not all, of the applied loading. Four types of reinforcing steel are commonly used in micropiles: standard rebar, continuous-thread steel bars, continuous-thread hollow steel bars (for Type E micropiles), and steel pipe casing. Information about each type of reinforcing steel is included in FHWA-NHI-05-039 (Sabatini, et al. 2005).

Most of a micropile cross-section is comprised of grout. For typical micropile applications, neat cement grout (i.e., just cement and water) is used. For some applications, typically Type A micropiles, a sand-cement grout may be used. Effective use of grout is needed for micropile construction in order to achieve sufficient bond strength and to ensure structural integrity of the micropile, in particular to protect the reinforcing steel against corrosion. To satisfy resistance and durability objectives,

1. Grout should have adequate long-term strength;
2. Grout should be stable, i.e., resistant to bleed; and
3. Grout should be pumpable to ensure proper placement along the length and throughout the micropile cross-section.

As shown in Figure 6-3, these three characteristics may be considered competing demands with respect to selecting an appropriate water-cement (*w/c*) ratio. As the *w/c* ratio increases, pumpability improves (in terms of Figure 6-3, shear strength or resistance to flow decreases), but compressive strength and stability both decrease (in terms of Figure 6-3, loss of stability is indicated by increased bleed capacity). Conversely, as the *w/c* ratio decreases, compressive strength and stability increase, but pumpability decreases. A value of *w/c* ratio between 0.4 and 0.5 by weight is typical in micropile construction. Although the resistance to flow is off the chart in Figure 6-3 for this range of *w/c* ratio, experience indicates pumpability is typically satisfactory for grout in this range. Admixtures are sometimes used to improve pumpability if the resistance to flow is too great.

Methods for assessing whether grout material needs are satisfied include mud balance testing to evaluate specific gravity and *w/c* ratio, sampling grout cubes for compressive strength testing, and monitoring grout placement volume. Grout evaluation techniques are discussed in Section 6.4.

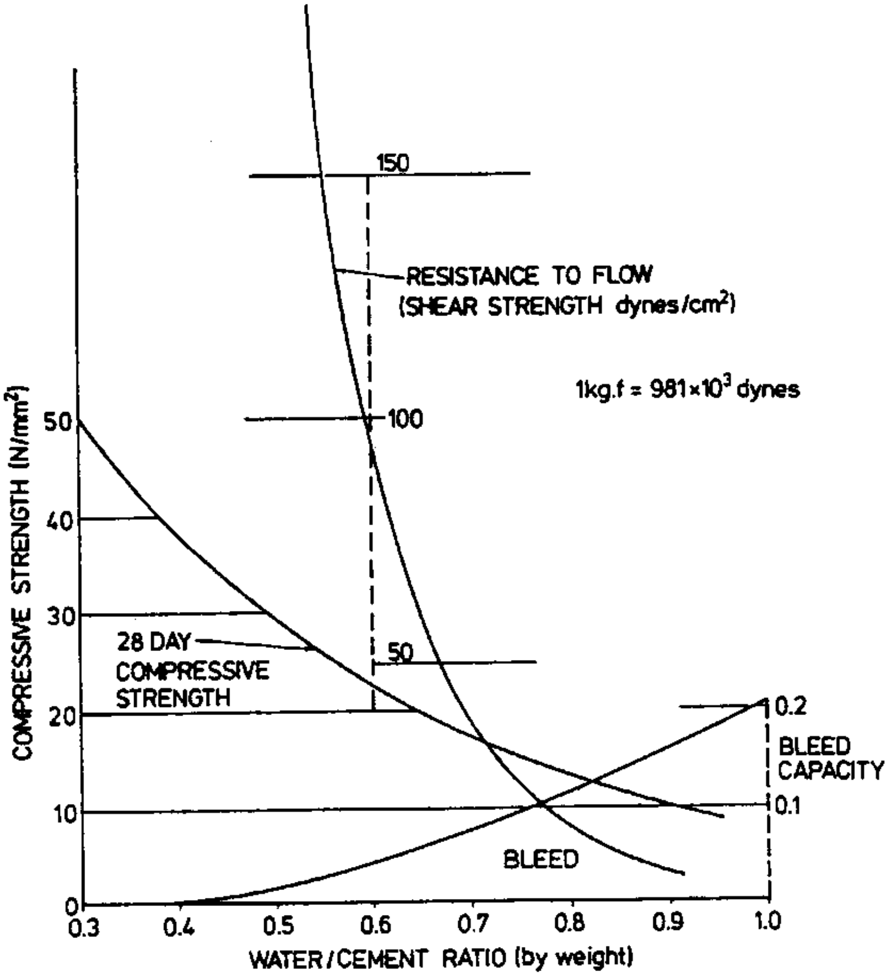

Figure 6-3 Effect of water-cement ratio on grout properties: compressive strength, shear strength, and bleed capacity (from Sabatini et al., 2005, after Littlejohn and Bruce, 1977).
Note 1 dyne/cm^2 = 1.45x10^{-5} psi; 1 N/mm^2 = 145 psi.

6.3 CONSTRUCTION

Contractors should understand the basic objectives of the micropile design and the general nature of subsurface conditions, and how those conditions might impact their ability to install micropiles successfully. They should use this understanding to develop an appropriate installation plan with drilling equipment that is suitable for the conditions of the project, adaptable to reasonable variations in subsurface conditions, and that includes contingencies for potential problems or risk items. Finally, implementation of the installation plan should include a thorough quality control system to manage and document micropile installation in a manner that will satisfy acceptance criteria. As micropile acceptance is often contingent on load test results, quality control measures should address load test setup and performance for projects including load tests.

6.3.1 Installation Plan

Prior to construction, the contractor should submit an installation plan for review by the responsible engineer. The installation plan should include, but may not be limited to:

1. Contractor and employee qualifications;
2. Contractor's understanding of ground conditions with a discussion on anticipated difficulties related to these ground conditions;
3. Performance criteria and tolerances;
4. Location, orientation, and unique identification number of each micropile;
5. Size and configuration (i.e., description of micropile cross-section) of each micropile;
6. Factored load and nominal resistance requirements for each micropile;
7. Drilling equipment, including manufacturer and model numbers, flushing media, and a discussion of the precautions to be implemented to minimize drilling deviations;
8. List of all equipment to be used for the project with equipment loads on structure or adjacent ground during construction;
9. General installation plan, including proposed sequence of installation, phasing, and scheduling;
10. Grout design mix, along with batching, mixing, and injection techniques;
11. Grout strength requirements;
12. Casing, including sizing, type, and elevations;
13. Reinforcement, including sizing, type, configuration, and corrosion protection, the size and location of couplers, and the type, size and spacing of centralizers;
14. Post-grouting methods (if anticipated to be used), procedure, and equipment;
15. Documentation of existing utilities and other sensitive elements that may be affected by the micropile work, and proposed measures to minimize impacts of the micropile work on these elements;
16. Plan to accommodate low headroom or nearby obstructions;
17. Load testing information including identification of micropiles to be tested, type of testing to be performed, maximum anticipated test load for each micropile, allowable deformations under test loads, and details of the testing procedures for each type of test to be performed (i.e., compression, tension, or lateral) including sketches showing typical layout for load tests (e.g., location of reaction piles, arrangement and details of reaction system and reference system, position of dial gauges, etc.);
18. Calibration information for load cells, pressure gauges, dial gauges, and any other testing or monitoring devices;
19. Details of connection to existing structures;
20. Remedial action plan describing measures to be implemented in the event of excessive movement of existing structures, release of spills to environmentally sensitive areas, and other potential hazards that could reasonably be anticipated at the start of the project; and
21. Spoil handling procedures.

The inspector should be familiar with the items in the installation plan and should have a copy of the installation plan, relevant contract documents, and logs of nearby borings.

6.3.2 Quality Control During Construction

Micropile construction should include quality control measures to check that:

- Micropiles are installed in the correct location and with the proper alignment;
- Micropile reinforcement satisfies material specifications (e.g., grade of steel) and is the correct size;
- Micropile reinforcement is installed in the center of the micropile excavation, with appropriate use of centralizing devices;
- Micropile grout is pumpable and satisfies the specified range of *w/c* ratio;
- Micropile grout is sampled to evaluate compressive strength according to the installation plan and project specifications; and
- Connection of the micropile to the footing or other member is completed according to the project requirements.

In addition, for micropile load tests, quality control measures should check that load test setup and performance are completed according to project requirements. Documentation of quality control activities should be an important part of the inspection and quality assurance program discussed in the next section.

6.4 INSPECTION AND QUALITY ASSURANCE

Construction inspection provides assurance micropiles are installed according to plans and specifications. Similarly, even when load tests are used, inspectors should observe installation and document any changes from plans and specifications. Any unanticipated ground conditions that may impact micropile performance should be documented.

Performance-based specifications are typical in micropile construction. Under this approach, the contractor is typically responsible for QC activities, with the owner typically performing a more limited regimen of QA activities for verification. Specialty contractors, who commonly install micropiles, may operate efficiently with the flexibility of the performance-based approach. Regardless of the arrangement, the items discussed in this section are typically suggested for inspection.

Micropile construction activities—drilling, installation of reinforcing steel, and grouting—are typically observed to assess conformance with project specifications, the approved micropile installation plan, and to document micropile installation. An overview of micropile inspection information is presented in Table 6-2. The table is organized by major construction activity, with a list of items and considerations included for each activity. Information about inspection of micropile construction is included in FHWA-NHI-05-039 (Sabatini et al. (2005).

TABLE 6-2 SUMMARY OF DOCUMENTATION RECOMMENDATIONS

Activity	Inspection Notes
Pre-construction	• Inspector and responsible engineer should communicate to establish ○ Expected conditions ○ Permissible deviations from expected conditions ○ Plans to report any deviations, problems, or surprises in a timely manner ○ Potential corrective actions • Inspector and contractor should coordinate to ○ Review installation plan ○ Verify conformance testing requirements and frequency ○ Review material storage conditions
Drilling	• Document dates and times, drilling equipment, tooling, type and dimensions of casing, casing depths, and fluid levels within hole. • Identify and log subsurface materials encountered during drilling. • Fluid levels in the drill hole should be maintained above groundwater to prevent instability. • Inspector should be watchful for evidence of ground loss (subsidence, stuck casing, removal of significant volumes of material without advancement). • Record any other observations of note during drilling operations. • Upon encountering any unanticipated ground conditions, problems during drilling, or deviations from the project specifications, inspector should alert responsible engineer in a timely manner.
Placement of Reinforcing Steel	• Just prior to installation, verify steel dimensions and that steel surface is free from flaking or pitting corrosion (light rust at surface is normal). Steel should be stored in a manner that prevents damage and corrosion. • Ensure proper sizing and condition of couplers. • Avoid excessive bending during installation. Excessive bending causes permanent deformation. • Verify and document depths of centralizers. • Placement should not require excessive force.
Grouting and Post-grouting	• Prior to mixing, cement should be stored to prevent moisture entry. Just prior to mixing, cement should be inspected for any indication of hydration. • Timing of grouting with respect to completion of drilling should be documented and verified for conformance with specifications. • Observe and document cleaning of micropile drill hole, including the timing of cleaning.

	• Inspect the *w/c* ratio of neat cement grout by measurement of the specific gravity of the grout with a mud balance (API Recommended Practice 13B-1). Verify conformance with the *w/c* ratio in the specifications at least once per micropile. • The specific gravity can be related to the *w/c* ratio of the grout by the relationship shown in Figure 6-4, which applies to neat cement grouts only. • Document any use of admixtures. • Collect grout specimens from the plant for compressive strength testing in accordance with specifications. • Monitor grout placement by logging volume and pressure of grout with depth. The contractor and the inspector should independently develop grouting logs. • Document any problems with temporary casing withdrawal. Casing should remain full of grout during extraction. • Quality of grout returned at the ground surface should be observed. • If post-grouted: log grout pressures and volumes for each grout port.

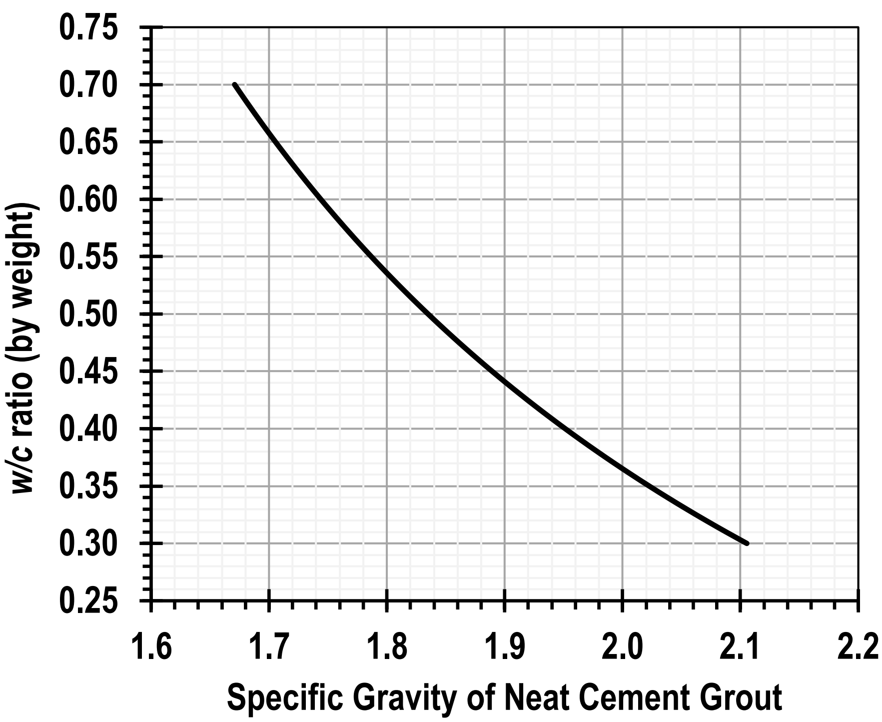

Figure 6-4 Relationship between specific gravity and *w/c* ratio by weight for neat cement grouts.

6.5 MICROPILE LOAD TESTING

Because post-construction integrity testing may not be performed on micropiles, a typical means of quality assurance for evaluation and acceptance of micropiles is through inspection records, which are frequently supplemented by static load tests on select micropiles. Because of its use for acceptance, static load testing is more common for micropiles than for other types of foundations discussed in this document.

Micropile static load tests are common for several reasons. The capacity of a single micropile is relatively small (e.g., compared to the capacity of a drilled shaft), so required test loads are more readily achievable without the need for massive load frames and hydraulic systems. In addition, the capacity of micropiles is dependent on installation methods, and static load testing provides a means of verifying that the installation methods are appropriate for the range of ground conditions encountered during construction. The dependence of micropile bond strength on contractor methods may provide a reason to verify design resistance values through load testing. Verifying resistance values through load testing may benefit owners (assurance of performance), engineers (reduction of design uncertainty), and contractors (demonstration of construction methods).

Micropile load tests can be categorized into two types of tests, each with a different objective. The two types of tests are summarized in Table 6-3. The first type of micropile load tests are proof tests, a common test performed on production micropiles during construction. Proof tests are used on production elements to demonstrate adequate resistance to support the factored load. Accordingly, the target test load for proof tests is commonly equal to the factored load. Upon reaching the target test load, the proof test is terminated. If the test micropile satisfies the load test acceptance criteria at the target load, the micropile is said to have passed; if the acceptance criteria are not satisfied, the micropile has failed and remedial measures may be required. Additional information regarding acceptance criteria and remedial measures are presented in Section 6.5.

The responsible engineer should establish project proof testing requirements, and the requirements should be defined in the project contract documents. FHWA-NHI-05-039 (Sabatini, et al. 2005) includes nonbinding recommendations of target load levels for proof tests and the number of proof tests to perform, citing the nonregulatory, nonbinding, and voluntary industry DFI/ADSC joint micropile committee specification (DFI and ADSC, 2004). However, the 2004 document largely predates LRFD implementation. In addition, ongoing NCHRP research regarding probabilistic calibration of resistance factors for micropiles may result in modifications to proof testing practices. For all projects, proof testing procedures, including the frequency of testing and the target test loads, should be clearly conveyed in the project contract documents, regardless of the guidance used to inform testing.

The second type of micropile load test is the verification test. Verification tests are similar to proof tests but are performed at the beginning of construction, typically on sacrificial micropiles. The objective of verification tests is to verify that the contractor’s methods result in micropile bond strengths that meet parameters assumed in design. Verification micropiles are loaded to a target load that typically exceeds the target load to be applied for proof tests. FHWA-NHI-05-039 (Sabatini, et al. 2005) suggests one verification micropile per project, but additional verification tests may be needed if significant geologic differences are present across a site, or if micropile characteristics or installation practices vary across the project. Verification tests may also be used during the design phase in order to refine the project micropile design. The special mobilization associated with design-phase tests may result in increased costs; accordingly, design-phase tests are generally only performed for large, critical, or especially challenging projects.

TABLE 6-3 TYPES OF MICROPILE LOAD TESTS

Load Test Type	Micropiles to be Tested	Timing	Typical Target Load
Proof	Production micropiles	During construction	May be specified in project contract documents; typically a factor of nominal resistance or factored load.
Verification	First micropile(s) installed during construction phase, typically sacrificial	At the start of construction	May be specified in project contract documents; typically greater than proof test target load

Micropile load tests are typically specified to be performed in general conformance with the following nonregulatory industry procedures: ASTM D1143 for compressive loading, ASTM D3689 for tensile loading, and ASTM D3966 for lateral loading. Tensile load tests are common since the ground can typically be used for the reaction force (as opposed to compressive tests, which need additional micropiles for reaction). The micropile designer should establish a loading schedule for all project micropile load tests. FHWA-NHI-05-039 (Sabatini, et al. 2005) includes additional information about load testing equipment and procedures, as well as possible schedules of applied loads based on DFI and ADSC (2004). The AASHTO Bridge Construction Specifications (AASHTO, 2017b) (23 CFR 625.4(d)(1)(v)) also include schedules of applied loads for proof and verification tests in the ground anchor section. Although the schedules are intended for ground anchors, they have been applied to micropiles. The design load specified in the loading schedule should be equal to the AASHTO LRFD factored load.

Project requirements may typically specify that a load test report be prepared and submitted to the owner for each load test within days of the test. FHWA suggests the items below should be included in the load test report:

- Brief description of the project;

- Description of the subsurface conditions, including a comparison of the subsurface conditions assumed in the design and those encountered during micropile installation;
- Key personnel including drill rig operator, superintendent, grout plan operator, and other personnel involved in micropile installation and testing;
- Micropile installation log;
- Load test results, including completed data sheets, plots of applied load versus displacement at the top of the micropile, and any other pertinent figures with results (e.g., axial force profiles for tests with strain gauges);
- Statement of load test requirements and acceptance criteria for the project;
- Comparison of load test requirements and acceptance criteria with observed performance during load test;
- Summary statement on the load test results (i.e., summary of how observed performance compares with acceptance criteria);
- Calibration reports for the hydraulic cylinder pressure gauge and load cell; and
- Material certifications, including grout compressive strength test results and steel mill certifications.

6.6 EVALUATION AND ACCEPTANCE

The flowchart of Figure 6-5 is an overview of evaluation and acceptance procedures for micropiles. As discussed in the previous section, load tests are a component of the acceptance procedure. One or more verification load tests typically may be performed prior to installation of production micropiles. Production micropiles may be designated for proof testing at the project onset, with the possibility of designating additional micropiles as production advances. Proof testing may also be used for foundation acceptance when inspection records and engineering evaluation are inconclusive. Acceptance of a micropile should consider the inspection records, appropriate engineering evaluation of the inspection records, and a passing proof test. If a micropile is not accepted, remedial measures may include replacing the micropile or accepting it with a reduced design load. Remedial measures are discussed at the end of this section. As indicated in the flowchart, remediated micropiles are typically proof tested (unless the remedial measure is to reduce the design load based on the initial proof test outcome).

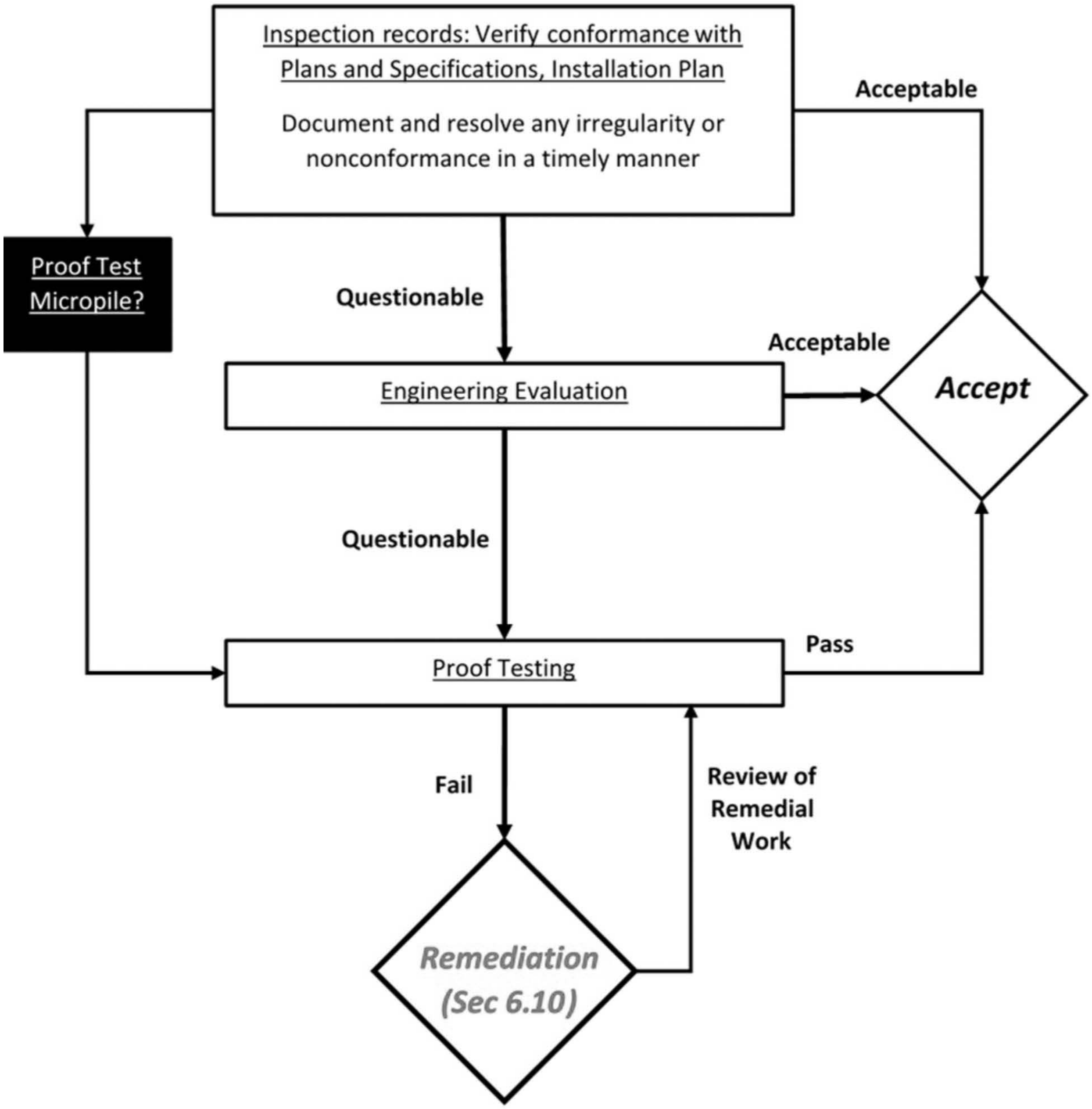

Figure 6-5 Overview of evaluation and acceptance process for micropiles

6.6.1 Documentation Recommendations

The previous sections on micropiles includes several lists of suggested information that should be recording during construction and load testing. The suggested documentation items that can be used for evaluation and acceptance of micropiles are summarized in Table 6-4. The documents should be reviewed by the responsible engineer. Photographs of construction and testing activities may be particularly useful during the evaluation and acceptance process. Given the ease of photograph capture, storage, and transmission facilitated by smart phones, photographs should be an integral component of micropile evaluation and acceptance.

TABLE 6-4 SUMMARY OF DOCUMENTATION

Activity	Documentation Items
General	• Micropile number or designation • Dates and times of installation and testing activities • Key personnel for inspection and testing activities • Photographs of inspection and testing activities
Drilling	• Drilling rig make and model • Type(s) and diameter of drill tooling used • Type and dimensions of casing • Casing depth/elevations, during installation and after partial casing extraction • Fluid levels within the micropile drill hole • Log of soil and rock types encountered with depth, including time for each depth • Final depth of micropile drill hole • Final length of bond zone • Records of micropile drill hole inclination • Any other observations of note during drilling operations
Placement of Reinforcing Steel	• Cross-section dimensions (e.g., diameter, wall thickness, etc.) • Lengths of reinforcing steel segments; total length installed, and stick-up length • Mill certificates • Certification of U.S. manufacturing for projects with Buy America contract provisions • Records of any damage to reinforcing steel, including couplers • Observation of any surface corrosion • Size and depth of centralizers • Depth of couplers
Grouting and Post-grouting	• Date and start and finish times of grouting • Target w/c ratio • Type of cement used • Type and quantity of admixtures used • Number of bags of cement used for mix • Measured specific gravity of grout • Record of sampling (i.e., number, dates, and times of grout cubes) • Log of pressure and volume of grout placed with depth • Plot of grout pressure versus grout volume

	• For post-grouted micropiles, the date and time of post-grouting and a log of pressure and volume for each grout tube.
Load Testing	• Project description • Comparison of observed vs. design subsurface conditions • Micropile installation log (i.e., all rows above) for the test micropile • Load test results: data sheets, load-displacement plots, any other figures • Comparison (with summary statement) of observed performance with acceptance criteria • Calibration reports • Material certifications

6.6.2 Evaluation Methods

This section describes the methods used for evaluation and acceptance of micropile installations. These methods include evaluation of construction observations and load test results.

Evaluation Based on Construction Inspection Observations

Evaluation based on construction inspection observations involves evaluation of the documentation records from Section 6.4 for conformance with plans and specifications, and the approved micropile installation plan. The responsible engineer should review documentation records to confirm bond length, bond length geology, and reinforcing steel geometry (cross-sectional as well as length). The responsible engineer should also review grouting records with care. Review of the grouting records should include evaluation of grout properties (*w/c* ratio and specific gravity, and grout cube strengths) and the grout pressure and volume logs. For post-grouted micropiles, plots of grout pressure versus volume should be reviewed to evaluate the effectiveness of post-grouting operations, particularly comparing the response to that for load tested micropiles. Any potential issues should be evaluated by engineering analysis or proof load testing.

Evaluation Based on Load Testing

The prevalence of load testing in micropile construction produces a basis for evaluation and acceptance. Clear definitions for a passing proof and verification tests should be established by the responsible engineer and conveyed through the project contract documents. Acceptance criteria for proof and verification tests are typically based on movement of the pile head and may include total movement, rate of movement, and creep movement. FHWA-NHI-05-039 (Sabatini et al. 2005) includes information for micropile load test evaluation, including suggested definitions for acceptable total, rate, and creep movement. It may be prudent to develop project-specific acceptance criteria to reflect local experience and practices or unique project circumstances (e.g., micropile length or cross-section, structure settlement sensitivity, etc.). In fact, several agencies, including

Illinois DOT, Indiana DOT, and Washington DOT, have adopted criteria based on the States' experiences.

6.6.3 Corrective Actions and Remedial Measures

Evaluation of micropiles may result in recommendations for corrective actions or remedial measures. Consistent with Figure 6-5, this section presents corrective actions and remedial measures for three types of micropile evaluations: verification micropiles, proof test micropiles, and micropiles not scheduled for load testing.

Verification Micropiles

Verification micropiles that fail to satisfy acceptance criteria may indicate problems with design assumptions, construction methods, or both. Accordingly, corrective actions to improve resistance generally involve significant changes to micropile design or installation procedures. Potential corrective actions include:

- Increase micropile bond length;
- Change micropile type, e.g., to include post-grouting;
- Revise post-grouting parameters, e.g., *w/c* ratio of grout, target grout pressure, hold time, volume limits;
- Revise grout parameters, e.g., *w/c* ratio, admixtures; and
- Increase micropile structural strength or stiffness (if structural resistance is suspected to control).

Upon implementation of corrective actions, an additional verification test (or tests) should be performed on micropiles constructed following the modified design or construction technique.

Proof Test Micropiles

If verification micropiles are successfully tested (with or without corrective measures), isolated proof tests that fail to satisfy acceptance criteria may indicate problems with installation methods for the specific test micropile or variation in subsurface conditions. A method for determining if the failed proof test result is isolated is to perform a proof test on a nearby micropile, preferably one installed on the same day as the failed micropile. In addition, installation documentation for the failed micropile should be reviewed carefully to identify potential explanations for the test result. If an explanation is identified, any problematic installation practices should be resolved quickly to limit impacts on subsequent micropiles. In addition, records for other micropiles on the project should be re-reviewed to evaluate the possibility that the installation problem occurred for other micropiles, particularly those that were not proof tested. Any such micropiles should be proof tested. If problems with proof test acceptance persist, the micropile design and installation methods should be revised according to the information provided for verification micropiles in the previous section.

After investigating explanations for the failed proof test result, remedial measures may be needed or the pile may be accepted "as-is". Evaluation of the foundation system involving the failed proof test micropile may reveal that the foundation has sufficient reserve strength with the reduced micropile resistance indicated by the load test. The reduced resistance should be determined from the proof test result, and appropriate resistance factors should be applied. If sufficient reserve capacity exists, it may be justifiable to accept the micropile as-is.

If the evaluation determines that action is necessary, potential remedial measures are described below.

- *Replacement micropiles:* Installation of replacement micropiles is a common remedial measure for failed proof tests. Replacement micropiles should be proof tested. Installation of replacement micropiles will change the load distribution within the pile cap and among the micropile group. Accordingly, engineers responsible for the structural design of the substructure should be involved early in discussions, evaluation, and design of micropiles.

- *Post-grouting:* In some circumstances, where grout pipes have been installed in the micropiles, it may be possible to post-grout the micropile to resolve an installation issue. Post-grouting remediations should be accompanied by performance of another proof test after the post-grouting.

Micropiles Not Scheduled for Load Testing

Evaluation of micropiles that are not scheduled for load testing is generally based on construction inspection documents. If review of the documents reveals items that are not in conformance with the plans and specifications, the responsible engineer should evaluate the impact of the non-conformance items on micropile performance. If the evaluation indicates potential performance problems, the micropile should be proof load tested. Since proof tests are generally performed throughout the duration of project micropile installation, proof testing questionable foundation elements is often more practical for micropiles than for other types of foundations. Indeed, the ability to proof test questionable micropiles is a valuable tool in the acceptance toolbox.

6.7 POTENTIAL ISSUES IN MICROPILE ASSESSMENT

The unique characteristics of micropiles, from application and design through installation and acceptance, lead to a unique set of common problems during micropile acceptance.

- Installation Documentation

Micropile installation can be a challenging type of construction. The challenges of micropile construction may heighten the need for the inspection, QA, QC, and documentation needed for micropile acceptance. Thorough records of micropile installation should be maintained to inform acceptance decisions and evaluate load test results. For example:

- Micropile installation outcomes may be dependent on contractor equipment and practices. Inspection and documentation of the drilling equipment, tooling, and details of installation helps to explain differences in construction outcomes such as drilling penetration rates, grout volume, and load test results. Because poor installation practices can result in damage to the ground that impacts micropile installation and eventual performance, records of installation practices are important for informed acceptance decisions.
- Observation and documentation of drilling penetration rates may be beneficial for verifying bond length material, and for comparing results among load tests. Records of drilling penetration rates accompanied by documentation of the drilling rig, operator, tooling, etc. may help to facilitate valid comparisons of penetration rates.
- A potential problem encountered during micropile installation is uncontrolled grouting. Uncontrolled grouting is an indication of unfavorable ground conditions that may lead to revision of construction practices and impact micropile performance. Inspection and documentation of the micropile grout volume is needed to identify and respond to potential problems.

In contrast, incomplete or insufficient records may not provide adequate basis for acceptance, especially for a micropile that is not load tested.

- Qualifications of Inspectors

Inspectors involved in QA and QC should be qualified. Inspectors who lack experience may not understand construction procedures, may not observe potential problems, and could produce records that may be less useful than those of experienced inspectors. Inspectors should be familiar with project requirements and thoughtfully engaged in the micropile construction activities throughout the installation process.

- Interpretation of Load Test Results

Axial load tests, typically a prominent component of acceptance, may be associated with several potentially common mistakes. Interpretation criteria based on micropile displacement should include the effect of elastic shortening (or lengthening) of the micropile. Criteria established based on total displacement without consideration of elastic shortening may be too stringent. Similarly, it may be appropriate to develop project-specific load test evaluation criteria rather than using generic specifications that may be too lax or too stringent.

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CHAPTER 7
ASSESSMENT AND ACCEPTANCE OF CONTINUOUS FLIGHT AUGER PILE FOUNDATIONS

This chapter describes evaluation and acceptance procedures for continuous flight auger (CFA) pile foundations and addresses special considerations for CFA piles. CFA piles are typically 18- to 48-inch diameter deep foundations installed by augering the full length of the pile in a single pass using a continuous flight auger (see Figure 7-1). When the auger reaches the pile tip elevation, the pile is filled with grout (a sand-cement mixture) or concrete (a pea-gravel-cement mixture) pumped through the hollow center of the auger as it is withdrawn. The central point of this method is that the pile excavation is stabilized by the presence of the soil-filled auger flights during drilling until the auger and soil is extracted and replaced by the concrete or grout. Reinforcement is then placed into the fluid concrete or grout before initial set, a process often referred to as “wet-sticking” the rebar cage. Drilled displacement (DD) piles are included as a special variation of CFA piles; the process is similar except that the auger is equipped with a tool that displaces the soil laterally as the auger advances, thereby minimizing the soil that is extracted. Drilled Displacement (DD) piles have more limited application due to the much greater torque required to displace soil during augering instead of simply excavating it. More extensive and detailed information on design and construction of CFA and DD pile foundations, including details regarding verification testing and other components of quality assurance, is provided in FHWA GEC 8 (Brown, et al., 2007). Since the use of sand-cement grout for CFA piles is a common practice in North America, this chapter will reference the term “grout” as the general term for the structural material that forms these piles. Concrete with small coarse aggregate is also used following the same general construction process.

The chapter includes descriptions of the typical process for design, construction, QA, and QC) of CFA pile foundations to provide information about appropriate perspective regarding where each activity “fits” into producing foundations that reliably satisfy performance requirements.

7.1 DESIGN

Construction of CFA pile foundations may be driven by performance demands related to axial resistance and verification during construction that the necessary embedment has been achieved to develop the required axial resistance. The relatively smaller lateral strength of these piles (compared to larger drilled shafts) is normally developed within the upper 10 or so pile diameters, and within this depth range the installation of reinforcement and structural integrity of the pile are most important. In some circumstances, the design may also utilize a lesser amount of reinforcement for the lowermost length of the pile with enough strength to provide tensile strength for uplift forces. Installation of even a single bar extending the full length of the pile can provide an additional measure of pile integrity below the reinforcing cage.

Figure 7-1 CFA Piling Rig (photo by authors)

The axial resistance that can be mobilized by CFA piles is affected by numerous factors, including:

- side resistance along the length of the pile, which typically provides most of the axial resistance, is controlled by the strength of the soil at the pile/soil interface *after the pile is installed*. To develop the side resistance, the drill rig must be able to advance to a sufficient depth into the bearing formation and must be able to do so without adversely affecting the strength of the soil.

- base resistance at the pile toe sometimes provides only a small contribution to the total resistance, but it can be significant if the pile bears on a particularly hard stratum. If the design includes base resistance, then the process of verifying that the pile has reached the target bearing layer and the initiation of grout placement to achieve the needed bearing at the pile toe both represent a more significant part of the quality control and quality assurance process.

Recent developments in equipment now allow agencies to utilize CFA piles up to a 48-inch diameter, which means that CFA piles can provide large flexural strength, making them a more feasible alternative for transportation structures (Figure 7-2).

It is worth noting that, although CFA piles have been widely used in commercial construction for building and industrial structures in North America, their use in transportation infrastructure work has been limited and public agencies may not have a great deal of experience with these piles. The quality control and quality assurance procedures summarized in this chapter may provide an opportunity to use this foundation type with greater confidence in the reliability and integrity of the completed foundations. Adoption of this technology may benefit from a thorough testing program.

Figure 7-2 Placing Reinforcement in a 48-inch diameter CFA Pile (photo by authors)

Implementation of CFA pile foundations should include a testing program to demonstrate constructability, quality assurance methods, and performance verification using static load tests. It may be useful to supplement static load tests with rapid load tests or high strain dynamic test measurements as a means of quality assurance. The design of CFA pile foundations is not presently covered by the AASHTO Bridge Design Specifications (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)), although selection of resistance factors and structural design methodology (as applicable to CFA piles) should be similar to those used for drilled shaft foundations. Procedures for design of CFA pile foundations are provided in FHWA GEC 8 (Brown, et al., 2007).

To address constructability during design of CFA pile foundations, it is important that site characterization be appropriate for the planned structure and anticipated ground conditions and be used to identify potential risks related to pile installation, as discussed in Section 7.1.1. Also, the demands and potential risks associated with pile installation should be documented and clearly communicated to the contractor.

7.1.1 Site Characterization

For CFA piles, a thorough site characterization program may be important in deciding whether CFA piles might be a viable option, estimating the production pile lengths reliably, identifying potential pile installation risks, and mitigating uncertainties related to the pile installation operations. Potential ground conditions that may pose risks and uncertainties include extremely soft or loose soils, potential obstructions or hard layers above the minimum penetration depth, artesian groundwater conditions, or very dry soils. Constructability concerns with these conditions are summarized in the following section.

Since variability in stratigraphy at the site can result in large variations in pile length, it is important that stratigraphy be established prior to pile type selection so that the viability of CFA piles can be confirmed. A supplemental investigation may sometimes be performed to fill gaps in the subsurface information and more reliably estimate pile lengths, but it may be useful to reduce uncertainties regarding stratigraphic variability and pile lengths for sites where CFA piles are likely to be an attractive option. Equipment constraints are such that length limitations exist for CFA piles of different diameters.

Where temporary works such as shoring for footings, cofferdams, or work trestles are required, site characterization should be performed to provide information necessary for the contractor to prepare a design of these features and estimate costs. Information on shallow soils and groundwater conditions that may have little importance for the performance of permanent foundations can be very important for design of temporary works for construction.

For design-build project delivery, the contractor team should select pile type and estimate pile lengths based on available pre-bid information and include bid contingency for potential risks and uncertainty in estimated costs. By reducing uncertainty related to geotechnical issues, the risk contingencies may be reduced, and the owner may benefit from competitive bid prices and potentially reduced risk of construction claims.

7.1.2 CFA Pile Type Selection and Design

Besides obvious design considerations affecting foundation type selection, considerations of constructability and quality assurance for acceptance are important components of foundation selection. A thorough vetting of construction challenges and potential risks associated with each foundation type should be considered with respect to final foundation type selection during design.

Design of CFA piles should include consideration of constructability challenges, such as:

- Extremely soft soils that may be unstable for a grout-filled hole after auger removal;
- Very loose granular soils with shallow groundwater, which can potentially result in soil loss and ground subsidence around the pile if/when the augers encounter a hard underlying stratum;
- Very stiff cohesive or cemented soils (e.g., caliche, sandstone layers) that can be difficult to penetrate; rock is not normally penetrated with CFA pile equipment (although many soft Florida limestones have been drilled successfully using appropriate tooling);
- Artesian groundwater conditions that can produce upward flow through the fluid grout; and
- Extremely dry granular soils that may require special consideration for the grout mix due to a tendency for the soil to dewater the grout and cause difficulties in placing reinforcement.

DD piles may be well suited to soft soils or loose granular materials, but these may piles have more significant limitations relative to depth and penetration of dense or strong soils.

A pile testing program provides an opportunity for evaluation of installation challenges prior to the start of production pile installation. The scope and extent of pre-production testing varies with the size of the project and the magnitude of uncertainties related to pile installation and performance. Pre-production tests can be used to evaluate pile performance, identify rig performance during drilling, and establish criteria to be used for production piles. In some cases, penetration of bearing strata can be identified by the behavior of the rig during auger advancement. Other drilling parameters, such as rotation speed and penetration rate, may also be established to minimize the risk of soil loss in soft or loose soil. The target volume of grout placed during auger extraction is also typically established during the pile testing program for the specific site conditions.

7.1.3 Pile Caps and Connections

Design of pile caps and pile-to-structure connections, and construction details associated with these connections are an important part of design for constructability. Temporary works needed to construct the pile cap can be a potentially significant challenge for projects with tight working spaces, conflicts with utilities, or other nearby structures. Dewatering of footing excavations can also be a significant and costly challenge for situations such as contaminated sites or sites with shallow groundwater conditions. Finishing at the top of the pile can be a challenge where very soft surface soils are present, because the hole must be stable at the top as the pile top is cleaned, topped off with grout, and the reinforcement placed.

7.1.4 Communication of Design Information Needed for Acceptance

To achieve the required quality and acceptance of CFA piles, contract documents should clearly convey all requirements needed to achieve acceptance. Requirements should include, but are not limited to:

- the required nominal resistance that should be achieved for each pile;
- the additional nominal resistance needed to accommodate downdrag from soil layers that may settle after installation of the piles;
- minimum pile penetration at each pile location;
- material strength needed and the process for verification;
- installation tolerances (location, alignment, proximity of the work to freshly placed piles);
- any details related to the pile cap connection that affects pile installation; and
- methodology to be used to establish pile installation criteria.

The final installation criteria used for production piling may vary based on stratigraphy and test pile measurements. Examples might include target tip elevation, drill rig refusal criterion, possibly penetration into bearing stratum (including a definition of how that is determined), and any drilling parameters determined during the test pile program to minimize the risk of soil loss and ground subsidence in soft or loose soil. The methodology used for developing the installation criteria should be transparent and clearly communicated to all the participants in the project (e.g., constructors, inspectors, construction managers) so that the process can be understood and documented throughout the project.

7.2 CONSTRUCTION

Contractors should understand the basic objectives of the pile design and the general nature of subsurface conditions, and how those conditions might impact their ability to install the piles successfully. They should then use this understanding to develop an appropriate construction plan with equipment that is suitable for the conditions of the project, adaptable to reasonable variations in subsurface conditions, and with contingencies for potential problems or potentially risk items. Finally, implementation of the construction plan should include a thorough quality control system to manage and document the day-to-day work to install foundations that will satisfy the acceptance criteria.

7.2.1 Installation Plan

The installation plan for CFA pile foundations should demonstrate an understanding of the project requirements for acceptance of the piles and should include details of the operations and equipment to be used to achieve these requirements. The plan should be complete and appropriate to cover the range of anticipated ground conditions, and adaptable to reasonable variations in subsurface conditions with contingencies for potential problems or potential risk items. The installation plan should be developed prior to the start of any test piles and production foundation works and should be critically reviewed by the design and inspection team prior to commencing pile installation so that all parties understand how the work should be performed. The installation plan should also address the quality control systems that the contractor should employ during construction to maintain consistent quality and to identify any potential issues that may require adjustment as the work progresses.

The timing and sequence of installing piles within a group should also be addressed so that piles are not drilled within specified distance limits of freshly placed grout, which could potentially cause communication between holes and undermine the structural integrity of the pile.

Specific to CFA pile foundations, the installation plan should include a description of:

- the tool and equipment suitability for the specific ground conditions at the site, including the cutting heads to be used and the type of discharge port for grouting;
- a plan showing the sequence of pile installation within each group;
- preliminary drilling and grouting parameters (along with acceptable ranges) for pile installation, including auger rotation speed, drilling penetration and withdrawal rates, torque, applied crowd pressures, and target grout volume factors;
- equipment and procedures for measuring and recording the drilling and grouting parameters during pile installation;
- how volume measurements should be calibrated and periodically checked;
- methods to place the reinforcement, including method of centering reinforcement in the pile and details of temporary support of the reinforcement after pile completion;
- mix designs for all grout or concrete to be used;
- methods to initiate grout placement and establish a grout head above the bottom of the auger;
- methods to finish the top of the pile and ensure clean grout in a stable hole at the top;
- contingency plans for equipment failures during drilling or grouting operations; and
- procedures for protecting adjacent structures, including a monitoring plan.

The installation plan should also address contingencies for potential difficulties that might be encountered during drilling or grouting, such as failure to achieve minimum pile penetration, excessive soil mining, insufficient grout volume placed, or interruption in grouting. Normally, encountering such issues during pile installation would necessitate re-drilling of the pile in the same location.

Finally, the plan should also address any provisions necessary during construction to accommodate or complete post-installation integrity testing, such as sonic echo testing at the pile top or crosshole sonic or thermal integrity measurements. The latter two measurements typically require incorporation of access tubes or instrumentation into the reinforcement.

The inclusion of pre-production test piles may be a useful tool, as this work affords the opportunity for the installation plan to be demonstrated to be effective and any adjustments or modifications to the plan be developed, agreed upon, and implemented prior to the start of production foundation work. This work allows development of pile installation criteria, and drilling and grouting parameters for site-specific ground conditions prior to the start of production pile installation, therefore enhancing the efficiency and reliability of this work.

7.2.2 Quality Control During Construction

Quality control procedures for CFA pile installation should be included in the installation plan and should address items such as:

- checks on location, alignment, and position of the pile;
- methods to measure and monitor drilling parameters (auger rotation, depth, torque, and crowd) to ensure that soil loss is controlled and the required minimum pile diameter is achieved for the entire length of the pile;
- methods to measure and monitor auger withdrawal rate and grout volume and pressure during placement, including incremental measurements along the length of the pile; and
- systems to record and document the measurements described above.

Documentation of the observations and records related to quality control checks should be important components in the quality assurance plan. Automated monitoring equipment may provide “real time” evaluation of each pile, as well as a potentially accurate record of the work.

A pre-production testing plan should normally be an integral part of a CFA pile project, and the range of control parameters for drilling and grouting established at the test piles may provide a basis for finalizing the installation plan and quality control plan.

7.2.3 Performance Monitoring and Control During Construction

Technology is available to obtain the measurements and feedback needed to provide operators with information for developing judgment and control of CFA pile construction operations, since visual observations alone may be insufficient to provide the necessary quality control of CFA piles for transportation structure foundations. The information obtained provides documentation of pile installation for quality assurance and should be an integral part of the CFA pile construction process. Performance monitoring systems should provide:

- Monitoring and control of the drilling phase; records of the rate of penetration, torque, and crowd forces of the machine as a function of the depth of the auger.
- Monitoring and control of the grouting phase; records of the movement of the auger during grouting, along with the grout pressure and volume of grout pumped as a function of auger depth.

In-cab display of this information as illustrated in Figure 7-3 may provide the operator with better control of the drilling and grouting operation while maintaining consistent quality. If a problem develops during pile installation, the construction team can immediately take corrective action or institute remedial plans (such as abandonment and redrilling) so that completion of a defective pile is avoided. More information on the systems used for performance monitoring is provided in GEC 8.

Inspection can be facilitated when the inspector has open access to the automated monitoring output via tablet or some other similar method of observation. The quality assurance program may benefit from information sharing among the designer, project engineer, contractor, and inspectors.

Figure 7-3 In-cab Display of Performance Monitoring System (photo by authors)

7.3 INSPECTION AND QUALITY ASSURANCE

Acceptance of CFA piles is informed by, among other things, the observations, documentation, and communication of the work by on-site inspectors; the QC program; and the records of performance monitoring during construction. FHWA GEC 8 (Brown et al. 2007) describes the various activities of inspectors and includes checklists of tasks and items that should be reviewed and example forms. Specific details vary with pile and drill rig type, agency requirements, and project delivery methods.

Inspectors should review the foundation design report, project plans, and specifications, and discuss them with the designer. The inspector should understand the design objectives and any potential special risks or concerns related to the planned construction. The preconstruction review should also include a clear understanding of the contractor's approved installation plan, and the inspectors should be included in any preconstruction meetings related to the piling.

In general, the items to be inspected can be grouped as:

- Inspection of work related to compliance with the contract specifications and approved installation plan.
- Inspection of pile installation equipment, including grouting equipment and calibration before and during operation.
- Inspection of test piles installation.
- Inspection during production pile drilling and grouting, pile finishing, and maintenance of records.
- Inspection of materials, including reinforcement and grout characteristics, along with collection of grout samples for testing.

In general, the inspector should be the person in the field who verifies that the pile has been installed to the satisfaction of the installation criteria and to the target tip elevation. In some cases, particularly with drilled displacement piles, the inspector may determine that the pile drilling may stop at an elevation above the target tip elevation when certain drilling criteria are met (including any minimum penetration requirements). All these activities should be clearly defined and understood by the parties prior to the start of construction.

Since records from automated monitoring equipment may not be available to the inspector in real time, communication between the operator and inspector is important so that any issues that may affect acceptance can be dealt with in a timely manner. Based on the assessment of drilling and grouting operations during pile installation, the inspector may conclude that anomalies have occurred that preclude pile acceptance; in such a circumstance a typical procedure could be to extract the augers from the pile while reversing rotation to leave excavated soil (or grout) behind, followed by re-drilling and re-grouting the pile.

If circumstances such as soil loss are thought to have occurred, the responsible engineer should be consulted in a timely manner to decide if additional measures are needed to compensate for reduced axial resistance. For example, augers becoming unable to advance during drilling in a deep hard layer and continuing to rotate may result in soil extracted from shallower loose granular soils, even visibly causing ground subsidence around the pile. The engineer may require some additional pile length to be added to compensate, or additional piles may be installed within a foundation group. Any such occurrences and corrective measures should be documented in detail in the inspection records. It is noted that soil loss from excessive auger rotation is dependent on soil conditions and auger rotation may not be much of a concern in a predominantly cohesive soil profile.

If persistent anomalies are observed, communication between the engineer and the contractor may be needed to evaluate the source of the difficulty and make appropriate adjustments to the installation procedures or criteria. Likewise, if the inspector observes conditions that may be indicative of unusual ground conditions, the responsible engineer should be consulted.

Finally, the preparation of the top of the pile, such as installing a surface casing, cleaning debris from the grout, supporting the cage, or completing a connection detail to pile cap, should be inspected and documented.

Communication between inspectors and the design engineer should be maintained to promote post construction evaluation and acceptance.

7.4 EVALUATION AND ACCEPTANCE

This section reviews assessment methods and the documentation needed for acceptance of CFA pile foundations. The evaluation needed for acceptance of CFA piles typically occurs during construction and may be based on pile load tests, performance monitoring during installation, achievement of the installation criteria, and documentation by the inspector. Post-installation assessment may also include non-destructive testing/non-destructive evaluation for verification of pile integrity.

7.4.1 Assessment Methods and Documentation

Initial assessment of CFA piles may be based on several observations including, but not limited to:

- Achieving the installation criteria during drilling;
- Achieving the grout volume and pressure parameters during grouting;
- Documentation of the pile completion (rebar placement, pile head finishing and protection) by the inspector; and
- A review of the material test records.

Records from an automated performance monitoring system should be a part of the inspection documentation included for review. Two example graphical output plots for a pile are provided in Figure 7-4 and Figure 7-5. These graphics may display different parameters depending upon project-specific conditions and job requirements.

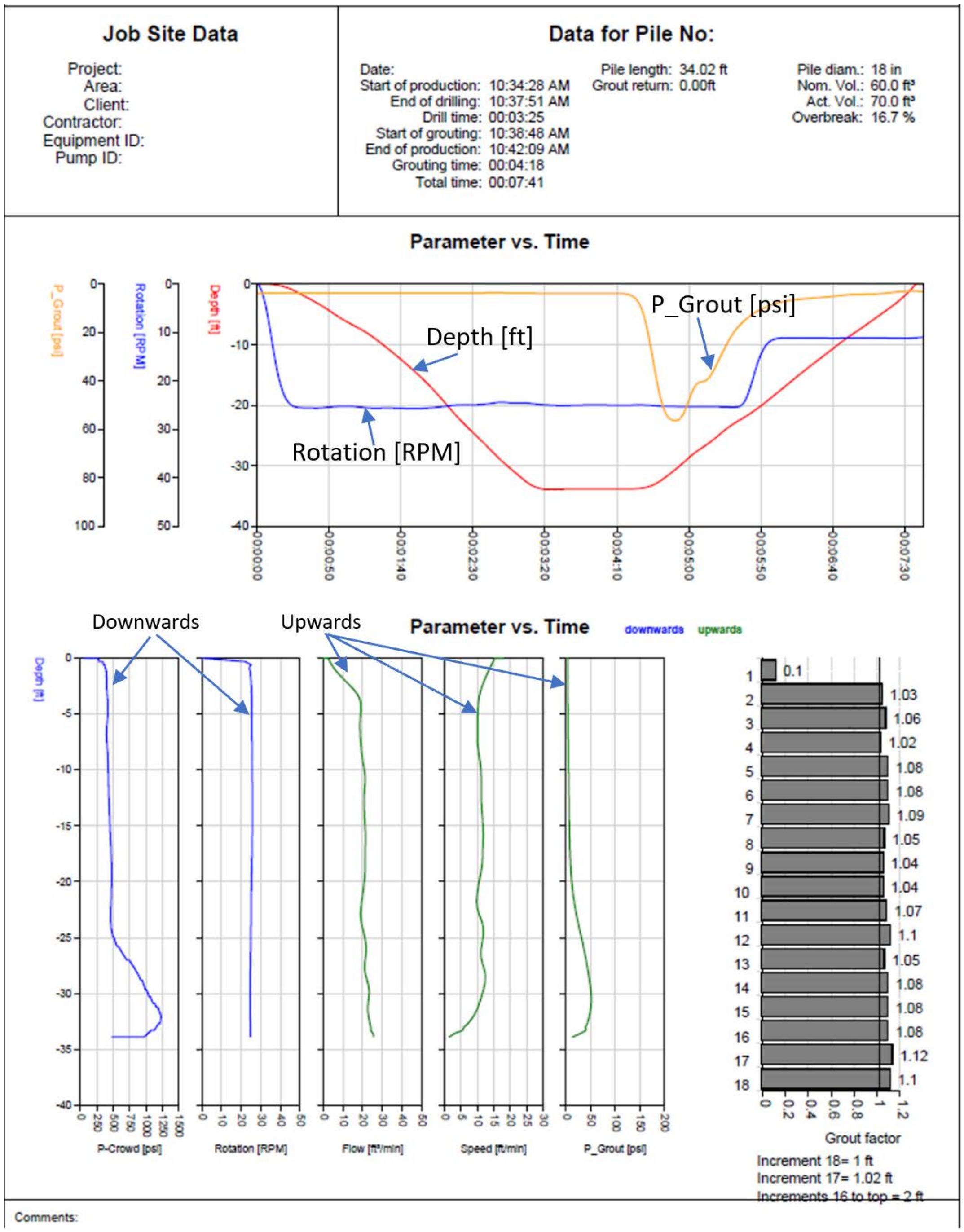

Figure 7-4 Graphical Output from Automated Monitoring System on a CFA Pile Drilling Rig – Example 1 (source: authors project records)

Figure 7-4 provides an example plot of measurements for a relatively simple case of a 35-ft long drilled displacement pile extending into medium to stiff clay. The plot on the lower left labeled "P-Crowd (psi)" is a measure of the hydraulic pressure applying crowd force (or hydraulic pressure measuring downward force applied to the augers) and is plotted as a function of depth; different systems use different labels for this parameter. Other items plotted versus depth include rotation speed of the auger, flow volume of grout, speed of the augers during extraction, and pressure on the grout during pumping. The "grout factor" is a measure of grout volume divided by theoretical volume; these relatively low numbers (slightly greater than 1.0) reflect the simple ground conditions at this site as well as the drilled displacement pile construction method.

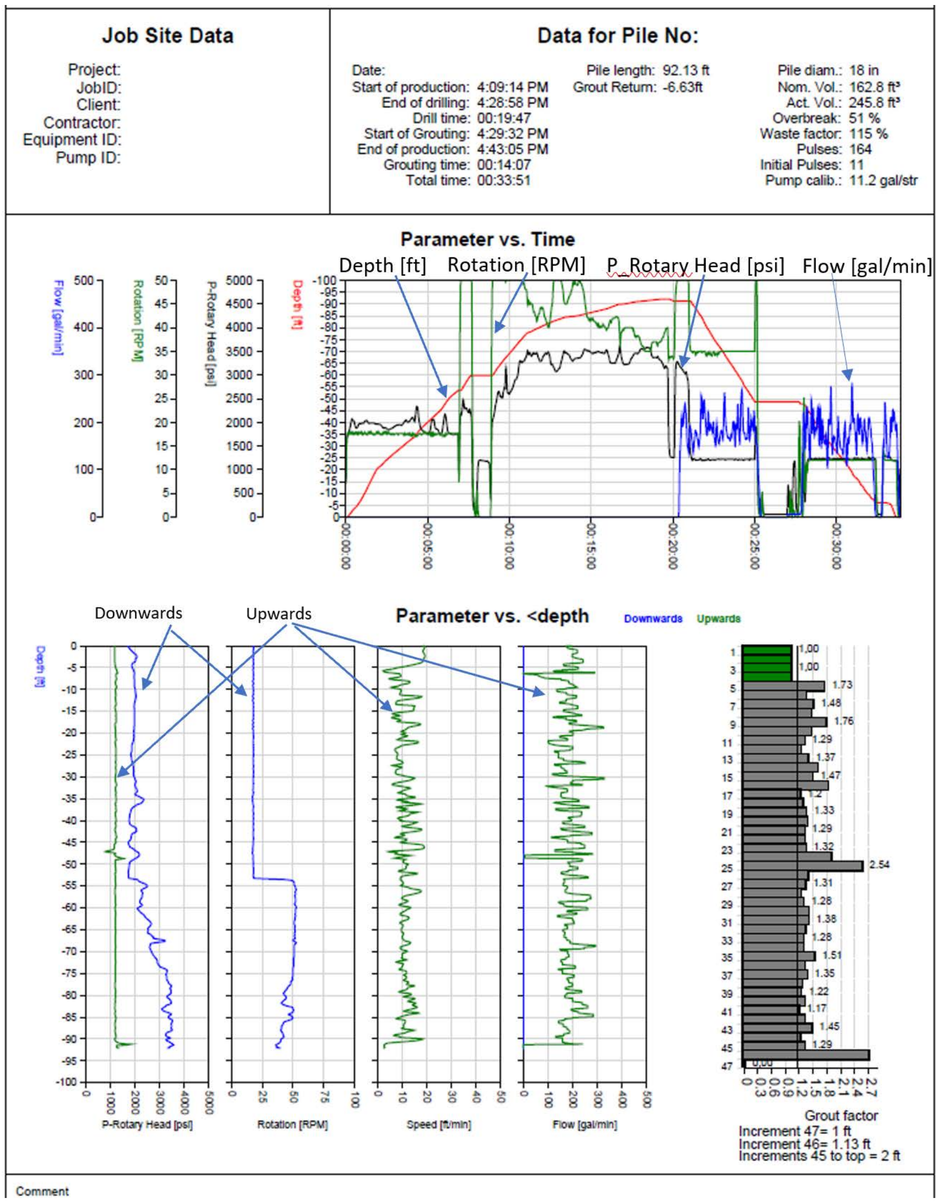

Figure 7-5 Graphical Output from Automated Monitoring System on a CFA Pile Drilling Rig – Example 2 (source: authors project records)

Figure 7-5 provides an example plot of the measurements for a 92-ft long pile extending through about 55 feet of soft clay into dense sand. The plot on the lower left labeled "P-Rotary Head (psi)" is a measure of the hydraulic pressure applying torque; different systems use different labels for this parameter. This plot shows the applied torque increasing at about 55-ft depth, and the operator increases the rotation speed (the next plot to the right) at the same depth. Other plots show the speed of the auger withdrawal and the grout flow volumes. The grout factor for this site is higher than for the site in Figure 7-4 and likely reflects the different ground conditions here.

Post-construction integrity testing is typically part of CFA assessment and may include non-destructive tests (NDT), such as sonic echo (SE), crosshole sonic logging (CSL), or thermal integrity profiling (TIP). The SE and CSL methods are described in FHWA GEC 8 (Brown et al. 2007), as well as in FHWA GEC 10 (Brown et al. 2018) for drilled shaft foundations; TIP was not routinely used for CFA piling at the time of FHWA GEC 8 (Brown et al. 2007) but has more recently been used for this application in a manner similar to that used for drilled shafts, as described in FHWA GEC 10 (Brown, et al., 2018). A useful and more recent reference on NDT for CFA piles is provided by DFI (2012), which summarizes available NDT methods along with potential advantages and limitations of each. This document also provides example records and graphical presentation of the output from different NDT methods, illustrating identification of potential flaws in CFA piles.

SE can be performed rapidly, inexpensively, and without any internal instrumentation or access tubes in the pile. This test method should be considered the minimum post-construction NDT technique for all CFA piles and may be sufficient for many routine projects. The test is simple to perform and involves impacting the top of the pile with a low strain compression wave and profiling the pile based upon the return signal to obtain an impedance (related to pile area and modulus) profile for verification of pile integrity. The main limitation of the test is that it is sensitive only to relatively large pile imperfections and may sometimes be weak in detecting reflections at great depth in long, slender piles (i.e., depth to diameter ratio of greater than 30). Still, the test method may be considered a simple and reliable method to detect potentially significant deficiencies in the zone of the pile where flexural strength demands are important and may be easily implemented at low cost.

The evaluation of SE measurements for CFA piles calls for some judgment and experience in the interpretation of the results regarding identification of the pile toe and any reflections of the signal above the pile toe. The assessment of the pile integrity may follow the logic summarized as follows:

- a clear identification of the pile toe reflection with no strong reflections above the toe is consistent with a sound pile;
- a weak or unidentifiable pile toe reflection with no strong reflections above the toe is consistent with a sound pile to the maximum depth of the signal; attenuation of the signal prior to reaching the pile toe precludes verification of pile

integrity for the entire length, but the lack of a strong reflection provides verification that the pile has no major defects in the upper portion of the pile;
- a clear identification of the pile toe reflection with significant impedance reductions above the toe suggests that the pile may have some reduction in area above the toe; and
- a clear identification of a strong reflection indicative of significant impedance reductions above the toe is consistent with an unsound pile.

CSL and TIP methods need downhole tubes for access (or embedded sensor cables as an option for TIP) and therefore involve adding tubes or gauges to the reinforcement cage. In this situation, these techniques are generally considered to have greater reliability in detecting imperfections in a completed pile and are recommended for larger diameter piles within the zones of high flexural demand where a full cage is needed. Piles extending through weak soil layers into a strong bearing layer is another circumstance in which structural integrity into the bearing layer may be more critical, particularly if there are complicating geological features, such as in weak limestone. Some methods for CSL and TIP may be employed with a single center bar, but the test results have limitations compared to experiences with full cage systems as used for drilled shafts. Additionally, if a full cage is not needed, then the structural demand is usually low and sonic echo testing is likely to be considered sufficient to verify pile integrity.

Evaluation of CSL and TIP measurements for CFA piles follows the general approach used for drilled shafts as described in Chapter 5 and will not be repeated here.

The decision on the type and level of post-construction NDT employed for CFA piling on a transportation project suggests consideration of the following factors:

- the structural demands on the pile with depth;
- the level of redundancy inherent in the pile foundation system;
- the potential for risks associated with the geology, e.g., karstic features, very weak or unstable layers;
- the reliability of the automated monitoring system; and
- the experience of the agency, contractor, and engineer with CFA piling.

In some circumstances, a hybrid approach using SE supplemented by more rigorous techniques in select or critical locations may be employed. Finally, the documentation for CFA piles should include resolution of any non-compliance issues or identification of such issues for post-construction assessment.

A flow chart in Figure 7-6 describes components of the assessment process for CFA piles.

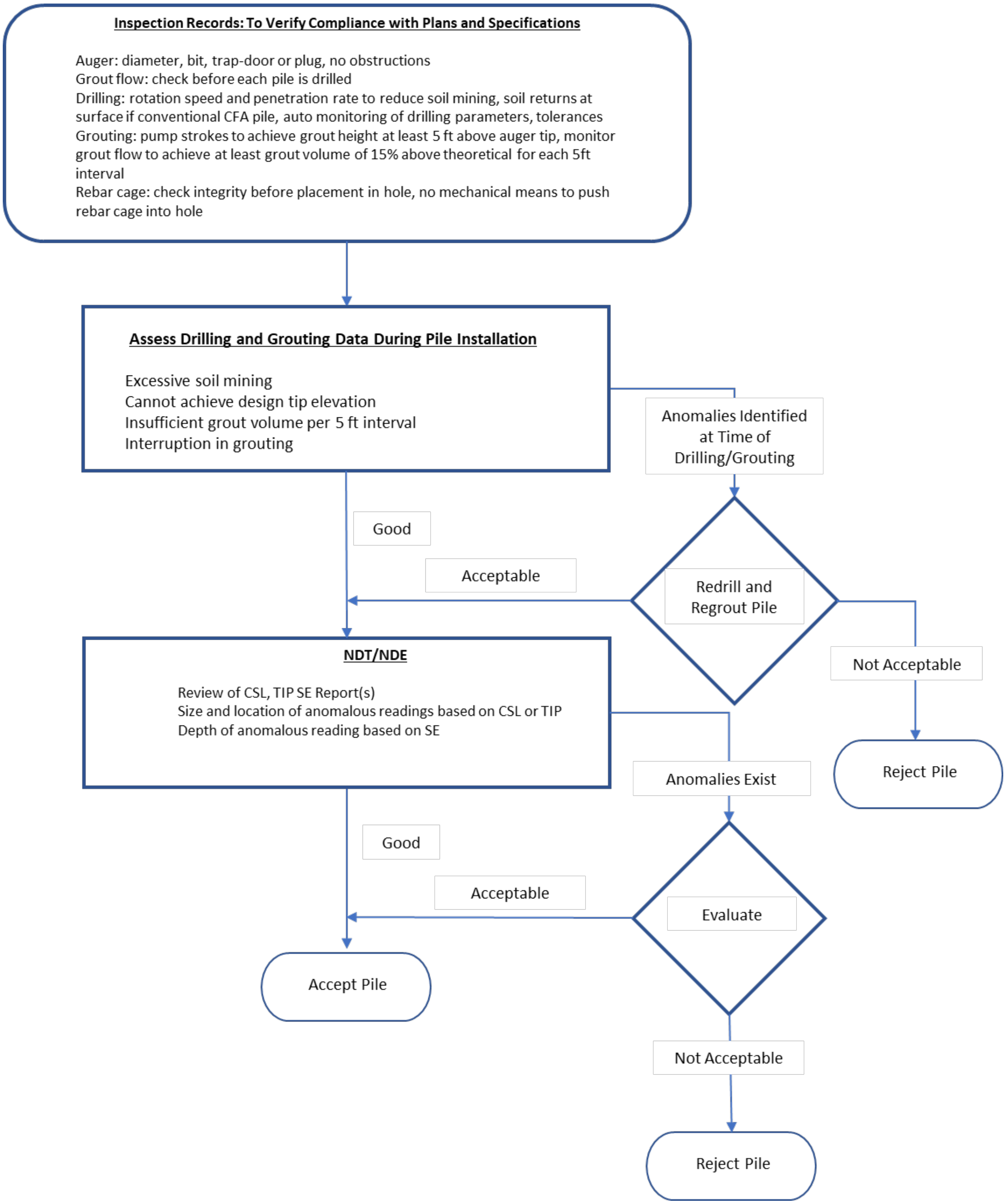

Figure 7-6 Key components of the CFA pile installation process

7.4.2 Post-construction Assessment

Following the general flow chart outlined in Chapter 2, post-construction assessment by the responsible engineer should largely be a review of inspection documents highlighted in the previous section, plus a review of any post-construction testing or inspection that might be needed.

With a complete inspection record of all piles in a foundation, along with the appropriate level of post-construction integrity tests as applicable, the responsible engineer may have the information to evaluate the installation of the piles for the foundation as an entire entity and assess the foundation for acceptance. Where any irregularities or unusual circumstances are identified, these may be placed in context relative to the overall foundation demands. For example, CFA pile foundations often incorporate a large degree of redundancy that may be tolerant of minor imperfections or irregularities in an individual pile. Although all piles in a group are typically installed to the same depth or criteria based on the pile with the highest demand, the actual demand on some piles is typically lower and may allow acceptance of a pile that may not have achieved the criteria during installation. So, the evaluation process may offer an opportunity to achieve acceptance based on rational engineering principles applied to the entire group rather than an individual pile.

When an imperfection is suspected in a completed pile, the magnitude and depth of the imperfection should be considered as a part of an engineering evaluation of the potential impact on the pile performance. For example, most CFA piles derive the majority of axial resistance through side resistance along the length of the pile. Therefore, an imperfection in the lowermost portion of the pile may compromise only a small portion of the nominal axial resistance of the pile and the impact of a reduced resistance from one pile on the performance of the pile group should be evaluated. A modest reduction in pile area or pile impedance, but not a full loss of cross-section, in the lower sections of the pile may still be sufficient to transfer some smaller force to the lowermost section of the pile so that the axial resistance below the imperfection is not lost. These considerations call for engineering evaluation of the imperfection.

In some cases, it may be possible to perform post-installation axial load tests to evaluate the axial resistance of a suspect CFA pile, particularly using high strain dynamic or rapid load testing methods. However, since CFA piles are relatively low cost on a per pile basis, in some cases it may be more cost effective to simply install another pile within the foundation.

Where the evaluation cannot determine the foundation to be acceptable, remedial work may be required, as discussed in Section 7.4.3.

The responsible engineer should document results of the post-construction assessment and any engineering evaluation or other resolution of anomalies, questions, imperfections, or non-conformance issues.

7.4.3 Remediation

Should the evaluation of a completed CFA pile identify that a deficiency exists or is likely to exist, remediation work may be necessary. Examples might include a pile with a structural defect, or a badly out of position pile, or a pile that for whatever reason cannot achieve the needed axial resistance.

With good QA and automated monitoring, many problems with CFA piles may be identified before a pile is completed and reinforcement placed. When a problem is identified during production pile drilling, it is typically possible to simply re-drill the pile in the same location and thereby construct an acceptable pile as originally designed.

When a pile is determined to be deficient and the remaining piles in the group cannot accommodate the additional demand from the deficiency, then a common solution is to simply add a replacement pile (or piles). This remediation may need structural modification of the pile cap and therefore call for coordination with the responsible engineer for the substructure. Modification of the pile group configuration also affects the distribution of load within the piles in the group.

Repair of an individual CFA pile may not be a cost-effective solution compared to simply adding another pile. For larger (for example, 48-inch diameter) CFA piles with a deficiency near the top of the pile, repair options could be considered along the same lines as might be performed for a drilled shaft. Chapter 5 discusses potential repair options used for drilled shaft foundations.

Because of the potentially cascading effect of changes to the pile group layout, the designers and contractor should confer and develop a remediation plan. Implementation of the remediation plan should include inspection, quality assurance, and documentation so that the assessment process can achieve acceptance after the work is completed.

7.4.4 Acceptance

Completion of the assessment includes collecting and maintaining the records used in the acceptance process, including the post-construction testing and a report of the outcome of the evaluation (with documentation of any analyses performed) and resolution of any discrepancies or non-conformance issues, and the records of any remediation or corrective actions taken.

7.5 POTENTIAL ISSUES IN CFA PILE ASSESSMENT

As described in this chapter, assessment of as-built CFA pile foundations may rely on observations made and recorded by inspection personnel and automated monitoring equipment during the installation process, supplemented by load testing and post-construction NDT. These sources of information should be complementary and interdependent, with each having strengths and limitations as assessment tools.

- Test pile program

With CFA piles, a test pile program may provide useful correlation between the drilling parameters and performance requirements for the specific ground conditions at the site, and the measured axial resistance of test piles provides verification that the drilling and grouting parameters used for the test piles can achieve the target resistance. Where significant variations in stratigraphy or ground conditions exists, a test pile program covering a representative range of conditions is needed.

- Inspection and documentation

The use of automated monitoring equipment supplements the observations of the inspector and allows drill rig operator to exercise better quality control during drilling and grouting operations; however, these systems should not be a substitute for inspection by trained and experienced personnel. The inspector can observe potentially unusual occurrences and many facets of the installation process that may not be detected by automated systems, such as initiation of grouting, completion of grouting after the grout appears at the ground surface, placement of reinforcement, finishing the top of the pile, and materials sampling. Insufficient or incomplete documentation may not allow effective interpretation of potential anomalies identified by NDT.

- QC problems during construction

As described in this chapter, a QC problem during pile installation may be correctable during construction by extracting augers and redrilling a pile. After the grout has hardened, potential problems that could compromise acceptance may not be easily remediated.

- Interpretation of NDT measurements

NDT methods are used to complement inspection and should not be relied upon exclusively as a basis of acceptance. Anomalous NDT measurements call for interpretation by an experienced operator to assess the potential for an imperfection and by the responsible engineer to assess any potential deficiency.

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CHAPTER 8
References

ADSC: The International Association of Foundation Drilling and DFI: Deep Foundations Institute. (2004). "Drilled Shaft Inspector's Manual," 2nd Ed., ADSC/DFI Joint Caisson-Drilled Shaft Committee. Dallas, TX.

Agrawal, A.K., F. Jalinoos, N. Davis, and M. Sanayei (2018) Foundation Reuse for Highway Bridges, FHWA Report FHWA-HIF-18-005, 234 pp.

American Association of State Highway and Transportation Officials (2017a). AASHTO LRFD Bridge Design Specifications, 8th Edition.

American Association of State Highway and Transportation Officials (2017b). AASHTO LRFD Bridge Construction Specifications, 4th Edition.

American Petroleum Institute, API (2020). Recommended Practice 13B-1, Recommended Practice for Field Testing Wet-based Drilled Fluids.

Barker, R.M., J.M. Duncan, K.B. Rojiani, P.S.K. Ooi, C.K. Tan, and S.G. Kim, (1991). *Manuals for the Design of Bridge Foundations: Shallow Foundations, Driven Piles, Retaining Walls and Abutments, Drilled Shafts, Estimating Tolerable Movements, and Load Factor Design Specifications and Commentary*, NCHRP Report 343, Transportation Research Board, Washington, D.C.

Brown, D., Dapp, S., Thompson, R. and Lazarte, C. (2007). "Design and Construction of Continuous Flight Auger Piles," Geotechnical Engineering Circular No. 8 (GEC 8), Federal Highway Administration Office of Technology Application, Office of Engineering/Bridge Division, 294p.

Brown, D. and Thompson, R. (2011). "NCHRP Synthesis 418, Developing Production Pile Driving Criteria from Test Pile Data," Transportation Research Board, National Academies, Washington, D.C., 505p.

Brown, D., and Thompson, W.R., (2015). "NCHRP Synthesis 478, Design and Load Testing of Large Diameter Open-Ended Driven Piles", Transportation Research Board, National Academies, Washington, D.C., 136p.

Brown, D.A., Turner, J.P., Castelli, R.J., and Loehr, E.J. (2018). "Drilled Shafts: Construction Procedures and Design Methods," Geotechnical Engineering Circular No. 10 (GEC 10), Federal Highway Administration, Washington, D.C., 754 p.

Bruce, D.A. and E.K. Chu (1995), “Micropiles for Seismic Retrofit,” Proceedings of the National Seismic Conference on Bridges and Highways, FHWA and Caltrans, San Diego, CA, Dec. 10-13, 17 pp.

Bruneau, M., Kenarangi, H., and Murphy, T.P. (2018). “Contribution of Steel Casing to Single Shaft Foundation Structural Resistance,” NCHRP Research Report 872, Transportation Research Board, National Academy of Sciences, Washington, D.C. 178 p.

California Department of Transportation (CALTRANS). (2005). “Method of Ascertaining the Homogeneity of Concrete in Cast-in-Drilled-Hole (CIDH) Piles Using the Gamma-Gamma Test Method,” California Test 233, Sacramento, CA, 21 p.

California Department of Transportation (CALTRANS), (2019). “Foundation Manual,” Revision 2, Oct 2015, Sacramento, CA, 522 p.

California Department of Transportation (CALTRANS), (2019). “Bridge Construction Records and Procedures,” Vol. 2, Updated Jan 18, 2019, Sacramento, CA, 568 p.

California Department of Transportation (CALTRANS), “ADSC Standard Mitigation Plan,” available at: http://www.dot.ca.gov/hq/esc/geotech/ft/adscmitplan.htm

Deep Foundations Institute (DFI), (2012). “Guideline for Interpretation of Nondestructive Integrity Testing of Augered Cast-in-Place and Drilled Displacement Piles,” prepared by the Augered Cast-in-Place Pile Committee of DFI, First Edition, 42p.

Deep Foundations Institute (DFI). (2018). “Terminology and Evaluation Criteria of Crosshole Sonic Logging (CSL) as Applied to Deep Foundations,” Task Committee Report, DFI, Hawthorne, NJ, 17 p.

Federal Highway Administration (1996). FHWA Geotechnical Engineering Notebook, Geotechnical Guideline No.15, “Geotechnical “Differing Site Conditions””. Federal Highway Administration, Washington, D.C., 36p.

Ferguson, P.M., Breen, J.E., and Jirsa, J.O. (1988). “Reinforced Concrete Fundamentals”. 5th Edition, John Wiley & Sons, Inc., New York.

Gómez, J., C. Englert, and H. Robinson (2013), “Design of A-Walls for Stabilization of Slopes and Embankments in Soft Soils,” Proceedings of the 7th International Conference on Case Histories in Geotechnical Engineering, April 29–May 4, Chicago, IL.

Hanigan, P.J., Rausche, F., Likins, G.E., Robinson, B.R., and Becker, M.L. (2016). “Design and Construction of Driven Pile Foundations,” Geotechnical Engineering Circular No. 12 (GEC 12), Federal Highway Administration, Washington, D.C, 1058p.

Hussein, M.H., McGillivray, R.T., and Brown, D.A. (2012). "Knowledge is Bliss – A Case for Supplemental Pile Testing to Ascertain Fidelity," Proceedings, ASCE GeoCongress 2012, pp. 322-332.

Jones, W.C. and Wu, Y. (2005). "Experiences with Cross-Hole Sonic Logging and Concrete Coring for Verification of Drilled Shaft Integrity," Proceedings, GEO3: Geo Construction Quality Assurance/Quality Control, D.A. Bruce and A.W. Cadden, Editors, ADSC: International Association of Foundation Drilling, Dallas, TX, pp. 376-387.

Joint Micropiles Committee of the Deep Foundations Institute and ADSC: The International Association of Foundation Drilling (2004), Guide to Drafting a Specification for High Capacity Drilled and Grouted Micropiles for Structural Support, 39 pp.

Littlejohn, G.S. and D.A. Bruce (1977), Rock Anchors State-of-the-Art, Foundation Publications Ltd., Brentwood, Essex, England, 50 pp.

Loehr, J.E. and D.A. Brown (2008), A Method for Predicting Mobilization of Resistance for Micropiles Used in Slope Stabilization Applications. International Association of Foundation Drilling (ADSC-IAFD), Irving, Texas.

Loehr, E.J., Lutenegger, A., Rosenblad, B., and Boeckmann, A., (2017). "Geotechnical Site Characterization, Geotechnical Engineering Circular No. 5 (GEC 5), Federal ighway Administration, Washington, D.C, 680p.

National Highway Institute (NHI). (2002). "Drilled Shaft Foundation Inspection," Report FHWA-NHI-03-18. Federal Highway Administration, Washington, D.C., 776 p.

Parkes, J., Castelli, R., Zelenko, B., O'Connor, R., Montesi, M. and Godfrey, E. (2018). "Design, Analysis, and Testing of Laterally Loaded Deep Foundations that Support Transportation Facilities", Geotechnical Engineering Circular No. 009 (GEC 9), FHWA-HIF-18-031, Federal Highway Administration, Washington, D.C., 296 p.

Petek, K., McVay, M, and Mitchell, R. (2020). "Development of Guidelines for Bearing Resistance of Large Diameter Open-End Steel Piles," FHWA-HRT-20-011, 162p.

Sabatini, P.J., B. Tanyu, T. Armour, P. Groneck, and J. Keeley (2005), Micropile Design and Construction, Reference Manual for NHI Course 132078, FHWA Report FHWA-NHI-05-039, 436 pp.

Terzaghi, K., R.B. Peck, and G. Mesri (1996). *Soil Mechanics in Engineering Practice*, 3rd Edition, John Wiley and Sons, 592 pp.

Transportation Research Board (TRB) (2002). "Glossary of Highway Quality Assurance Terms", Transportation Research Circular E-C037, Committee on Management of Quality Assurance (A2F03), Transportation Research Board, Washington, D.C., 27p.