Louisiana Transportation Research Center

Final Report 546

Testing Protocol for Predicting Driven Pile Behavior within Pre-bored Soil

by

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16. Abstract

Piles at a project site derive their load carrying capacity from “side friction” along their embedded lengths as well as from “end resistance.” Pre-boring is a method used to facilitate driving of displacement piles through hard/dense soils. A pilot hole, generally smaller in size than the pile to be installed, is first bored to a specified depth. By pre-boring a pilot hole, the “end bearing” and “side friction” within the pre-bore zone are reduced, thus aiding the driving of the pile. However, pre-boring complicates the prediction of long-term pile capacity (specifically side friction) within the pre-bored zone and the Wave Equation Analysis of Pile (WEAP) analysis, which aims to predict pile drivability. The objective of this project was to compile the state-of-the-art and best practice results available on the subject of pre-bored piles and develop a research and instrumentation testing plan for future field data collection and select multiple pile driving sites representing different soil strengths. Subsurface geologic characteristics of Louisiana were used to recommend multiple pile driving sites for future testing of piles. A plan was recommended for driving multiple test piles at each site using differently sized pre-bored holes with no pre-boring as control for comparison. Instrumentation and monitoring plan utilizing vibrating wire strain gauges or embedded data collector technology during static load test as well as pile dynamic analyzer (PDA) during initial pile driving and restrikes was suggested to be included in the pile testing protocol. The field load testing and instrumentation data obtained during the proposed protocol can be used by DOTD and consulting engineers in evaluating the change in “side friction” capacity of piles while utilizing different size pre-bored hole. The database of information generated from the different sites will help reduce uncertainty in long term pile capacity prediction and constructability issues when using a pre-bored hole for pile installation.

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ABSTRACT

The Louisiana Department of Transportation and Development (DOTD) use deep foundations, consisting of precast concrete piles, open- or closed-end steel pipe piles, steel H-piles, or auger-cast piles to support buildings, highway bridges, and other infrastructure systems. The piles at a project site derive their load carrying capacity from "side friction" along their embedded lengths as well as from "end resistance."

Pre-boring is a method used to facilitate driving of large displacement piles in hard/dense soils. A pilot hole, generally smaller in size than the pile to be installed, is first bored to a specified depth. By pre-boring a pilot hole, the "end bearing" and "side friction" within the pre-bored zone are reduced, thus aiding the driving of the pile. However, pre-boring complicates the prediction of long-term pile capacity (specifically side friction) within the pre-bored zone and the Wave Equation Analysis of Pile (WEAP) analysis, which aims to predict pile drivability. It is assumed that there are three major unknowns that accompany the pre-bored zone: (1) reduction of end bearing as it pertains to pile driving within the zone, (2) reduction of side friction as it pertains to pile driving within the zone, and (3) reduction of side friction as it pertains to long-term pile capacity within the zone. It is expected that the relative strength of the soil as well as the diameter of the pilot hole relative to the pile will have an impact on pile drivability and its long term load carrying capacity.

The objective of this project was to compile the state-of-the-art and best practice results available on the subject of pre-bored piles and develop a research and instrumentation testing plan for future field data collection and select multiple pile driving sites representing different soil strengths. The referenced research objectives were accomplished by performing a literature review, survey with State Highway and other agencies, survey with Louisiana construction companies; investigating instrumentation protocol and site selection guidelines; developing specific guidelines for future data collection; and preparing a final report with recommendations.

Subsurface geologic characteristics of Louisiana were used to recommend multiple pile driving sites for future testing of piles. A plan was recommended for driving multiple test piles at each site using differently sized pre-bored holes with no pre-boring as control for comparison. Instrumentation and a monitoring plan utilizing vibrating wire strain gauges or embedded data collector technology during static load test as well as pile dynamic analyzer (PDA) during initial pile driving and restrikes was suggested to be included in the pile testing protocol. The field load testing and instrumentation data obtained during the proposed

protocol can be used by DOTD and consulting engineers in evaluating the change in "side friction" capacity of piles while utilizing different size pre-bored hole. The database of information generated from the different sites will help reduce uncertainty in long-term pile capacity prediction and constructability issues when using a pre-bored hole for pile installation. Quantifying such an impact will greatly help geotechnical design engineers to understand the interactions among the factors of pre-boring, pile size, soil conditions, pile driving, etc., and improve the design and construction qualities of pile foundations in hard/dense soils.

This final report contains an implementation plan, which includes the outcome of this research, a realistic assessment of impediments to successful implementation, the activities necessary for successful implementation, and the criteria for judging the progress and consequences of implementation. This research will benefit geotechnical, structural, and construction engineers involved in the design, construction, and installation of pile foundations for DOTD and other private projects. Furthermore, this study will benefit the pile driving contractors industry by advancing the knowledge related to predicting driven pile behavior within pre-bored soil.

ACKNOWLEDGMENTS

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IMPLEMENTATION STATEMENT

A protocol for evaluating the effects of pre-boring on the pile capacity during pile installation and long-term pile capacity is presented. The implementation of this protocol includes (1) recommendations for selecting and identifying multiple sites to test piles, (2) recommended subsurface investigation to be conducted at the test site, (3) pile instrumentation options with different levels of instrumentation effort, (4) pile installation records to be compiled, (5) a pile testing plan based on the type of test site being evaluated, (6) pile installation and load testing plan based on the type of test site being evaluated, and (7) an evaluation of the test pile performance by performing a GRL Wave Equation Analyses (GRLWEAP). The implementation of the protocols for evaluating the effects of pre-drilling on the capacity of piles will be evaluated after ever test site has been tested and report prepared for the test site.

A Geotechnical Design Engineer (GDE) needs to be identified within the DOTD Pavement and Geotechnical Design section who will be the contact person for in-house geotechnical engineers and geotechnical consultants when predrilling may be necessary. When the GDE identifies a possible project, the GDE should contact the Research Geotechnical Engineer (RGE) and submit the necessary information for evaluation. Once DOTD and LTRC have determined that the project is a good candidate for the study, the protocols presented in this report can proceed. Identification of all members of the implementation team is essential to effective communication and success of this research. The RGE will transmit the test pile program analysis report and provide a summary report of the research to LTRC/DOTD. The research summary report will include guidance in selecting additional test pile site locations, recommended changes in protocols for test pile sites, and an estimate of when adequate data has been collected to provide a final research report. In addition to these reports, routine biannual reports will be submitted to LTRC as part of the contract administration.

Implementation of the protocols presented will require early planning and identification of all personnel that will be involved. The following roles and levels of responsibility have been identified:

- *Geotechnical Design Engineer (GDE):* DOTD Geotechnical Design Personnel and/or Geotechnical Consultants working on DOTD projects will need to identify projects where pre-drilling is needed to facilitate pile installation.
- *Research Geotechnical Engineer (RGE):* The RGE who will be evaluating the effects of pre-boring on pile capacity will need to be contacted to evaluate the project suitability and identify any gaps in geotechnical data. The geotechnical information (i.e., geotechnical report) that will need to be provided to the researcher should include

subsurface investigation results, static pile capacity analyses, GRLWEAP drivability analyses performed without and with predrilling effects, pile load test and design requirements, and design plans and notes.

- *Geotechnical Instrumentation Engineer (GIE):* The GIE who will be installing the pile instrumentation and recording the data during the static load test will need to be identified. The GIE can either be a part of the research team working under the RGE or can work directly for DOTD by either in-house personnel or subcontractor specialist. It is recommended that the GIE be the same for all projects in order to maintain consistent and reliable results.
- *DOTD / LTRC Geotechnical Contract Manager*: He or she will need to approve the project to be included as part of this research based on the recommendations of the RGE, GDE, and DOTD team evaluating the project.
- *Geotechnical Design Engineer (GDE)*: The GDE will prepare plans, drawings, and special provisions for the project and submit to the RGE for review and contribution of research elements necessary to be included with the DOTD construction documents.
- *Research Geotechnical Engineer (RGE)*: The RGE will review the construction documents (plans specifications/special provisions) and will supplement these documents with pile instrumentation plans, special provision requirements for the conduct of the pile instrumentation, static load testing, dynamic load testing, and contractor submittal requirements. The RGE will work with the GIE to make sure that the instrumentation plan can be implemented properly and be cost-effective.
- *Geotechnical Design Engineer (GDE)*: The GDE will notify the RGE when the project is awarded.
- *Construction Project Engineer (CPE)*: The CPE will contact the GDE, RGE, and GIE to attend the preconstruction conference to discuss the project geotechnical requirements. In lieu of discussing the research geotechnical requirements during the preconstruction conference, the CPE may require a separate geotechnical meeting to discuss the geotechnical project requirements.
- *Geotechnical Research Engineer (GRE) and Geotechnical Instrumentation Engineer (GIE)*: The RGE and GIE will be notified by the CPE a minimum of 45 days prior to casting the square precast prestressed concrete piles so that instrumentation.
- *Geotechnical Instrumentation Engineer (GIE)*: The GIE will be responsible for instrumenting the piles for the test pile program and ensuring that all gauges are in proper working order.
- *Construction Project Engineer (CPE)*: The contractor will be responsible for safe transport of the instrumented pile and for any damages and delays that may occur if the instrumented pile is damaged during transport to the project site. The CPE will notify the

GIE and RGE when the instrumented pile has arrived to the project site for inspection by the GIE/RGE. The CPE will need to coordinate with the contractor, RGE, GIE, and GDE on when the test pile program will be conducted.

- *Geotechnical Research Engineer (GRE) and Geotechnical Instrumentation Engineer (GIE)*: The RGE and GIE will need to be on-site during the conduct of the test pile load testing program. The RGE will need to work with the personnel conducting the dynamic testing with the Pile Driving Analyzer (PDA).
- *Research Geotechnical Engineer (RGE)*: The RGE will need to submit preliminary findings to the GDE for use in establishing plan lengths and pile driving criteria. The RGE will then evaluate the data obtained and put together a research report for the test pile program conducted.

TABLE OF CONTENTS

LIST OF FIGURES

INTRODUCTION

The Louisiana Department of Transportation and Development (DOTD) uses deep foundations, consisting of precast concrete piles, open- or closed-end steel pipe piles, steel H-piles or auger-cast piles to support buildings, highway bridges, and other infrastructure systems. The piles at a project site derive their load carrying capacity from (a) “side friction” along their embedded lengths as well as from (b) “end resistance.”

Pre-boring is a method used to facilitate driving of large displacement piles through hard/dense soils. A pilot hole, generally smaller in size than the pile to be installed, is first bored to a specified depth. By pre-boring a pilot hole, the “end bearing” and “side friction” within the pre-bore zone are reduced, thus aiding the driving of the pile. However, pre-boring complicates (a) the prediction of long-term pile capacity (specifically side friction) within the pre-bored zone and (b) the Wave Equation Analysis of Pile (WEAP) analysis, which aims to predict pile drivability. It is assumed that long-term end bearing within the pre-bored zone will not be an issue, as current DOTD specifications prohibit pre-boring to the pile tip elevation. However, there are three major unknowns that accompany the pre-bored zone: (1) reduction of end bearing as it pertains to pile driving within the zone, (2) reduction of side friction as it pertains to pile driving within the zone, and (3) reduction of side friction as it pertains to long-term pile capacity within the zone.

It is expected that the relative strength of the soil as well as the diameter of the pilot hole relative to the pile will have an impact on pile drivability and its long-term capacity. Quantifying such an impact will greatly help geotechnical design engineers to understand the interactions among the factors of pre-boring, pile size, soil conditions, pile driving, etc. and improve the design and construction of driven pile foundations installed in hard/dense soils.

OBJECTIVE

The objective of this project was to compile the state-of-the-art and best practice results available on the subject of pre-bored piles and develop a research and instrumentation testing plan for field data collection and select multiple pile driving sites representing different soil strengths. The outcome of the research includes a plan for driving multiple test piles at each site using differently sized predrill holes with no pre-boring as control for comparison and performing monitoring during driving, restrikes, and static load tests using pile dynamic analysis (PDA) as well as strain gauge instrumentation.

SCOPE

The scope of this project was to compile the state-of-the-art and best practice results available on the subject of pre-bored piles and develop a research and instrumentation testing plan for field data collection and select multiple pile driving sites representing different soil strengths. A review of standard specifications for construction of bridges and highways of all state highway agencies was performed to investigate current practices related to pre-bored pile installation. Geologic characteristics of Louisiana were reviewed to select multiple pile driving sites representing different soil strengths and subsurface stratigraphy. A plan was developed to test instrumented piles and evaluate the effects of pre-bored hole diameter and length on long term pile capacity and ease of drivability. The following deliverables are included in this report:

1. *Prediction of axial pile capacity*: A summary of static and dynamic formulas available for predicting axial pile capacity is included in the final report.

2. *Review of best practices on pre-bored piles*: A summary of in-state and out-of-state data collected and the databases from where the data was obtained is presented in this final report. The report also summarizes practices related to pile behavior within pre-bored soil in different geographic regions within the United States.

3. *Guidelines for future data collection*: Specific guidelines for future field testing and data collection has been developed for pre-bored sites. A plan for driving multiple test piles at each site using differently sized predrill holes with no pre-boring as control for comparison and performing monitoring during driving, restrikes, and static load tests using pile dynamic analysis (PDA) as well as strain gauge instrumentation is discussed.

4. *Implementation plan*: This final report contains an implementation plan, which includes (1) the recommended plan for driving multiple test piles at sites using different size predrill holes, (2) a realistic assessment of impediments to successful implementation, (3) the activities necessary for successful implementation, and (4) the criteria for judging the progress and consequences of implementation.

METHODOLOGY

The research objectives were accomplished by performing the following tasks:

Task 1 – Summary on Prediction of Axial Pile Capacity

Several methods are available for predicting axial pile capacity based upon static and dynamic methodology. The following paragraphs summarize the commonly used methods for predicting axial pile capacity.

Static Analysis

DOTD uses the DRIVEN software for static pile load capacity analysis *[1]*. The DRIVEN program follows the methods and equations presented by Nordlund, Thurman, Meyerhof, Tomlinson, and Hannigan, et.al. *[2 - 7]*.

A single pile derives its load-carrying ability from the frictional resistance of the soil around the shaft and the bearing capacity at the pile tip:

$$Q = Q_p + Q_s \tag{1}$$

where,

$$Q_p = A_p * q_p \tag{2}$$

and

$$Qs = \int_0^L f_s \; C_d \, dz \tag{3}$$

in which,
Q = total pile capacity
Q_p = tip resistance
Q_s = frictional resistance
A_p = area of pile tip
q_p = bearing capacity at pile tip
f_s = ultimate skin resistance per unit area of shaft
C_d = effective perimeter of pile
L = length of pile in contact with soil
z = depth coordinate

The main requirement for design is to estimate the magnitude of f_s with depth for friction piles and q_p for end bearing piles.

Point Resistance: The point bearing capacity can be obtained from the equation:

$$q_p = c\, N_c + q\, N_q + \frac{\gamma\, B}{2}\, N_\gamma \tag{4}$$

where, N_c , N_q , and N_γ are dimensionless parameters that depend on the soil friction angle ϕ. The term c is the cohesion of the soil, q is the vertical stress at pile tip level, B is the pile diameter (width), and γ is the unit weight of the soil.

In most cases, ½ $\gamma B N_\gamma$ and cN_c are small when compared to qN_q . The net point bearing capacity can be approximated as:

$$Q_{pnet} = A_p\, \overline{q}\, N_q' \tag{5}$$

where $\overline{q} = \overline{\sigma_{v0}}$, the effective vertical stress at tip level, and Nq is a dimensional bearing capacity factor that varies with $\bar{\phi}$.

Shaft Resistance: The ultimate skin resistance per unit area of shaft is calculated as follows:

$$f_s = c_a + \sigma_h * \tan(\delta) \tag{6}$$

in which,
c_a = pile soil adhesion
σ_h = normal component of stress at pile-soil interface
δ = pile-soil friction angle

Nordlund developed a method of calculating skin friction based on field observations and results of several pile load tests in cohesionless soils *[2] [3]*. Several pile types are used, including timber, H, pipe, monotube, etc. The method accounts for pile taper and for differences in pile materials. Nordlund suggests the following equation for calculating the ultimate skin resistance per unit area *[2] [3]*:

$$f_s = K_\delta \; C_f \; \overline{P_d} \; \frac{sin(\omega + \delta)}{cos(\omega)} \tag{7}$$

The frictional resistance of the soil around the pile shaft is then given by:

$$Q_s = \int_0^L K_\delta \; C_f \overline{P_d} \; sin(\delta) \; C_d \; dz \tag{8}$$

in which,
Q_s = total skin friction capacity
K_δ = coefficient of lateral stress at depth z
P_d = effective overburden pressure
ω = angle of pile taper
δ = pile-soil friction angle
C_d = effective pile perimeter
C_f = correction factor for K_δ when $\delta \neq 0$

Dynamic Analysis

Several formulas have been developed that use dynamic information during pile driving to determine capacity of the piles. The dynamic formulas are energy balance equations. The equation relates energy delivered by the pile hammer to energy absorbed during pile penetration. Dynamic formulas are expressed generally in the form of the following equation:

$$eWH = Rs \tag{9}$$

where, e = efficiency of the hammer system, W = ram weight, H = ram stroke, R = pile resistance, and s = pile set (permanent pile displacement per blow of hammer). The pile resistance, R, is assumed to be related directly to the ultimate static pile capacity. The following paragraphs provides information about commonly used dynamic formulas:

The Engineering News (EN) Formula

The EN formula, developed by Wellington, is expressed as *[8]:*

$$Q_u = \frac{W\,H}{(s+c)} \tag{10}$$

where, Q_u = the ultimate static pile capacity, W = weight of hammer, H = drop of hammer, s = pile penetration for the last blow, and c = a constant (with units of length). Specific values of c depend on the hammer type and may also depend upon the ratio of the weight of pile to the weight of hammer ram.

Original Gates Equation

Gates originally developed his pile driving formula in 1957 *[9]*. The empirical equation is as follows:

$$Qu = \frac{6}{7}\sqrt{e\,E_r}\,\log(10\,N_b) \qquad (11)$$

where, Q_u = ultimate capacity (kips), E_r = energy of pile driving hammer (ft-lb), e = efficiency of hammer (0.75 for drop hammers, and 0.85 for all other hammers), N_b = number of hammer blows to penetrate the pile one inch.

Modified Gates Equation (Olson and Flaate)

Olson and Flaate offered a modified version of the original Gates equation *[10]*. The modifications were based on a statistical fit through the predicted versus measured data. Their modifications are as follows:

$$Ru = 1.11\sqrt{e\,E_r}\,\log(10\,N_b) - 34 \qquad for\ timber\ piles \qquad (12)$$

$$Ru = 1.39\sqrt{e\,E_r}\,\log(10\,N_b) - 54 \qquad for\ concrete\ piles \qquad (13)$$

$$Ru = 2.01\sqrt{e\,E_r}\,\log(10\,N_b) - 166 \qquad for\ steel\ piles \qquad (14)$$

$$Ru = 1.55\sqrt{e\,E_r}\,\log(10\,N_b) - 96 \qquad for\ all\ piles \qquad (15)$$

In the above equations, R_u are in kips, E_r is in units of ft-lbs, and N_b is in blows per inch.

Federal Highway Administration (FHWA) – Modified Gates Equation

The FHWA pile manual recommends a modified Gates formula that is herein referred to as FHWA-Gates *[11]*. Their equation is as follows:

$$Ru = 1.75 \sqrt{e\,E_r}\,\log(10\,N_b) - 100 \qquad (16)$$

Pile Capacity Estimate using Pile Driving Analyzer (PDA)

The PDA method refers to a procedure for determining pile capacity based on the temporal variation of pile head force and velocity. The PDA monitors instrumentation attached to the pile head, and measurements of strain and acceleration are recorded versus time. Strain measurements are converted to pile force, and acceleration measurements are converted to velocities. A simple dynamic model (CASE model) is applied to estimate the pile capacity. The calculations for the CASE model are simple enough for static pile capacity to be estimated during pile driving operations.

Task 2 – Literature Review of Existing Pre-bored Pile Studies

Driven piles are generally installed in the ground using pile driving impact hammers that drive the pile by first inducing downward velocity in a metal ram. Upon impact with the pile accessory, the ram creates a force far larger than its weight, which, if sufficiently large, moves the pile an increment into the ground.

During pile driving the soil surrounding the piles is disturbed and remolded. In saturated clays, silts, and fine sands, the soil pore water pressure is increased and typically results in a reduced pile capacity at the end-of-initial driving (EOID). After pile driving has ceased, the excess pore water pressure dissipates over time. Soil setup is the increase in pile capacity over time as excess pore water pressure dissipates. A pile soil setup factor is the ratio of increased skin friction over the skin friction at the end-of-initial driving. Rausche et al. reported soil setup ranges and recommended soil setup factors based on the predominant soil type along the pile shaft as shown in Table 1 *[12]*.

Table 1
Soil setup factors *[12]*

Soil Type	Range in Soil Setup Factors	Recommended Soil Setup Factor
Clay	1.2 – 5.5	2.0
Silt – Clay	1.0 – 2.0	1.0
Silt	1.5 – 5.0	1.5
Sand – Clay	1.0 – 6.0	1.5
Sand - Silt	1.2 – 2.0	1.2
Fine Sand	1.2 – 2.0	1.2
Sand	0.8 – 2.0	1.0
Sand – Gravel	1.2 – 2.0	1.0

Pile capacity soil setup in Louisiana has been investigated by Wang et al. in research from pile load test conducted on DOTD projects *[13]*. Soil setup factors computed by Wang et al. are plotted in Figure 1 *[13]*. The setup factors ranged from 1.0 to 3.2 over time, with a predominant maximum setup factor of approximately 2.0.

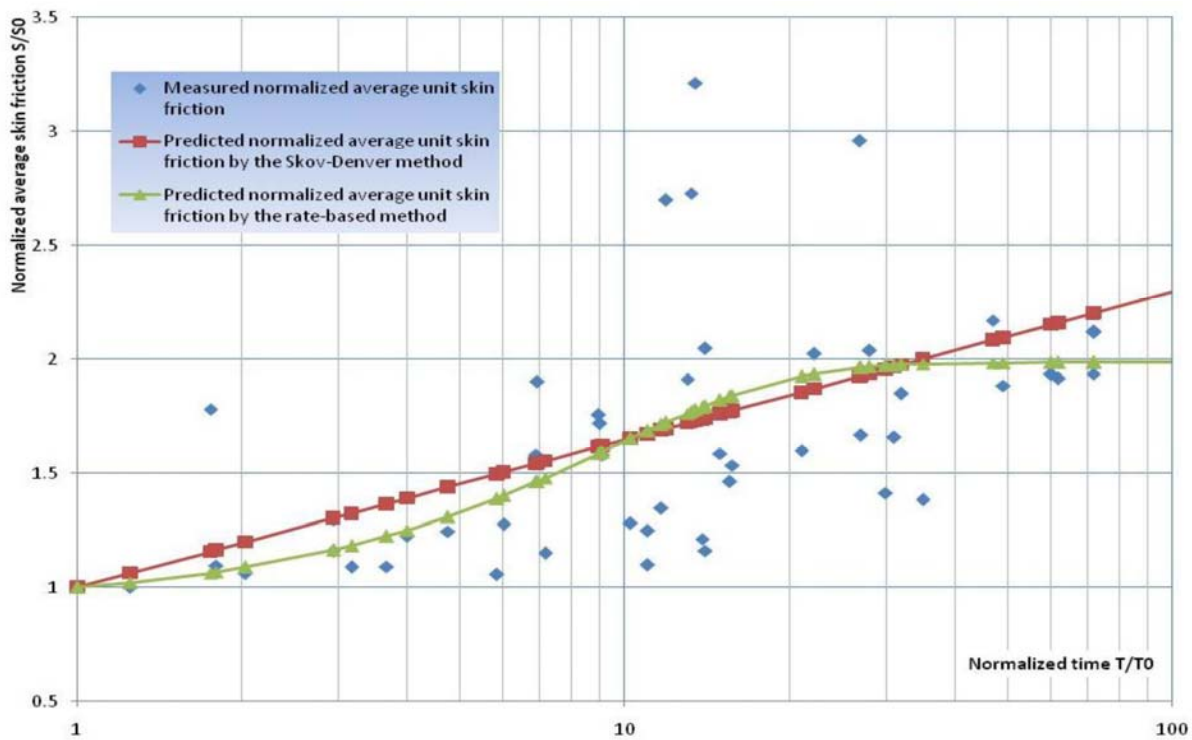

Figure 1
Louisiana pile setup factors ***[13]***

Alternatively, a reduction in pile capacity with time after pile installation has been observed in saturated dense non-cohesive silts, fine sand, and some shales. Pile relaxation is the decrease in pile capacity that results after pile driving has ceased. During pile driving, these soils tend to dilate and negative pore water pressure result in higher pile capacities at the EOID. As pore water pressure equalizes, the pile capacity decreases.

Pre-boring and jetting are pile installation techniques that are sometimes used to drive piles to a prescribed minimum pile penetration, as well as to reduce other foundation installation concerns, such as ground vibrations. Jetting is usually performed in cohesionless soils that can be freely eroded by water jets. Jetting, which can be very effective in sands, is usually ineffective in cohesive soils. For clays and other drillable materials, such as thin layers of rock, pre-boring the pile locations is more effective. The predrilled hole can be slightly smaller, equal to, or slightly larger than the pile diameter.

The use of pre-boring or jetting will result in greater soil disturbance than is typically encountered during pile driving and is considered in static pile capacity calculations. Therefore, when pre-boring or jetting is contemplated, the effect of either of these construction procedures on calculated compression, uplift, and lateral pile capacity should be considered. Poulos and Davis reported that the ultimate shaft resistance should be reduced by 50% of the originally calculated capacity in the jetted zone if the pile is jetted and then driven to the final penetration *[14]*. McClelland et al. reported that a decrease in shaft resistance over a predrilled depth can range from 50 to 85% of that calculated without pre-boring, depending upon the size of the predrilled hole *[15]*. Hence, the probable reduction in compression, uplift, and lateral capacity from jetting or pre-boring should be evaluated whenever pre-boring or jetting is being considered.

According to Unified Facilities Criteria (UFC) report on Pile Driving Equipment (UFC 3-220-02, 2004), pre-boring consists of drilling, auguring, or coring a hole in the ground and filling the hole with concrete or driving a pile into the hole *[16]*. This is generally done with a continuous flight auger. Filling the hole with concrete properly is a drilled shaft, and is beyond the scope of this manual. For driven piles, pre-boring is advantageous when the ground resistance is extremely high. For square concrete piles, the diameter of the bored shaft should be approximately 125% of the nominal pile size. Although pre-boring will generally reduce the driving resistance, it does so at the expense of shaft resistance, which decreases during the pre-boring. This diminution of the pile capacity must be taken into account when determining whether a pile can be pre-bored.

According to USACE Engineer Manual EM 1110-2-2906 (Design of Pile Foundations), pile driving can sometimes be supplemented by special driving assistance such as the addition of driving shoes, jetting, pre-boring, spudding, or followers *[17]*. The use of special assistance should be considered when one of two conditions exist. If a pile reaches refusal with a suitable hammer but does not achieve the necessary capacity, a modification to the installation procedures may be necessary. Simply increasing the size of the hammer may not be appropriate because the pile would be damaged due to excessive driving stresses. The second condition is an economic one, where the installation time and effort can be substantially reduced by the modifying installation procedures. In either case, the potential effect on the axial and lateral pile capacity must be closely evaluated. Contract specifications should define as clearly as possible what type of special driving assistance, if any, would be allowed and under what conditions they would be allowed.

Since special pile installation techniques usually result in reduced pile capacity, specifications normally preclude their use without written approval from the designer. Methods and rationale for the selection of equipment, field inspection, establishment of penetration limitations, record keeping requirements and methods for controlling the driving operation are contained elsewhere in this chapter.

A pilot or pre-bore hole may be required to: penetrate hard nonbearing strata, maintain accurate location and alignment when passing through materials that tend to deflect the pile, avoid possible damage to adjacent structures by reducing vibrations, prevent heave of adjacent buildings, or remove a specified amount of soil when installing displacement-type piles, thereby reducing foundation heave. Pre-boring normally takes place in cohesive soils and is usually required when concrete piles must penetrate man-made fills and embankments containing rock particles or other obstructions. It should be noted that on past Corps projects, concrete piles have been successfully driven through man-made fills such as levee embankments without pre-boring. Pre-boring through cohesionless soils is not recommended, since the pre-bored hole may not stay open and could require a casing. The most widely used method of pre-boring is by utilizing an auger attached to the side of the crane leads. When pre-boring is permitted, the hole diameter should not be greater than two-thirds the diameter or width of the pile and not extend more than three-fourths the length of the pile.

Oversizing the hole will result in a loss of skin friction and a reduction in the axial capacity and lateral support, thereby necessitating reevaluation of the pile foundation. When extensive pre-boring is needed, consideration should be given to using a drilled-shaft system rather than a driven-pile system.

According to Short and Williams, experience has shown that pre-boring only 75% of the pile diameter has little effect on reducing the driving resistance *[18]*. If the pre-driven hole is too small, the pile ends up forcing the upper stratified layers of sand into the bottom of the pre-drilled hole, thus making it difficult to reach design tip elevation. A more effective pre-drilled diameter is that equal to the diameter of the pile. Re-drive tests performed on piles that were pre-driven to various diameters indicated very little difference between a 0.75D- and 1.0D-pre-drilled hole in the skin frictional resistance. The obvious benefit of pre-boring is to reduce the number of blows required to install the pile, which has a great deal of benefit for noise pollution regulation and likewise.

Task 3 – Review of Existing Pre-bored Pile Specifications Followed by Louisiana DOTD

Based on review of the DOTD *Standard Specifications for Roads and Bridges,* the recommended current practice of using the pre-boring procedure is as follows *[19]:*

- *Maximum diameter of pre-boring hole is 80% of the pile size*

- *The depth of the pre-boring hole should stop within 3 feet from the recommended pile tip elevation.*

Additionally, the following paragraphs are taken from the draft version of the upcoming DOTD *Standard Specifications for Roads and Bridges* document regarding the pre-boring requirements.

804.08.1 Pre-boring

- *The size and depth of the pre-bored hole shall be included in the Pile Installation Plan. The depth of pre-bored holes shall not be below the scour elevation, unless accepted by the Engineer of Record.*

- *Develop the pre-boring depth limits based on the soil information obtained from soil boring logs or CPTs. Upon installation of the pile, fill voids around the pile with granular material meeting the requirements of 1003.09 and saturate with water.*

A survey questionnaire was also sent to Louisiana engineers, contractors, and designers to investigate current industry practices in related to pre-bored pile installation. Two individuals responded to the survey questionnaire. Their responses are included in the Appendix of this report.

Task 4 – Review of Existing Pre-bored Pile Specifications Followed by Other State Highways

The Standard Specifications for Roads and Bridges of USDOTs were reviewed to determine current practices related to pre-bored piles. Additionally, responses from the survey questionnaire on the state-of-the art and best practices of other state highway departments and agencies on the subject were reviewed.

Based on the authors' reviews, it is understood that different states have different requirements related to pre-bored hole diameter and maximum depth of the pre-bored hole. Depending upon the subsurface soil conditions, some states require the pre-bored hole diameter to be larger than the pile size, while other states recommend the use of a smaller-sized pre-bored hole diameter. The following sections summarize current practices by different state highway departments in regards to pre-bored piles.

- No specifications related to pre-bored pile were found for the states of Georgia, Idaho, Illinois, Nevada, New York, North Carolina, Pennsylvania, and Vermont.

States Generally Requiring Pre-bored Hole Diameter Smaller than Pile Size

- Alabama (2002) – According to the specifications, augering, wet-rotary, or other methods of boring pilot holes shall be used only when approved by the engineer or shown on the plans. Pilot holes shall be of a size smaller than the diameter or diagonal of the pile cross section that is sufficient to allow penetration of the pile to the specified depth. The contractor shall decide when the pilot hole will be terminated above the prescribed tip elevation so that the pile will attain the required bearing capacity at the required tip elevation established in the plans when driven with the approved hammer. After a pile is placed in a pilot hole, the voids around the pile shall be filled with clean sand before the pile is driven.

- Arkansas (2003) – According to the specifications, the contractor shall pre-bore holes at pile locations and to depths shown on the plans or as directed by the engineer. Pre-bored holes shall be smaller than the diameter or diagonal of the pile cross section and sufficient to allow penetration of the pile to the specified depth. If subsurface obstructions, such as boulders or rock layers, are encountered, the hole diameter may be increased to the least dimension that is adequate for pile installation. Any void space remaining around the pile after completion of driving shall be filled with sand, sand grout mixture, or other approved material.

- Indiana (2012) – According to the specifications, when shown in the plans, the contractor shall pre-bore holes at the locations shown and to the depth specified. Pre-bored holes shall be 2 in. smaller than the diameter or diagonal of the pile cross section that is sufficient to allow penetration of the pile to the specified penetration depth. If subsurface obstructions, such as boulders or rock layers, are encountered, the hole diameter may be increased to the least dimension which is adequate for pile installation. Augering, wet-rotary drilling, spudding, or other methods of pre-boring shall be used only when specified or approved in writing by the Engineer. The procedures shall be carried out so as not to impair the nominal driving resistance of the piles already in place or the safety of existing adjacent structures. Except for end bearing piles, pre-boring shall be stopped at least 5 ft. above the pile tip elevation shown on the plans. The pile shall be driven with an impact hammer to the specified penetration resistance. Where piles are to be end bearing on rock or hardpan, pre-boring may be carried to the surface of the rock or hardpan. The piles shall then be driven with an impact hammer to ensure proper seating.

- Kentucky (2008) – According to the specifications, with the engineer's written permission, water jet or core holes for prestressed, precast, or cast-in-place concrete piles can be used to create the pre-bored hole. The piles will then be placed in the hole and driven to secure the last few feet of their penetration. Jetting or coring holes for steel piles is not permitted unless the engineer directs. Unless otherwise specified in the plans or directed, jetted or cored holes should be prepared in compacted fills as necessary to secure the required penetration. Holes should be cored to a maximum diameter equal to the least cross sectional dimension of the piles driven. All voids that occur around a driven pile should be filled with free flowing sand.

- Maine (2002) – According to the specifications, when necessary to obtain the specified pile penetration and when authorized by the resident, the contractor shall furnish the necessary drilling apparatus and drill holes, not greater that the least dimension of the pile top, to the proper depth and drive the piles therein. Pre-augered holes shall be of a size smaller than the diameter of diagonal of the pile cross section. If subsurface obstructions, such as boulders or rock layers are encountered, the hole diameter may be increase to the least dimension needed for pile installation. Any void space remaining around any type pile after driving shall be completely filled with sand or other approved material. The used of spuds, which are driven and removed to make a hole for inserting a pile, shall not be permitted in lieu of pre-boring. Concrete shall not be placed in pipe piles until pile driving has progressed beyond a radius of 15 ft. from the pile to be concreted.

- Maryland (2001) – According to the specifications, where piling must perforate strata that resist driving, the contractor shall auger or drill holes through the strata. The size of the auger or hole to be used shall not be larger than the nominal diameter of a round pile or the minimum diameter of a circle in which an H pile will fit and shall be approved by the engineer before use. After the hole is completed, the pile shall be inserted and dry sand shall be used to completely fill any voids between the pile and the walls of the hole. Driving shall then be completed, after which any remaining voids shall be completely filled with dry sand.

- Montana (2006) – According to the specifications, when pile pre-bore is specified, the contractor shall use an auger, wet-rotary drill or other approved method. At each pile location, pilot holes should be drilled to a maximum of 1 in. in diameter less than the outside diameter of the round pile and a maximum of 4 in. less than the outside diagonal cross sectional measurement of square or H-pile, to the elevation specified.

- Nebraska (2007) – According to the specifications, the contractor has the option of starting piling in augured holes. Augured hole length shall not exceed 30 % of the below-ground length of the pile. Augured hole diameters shall not be more than 2 in. larger than the pile.

- New Hampshire (2010) – When specified in the contract documents, the contractor shall pre-bore holes at pile locations and to the depths shown on the plans. Pre-bored holes shall be of a size smaller than the diameter or diagonal of the pile cross section that is sufficient to allow penetration of pile to the specified depth. If subsurface obstructions, such as boulders or rock layers are encountered, the hole diameter may be increased to the least dimension that is adequate for pile installation. Any void space remaining around any type pile after driving shall be completely filled with sand or other approved material. The use of spuds, a short strong driven member that is removed to make a hole for inserting a pile, shall not be permitted in lieu of pre-boring.

- New Jersey (2007) – According to the specifications, when pre-boring holes for round piles, the contractor shall use an auger with a diameter that is between 2 in. smaller than the average nominal diameter of piles. When pre-boring holes for steel H-piles, an auger with a diameter that is 4 to 6 in. less than the nominal diagonal dimension of the piles shall be used. The void between the piles and the pre-bored holes should be backfilled with granular material.

- Oklahoma (1999) – According to the specifications, when required by the contract documents, holes can be pre-bored at pile locations to the depths specified in the contract documents or by the engineer. If the depth of pre-boring is not specified in the contract documents, pre-boring should be stopped for skin friction at least 5 ft. above the pile tip elevation. The pile will then be driven with an impact hammer to a specified blow count. Pre-boring for end bearing piles may extend to the surface of the rock or hardpan where piles are to be end-bearing on rock or hardpan. Pre-bored holes should be made smaller than the diameter or diagonal of the pile cross-section and sufficient to allow penetration of the pile to the specified depth. If subsurface obstructions, such as boulders or rock layers are encountered, the hole diameter can be increased to the least dimension that is adequate for pile installation.

- Oregon (2015) – According to the specification, the contractor can use augering, wet-rotary drilling or other methods of pre-boring only when specified or with written approval. The diameter of the pre-bored holes shall be smaller than the diameter or diagonal of the pile cross section, but should be sufficient to allow penetration of the pile to the specified depth. If subsurface obstructions, such as cobbles, boulders, or rock layers are encountered, the hole diameter may be increased to the least dimension that is adequate for pile installation. The use of a reinforced section (spud) to loosen the subsurface material at pile locations will not be allowed unless otherwise approved.
  (1) End-Bearing Piles – For end-bearing pile as classified by the engineer, pre-boring may be carried to the surface of the end-bearing foundation material. Following that, the pile should be driven with an approved impact pile hammer to the specified blow count.
  (2) Other Piles – For other piles, pre-boring shall be extended to the minimum pile penetration depth and then the pile driven drive with an approved impact pile hammer to the specified blow count. After completion of driving, any void space remaining around the pile shall be backfilled with sand or other approved material.

- Rhode Island (2004) – According to the specification, when required by the Special Provisions or as shown in the plans, the contractor shall pre-bore holes at pile locations to the depths shown on the plans, specified in the Special Provisions, or as authorized by the engineer. Pre-bored holes shall generally be smaller in diameter than the diameter or diagonal of the cross section of the pile, except in the case where pre-boring is specified where driving vibrations are not permissible. Pre-boring shall be of sufficient depth to allow penetration of the pile to the specified depth. If subsurface obstructions are encountered, the hole diameter may be increased to the least dimension that is adequate for pile installation. Any void space remaining around the pile after completion of driving or other installation, shall be filled with sand or other approved material. Piles to be driven through newly constructed embankments shall be driven in holes drilled or spudded through the embankment when the embankment is in excess of 5 ft. in height. The hole shall have a diameter of not less than the greatest dimension of the pile cross section plus 6 in. After driving the pile, the space around the pile shall be filled to the surface of the embankment with dry sand or fine gravel.

- South Carolina (2007) – According to the specification, pre-drill for piling should not be performed except where specifically noted in the plans or approved in writing by the engineer. When pre-drilled holes are allowed, the piling should be driven by the hammer to its final position and to the required ultimate bearing. If pre-drilled holes are larger than the pile, the space between the pile and the pre-drilled hole shall be backfilled with sand, pea-gravel, or an approved material and tamp in an approved manner.

- Texas (2004) – According to the specification, the maximum hole diameter permitted will be approximately 4 in. less than the diagonal of square piling or steel H-piling and 1 in. less than the diameter of round piling. The pilot holes should not be extended more than 5 ft. below the bottom of footings for foundation piling or 10 ft. below finished ground line for trestle piling, unless the specified penetration cannot be obtained by using the depth of holes indicated. The engineer may vary hole size and depth to obtain required penetration and bearing resistance.

- Utah (2012) – According to the specification, pre-drilling or pre-augering shall be used if the designated pile tip elevation cannot be reached by the approved pile driver. The pre-bored holes should not be greater in diameter than the diameter or other maximum dimension of the pile.

- Washington (2008) – According to the specification, pre-bored holes and pile spuds shall have a diameter no larger than the least outside dimension of the pile. After the pile is driven, the contractor shall fill all open spaces between the pile and the soil caused by the pre-boring or spudding with dry sand, or pea gravel, or controlled density fill as approved by the engineer.

- Wyoming (2010) – According to the specification, pre-drilled holes can be used when specified or approved by the engineer. The hole diameter shall not exceed the pile width. The hole shall be extended to the elevation specified by the engineer. After placing the pile in the hole, it should be driven to set firmly into bearing material. The space around the pile should be backfilled to the ground surface with dry sand, pea gravel, flowable fill, or other material approved by the engineer.

States Generally Requiring Pre-bored Hole Diameter Larger Than Pile Size

- Alaska (2004) – According to the specifications, if the desirable penetration shown on the plans by using the specified driving methods and equipment cannot be obtained, or if the engineer believes structural damage to the piling is likely to result from continuing these methods, other methods (as approved in writing) can be attempted to obtain penetration. These methods may include, but are not necessarily limited to (1) pre-boring, (2) blasting, (3) spudding, (4) jetting, and (5) using a heavier or faster striking hammer. It is recommended that written approval be obtained by the contractor before employing any alternative methods of pile driving or variations from the desirable tip elevation. When driving piles through new embankment and the depth of the embankment at the pile location is in excess of 5 ft., the pile can be driven in a hole made through the embankment. It is recommended to make the hole diameter no less than the nominal size of the pile plus 6 in. After driving the pile, the annular space around the pile should be filled with dry sand or pea gravel.

- Arizona (2008) – According to the specifications, the pre-bored hole shall have a diameter no less than the greatest dimension of the pile cross section plus 6 in. After driving the pile, the space around the pile shall be filled to ground surface with dry sand or pea gravel, or as specified on the plans.

- California (2010) – According to the specifications, for piles to be driven through embankments constructed under the contract, piles can be driven through predrilled holes where the depth of the new embankment at the pile location is in excess of 5 ft. The hole diameter must be at least 6 in. larger than the greatest dimension of the pile cross section. After driving the pile, the space around the pile should be filled with dry sand and pea gravel.

- Colorado (2005) – According to the specifications, if the piles do not reach the estimated tip elevation, holes shall be drilled to facilitate pile driving. The minimum diameter of the drilled holes shall be 1 in. larger than the outside diameter of steel pipe piles. The minimum diameter of the drilled holes shall be 2 in. larger than the web depth for H piles. The maximum diameter of the drilled holes shall be 2 in. larger than the minimum diameter specified above. If the maximum diameter of the drilled hole is exceeded due to sloughing, drifting, over-drilling, or other causes, the void area between the driven pile and the edge of the hole shall be filled with sand or pea gravel.

- Florida (2013) – According to the specifications, when using low displacement steel piling, such as structural shapes, piles should be driven through the compacted fill without the necessity of drilling holes through the fill except when the requirements for pre-boring are shown in the plans. When using concrete or other high displacement piles, pile holes may be drilled through fill, new or existing, to at least the elevation of the natural ground surface. The following list provides range of drill diameters for different square concrete piles:

  12-in. square piles .... 15 to 17 in.
  14-in. square piles .... 18 to 20 in.
  18-in. square piles .... 22 to 26 in.
  20-in. square piles .... 24 to 29 in.
  24-in. square piles .... 30 to 34 in.
  30-in. square piles .... 36 to 43 in.

  For predrilled holes required through rock or other hard (i.e., debris, obstructions, etc.) materials that may damage the pile during installation, predrill hole diameters should be approximately 2 in. larger than the largest dimension across the pile cross-section. The annular space around the piles should be filled with clean A-3 sand or sand meeting the requirements of 902-3.3. In the setting of permanent and test piling, the contractor may initially predrill holes to a depth up to 10 ft. or 20% of the pile length whichever is greater, except that, where installing piles in compacted fill, predrill the holes to the elevation of the natural ground surface. With prior written authorization from the engineer, the contractor may predrill holes to greater depths to minimize the effects of vibrations on existing structures adjacent to the work and/or for other reasons the contractor proposes.

- Hawaii (2005) – According to the specifications, pre-boring can be performed in locations where piles will be driven through embankments that are more than 5 ft. deep or when required in the contract documents. The predrilled hole diameter should be equal to pile diameter plus 6 in. For piles driven through natural ground, the holes should be drilled sufficiently large to allow penetration of piled to specified depth, but not large than diameter or diagonal of pile cross-section. If subsurface obstructions are encountered, such as boulders or rock layers, the hole diameter may be increased to the least dimension adequate for pile installation. Except for piles specified in the contract documents as end bearing, drilling should be stopped at least 5 ft. above pile tip elevation, or as ordered by the Engineer. After driving pile, the space around the pile should be filled to the ground surface with dry, calcareous sand.

- Iowa (2012) – According to the specifications, when required by the contract documents, the holes should be bored greater than the maximum cross sectional dimension of the pile. The holes should be bored to the elevations shown and to a minimum diameter 4 in. greater than the maximum cross sectional dimension of the pile 3 ft. from the butt. For holes drilled in non-collapsing soils, bentonite slurry may be placed in the hole after piles are driven. In collapsing soils, the bentonite slurry can be used at the time the hole is drilled.

- Kansas (2007) – According to the specifications, when specified, pile holes can be drilled before driving the piles. The holes should be drilled accurately so that the piles are set as shown in the contract documents. The maximum size of the pre-drilled holes is equal to the diameter of the pile plus 3 in. The depth of pre-drilled pile holes should be in accordance with contract documents. If pre-drilled pile holes are not specified, the contractor may choose to pre-drill pile holes, provided the engineer approves the contractor's method and limits. After the piles are driven to their final positions in the pre-drilled holes, the holes should be filled with loose sand or material specified in the contract documents.

- Massachusetts (1995) – According to the specifications, pre-boring shall only be permitted if approved in writing by the engineer or when specifically stated in the contract documents. Where timber, cast-in place, precast-prestressed concrete piles, or steel piles are to be driven through an embankment, and the depth of the embankment at the pile location is in excess of 1.5 m, the contractor shall make a hole for the full depth of the embankment for each pile with an auger or by other approved methods. The hole shall have a diameter of not less than the butt diameter of the pile. After driving the annular space around, the pile shall be filled to the ground surface with dry sand, fine gravel, or pea stone.

- Michigan (2003) – According to the specifications, when specified, pre-bore holes can be pre-bored to the elevation shown. The hole diameter should be equal to or slightly greater than the diameter of the pile. When pre-boring occurs within 20 ft. of a completed pile, the pile capacity should be rechecked by restriking the pile. All voids remaining the final drive should be backfilled with granular material Class II.

- Minnesota (2014) – According to the specifications, the contractor may perform water jetting if needed, or as required by the contract, to aid in driving displacement type piles. The jets should be withdrawn before reaching a preset depth approved by the engineer but not less than 5 ft. of the final tip elevation. Pre-boring for displacement type piles driven through embankments can be performed, if the embankment depth, measured below the bottom of the footing, is greater than 8 ft. The diameter of the pre-bored holes should admit the largest cross-sectional diameter of the pile without creating friction between the faces of the pile and the pre-bored hole.

- Missouri (2011) – According to the specifications, where piles are to be driven through more than 5 ft. of compacted embankment that has been in place for less than five years, holes shall be pre-bored entirely through the embankment to the lowest elevation of the natural ground line adjacent to the embankment, or as shown on the plans. The holes shall have a diameter no less than that of the pile. After the pile is placed in the hole and before driving begins, the space remaining around the pile shall be filled with sand or other approved material before and maintained full during the driving of the pile. Other locations where pre-boring for piles will be required will be shown on the plans. At such locations, holes shall be pre-bored to the elevation specified prior to pile placement. The holes shall have a diameter no less than that of the pile and shall be large enough to avoid damage to the pile being driven through the hole in hard material. The size of the hole shall be approved by the engineer before pre-boring is started. Pilot holes of lesser diameter than the pile shall not extend below the pile tip. Either prior to or after placement of the pile, the hole shall be filled with sand or other approved materials

- South Dakota (2004) – According to the specification, pre-boring shall be done when specified on the plans or directed by the engineer. Holes for timber piles shall be a minimum of 2 in. larger than the nominal diameter of the pile. The nominal diameter shall be measured 3 ft. from the butt of the pile. Holes for steel piles shall be not less than the following specified diameter:

8 HP (HP200) Piles* ....12 in. (300 mm)
10 HP (HP250) Piles* .... 15 in. (375 mm)
12 HP (HP310) Piles* .... 18 in. (450 mm)
14 HP (HP360) Piles* .... 21 in. (525 mm)
*All weights

After the piles are driven, the pre-bored holes shall be backfilled with coarse dry sand. The sand shall be compacted to prevent bridging.

- Virginia (2008) – According to the specification, the area of each pre-bored hole shall be approximately 10 % more than the area of the pile but not more than 20 % of the area.

- West Virginia (2010) – According to the specification, the diameter of the drilled hole shall be a size that will allow the pile, while being slowly lowered into the hole, to reach the bottom of the hole under the impetus of the pile weight. The minimum hole diameter shall be 2 in. larger than the diagonal across the pile cross section.

States with Varying Pre-bore Hole Construction Requirements

- Delaware (2001) – According to the specifications, when specifically indicated on the plans or specifically approved by the engineer, augering shall be used to facilitate pile driving. The contractor shall submit its proposed equipment and augering procedures to the engineer for approval prior to beginning pile driving operations. When round piles are used, the auger diameter shall not be greater than 2 in. less than the pile diameter. For other pile sizes, the diameter of the augers shall be as shown on the plans, or approved by the engineer. For an augered hole that is required through rock material or a very dense layer that may damage the pile during driving, the augered hole diameter shall be approximately 2 in. larger than the largest dimensions across the pile′s cross-section. When required by the plans or project subsurface conditions, the contractor shall maintain augered holes open both before and during pile driving operations. Bentonite slurry or an equivalent method shall be employed, if necessary, to maintain the holes in an open condition. Any voids between the pile and soil remaining after driving through an augered hole, cased or uncased, shall be filled with concrete sand or other approved clean sand in an approved manner. The use of spuds (a spud is a short, strong driven member that is removed to make a hole for inserting a pile) will not be permitted in lieu of augering.

- Ohio (2010) – According to the specification, the augered hole diameter shall be from 2 in. less to 4 in. more than the pile diameter for round piles. For steel H-piles, the augered hole diameter shall be from 6 in. less to 2 in. more than the pile's diagonal dimension but shall be such as to produce satisfactory pile driving results. The voids between the pile and the pre-bored hole shall be backfilled with a granular material satisfactory to the engineer.

- Wisconsin (2015) – According to the specification, pre-boring of holes shall be performed to the depth as required by the plans or special provisions.
  (1) For round piles, pre-bore hole diameter shall be approximately equal to the pile diameter. For other shapes, pre-bore holes of a diameter approximately equal to the greatest diagonal pile section dimension. The diameter can be increased as necessary for pile installation if subsurface obstructions are encountered.
  (2) For round piles in rock or consolidated materials, pre-bore hole diameter shall be at least 1 in. larger than the pile outside diameter. For other shapes, pre-bore holes of a diameter at least one inch larger than the greatest diagonal pile section dimension.

States with No Specific Pre-bore Hole Construction Requirements

- Connecticut (2004) – According the specification, in case the required penetration is not obtained by use of a hammer complying with the minimum requirements, the contractor shall employ such other driving methods as the use of a hammer with a greater mass than that being used, resort to jetting, spudding, pre-holing or a combination of these methods, and perform such other work as may be necessary to obtain the required penetration. However, no specific guidelines regarding pre-bored holes were found in their standard specifications.

- Mississippi (2004) – According to the specifications, the bridge engineer will make all determinations as to the necessity for pre-formed pile holes and the size and maximum depth of each hole required or permitted. If in the judgment of the engineer, pre-formed pile holes are not required and the contractor desires to use them, the contractor may be permitted to do so under conditions prescribed by the bridge engineer and at no additional cost to the state. However, no specific guidelines regarding pre-bored holes were found in their standard specifications.

- New Mexico (2014) – According to the specification, if specified, holes should be pre-bored at pile locations to the depths and size in accordance with the plans. After pile placement, any voids remaining around the pile shall be backfilled with sand or other approved material. The pre-bored holes shall be advanced to the depth established by the foundation engineer. However, no specific guidelines regarding pre-bored holes were found in their standard specifications.

- North Dakota (2008) – According to the specification, when specified penetration cannot be obtained without damaging the pile, the engineer may approve the use of jetting, pre-boring, or spudding to secure the required penetration. The final driving shall be with the hammer for determining bearing. When pilings are driven through a constructed embankment, having a thickness of 5 ft. or more below the bottom of footing, the embankment shall be pre-bored for each pile. All pilot holes not completely filled by piles shall be backfilled with sand or fine gravel before the substructure is built. However, no specific guidelines regarding pre-bored holes were found in their standard specifications.

- Tennessee (2006) – According to the specification, when pre-formed pile holes are used, they should be constructed by drilling or driving and withdrawing a suitable punch or chisel at or near the locations of the piles. If preformed pile holes are so oversized that the sides of a round pile or the corners of a square pile are not in contact with the soil, lateral stability shall be restored by filling the space between the pile and the sides of the hole with approved clean sand, at no cost to the Department. The hole shall be terminated before the required penetration is reached, and the pile should be driven by hammer to the final tip elevation to seat the pile and secure the minimum required bearing. However, no specific guidelines regarding pre-bored holes were found in their standard specifications.

Relevant pages from the standard specifications for construction of roads and bridges for different states are included in the Appendix of this report.

In addition to reviewing Standard Specifications for construction of Roads and Bridges of different states highway departments, a survey questionnaire was sent to different state highway personnel to investigate current practices in relation to pre-bored pile installation. Responses were received from five state highway agencies. Their responses are also included in the Appendix of this report.

Task 5 – Site Selection and Future Data Collection Guidelines

In Louisiana, pre-boring is used by DOTD mostly when driving piles through stiff clay or dense sand layers. Therefore, field data should be collected from different geographic locations within the state of Louisiana. The following recommendations are provided as guidelines for site selection and future data collection:

Site Selection

Louisiana lies within the Coastal Plain physiographic division of the contiguous United States. The generalized geologic map of Louisiana shown in Figure 2 depicts the majority of the surface soils to be Quaternary sediments of Holocene and Pleistocene age. The Holocene age alluvium soil deposits consist of sandy and gravelly channel deposits, sandy to muddy natural levee deposits, and organic muddy back swamp deposits. The Holocene age deposits contain approximately 55% of Louisiana's surface soils and are located primarily along the Mississippi River, Ouachita River, Red River, Atchafalaya River basin, other rivers and tributaries, and coastal marsh deposits. Pleistocene age soil deposits compose of approximately 20% of Louisiana surface deposits. Pleistocene terraces are remnants of pre-existing flood plains and are found along rivers in northern Louisiana and are found as parallel belts to the coast in southern Louisiana. The remaining 25% of the Louisiana's surface soils are of Tertiary age. Tertiary soil deposits in Louisiana range in age from Paleocene (Wilcox Group) to Pliocene (Willis and Citronelle formation, Upland allogroup). The majority of the Tertiary soils deposits consist Wilcox, Claiborne, and Fleming groups. The Wilcox and Claiborne soils consist of sandstone and mudstone that were deposited in deltaic and shallow marine environments. The Fleming group consists of sandstone, siltstone, and mudstone deposited mostly by rivers. The Pliocene soils consists of sandstone, gravelly sandstone, and mudstone of the Upland allogroup in west central Louisiana (Willis Formation) and east of the Mississippi River in the Florida Parishes of southeastern Louisiana (Citronelle Formation).

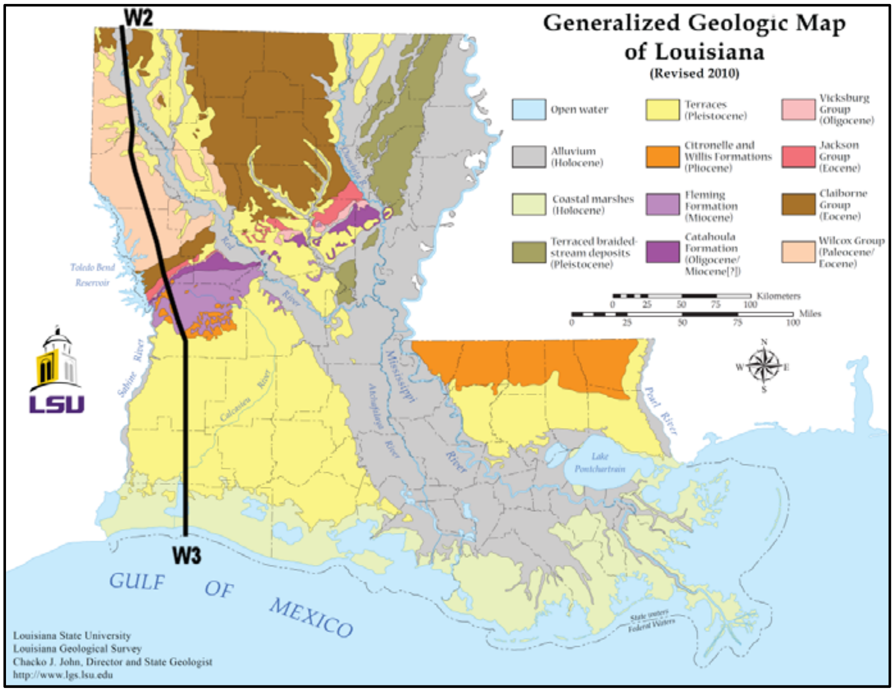

Figure 2
Generalized geologic map of Louisiana *[20]*

The geologic section soil profile W2 – W3 shown in (Figure 3) corresponds parallels US 71 north of Shreveport and extends southward through Lake Charles. The geologic section profile W2 – W3 shown in Figure 3 provides a north-south profile that depicts the probable subsurface stratigraphy that will be encountered during pile installation. The profile shows that Tertiary age soil deposits are predominantly encountered north of Ragley, LA, and that south of Ragley, Quaternary age soil deposits are encountered.

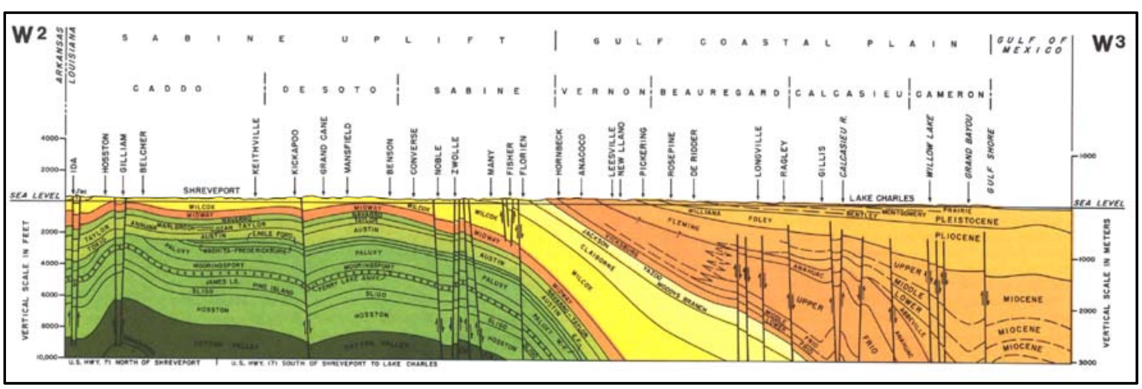

Figure 3
W2-W3 geologic section profile *[21]*

Based on the Louisiana geologic soil conditions previously discussed and anticipated pile installation problems that could potentially occur, two types of soil profile cases have been identified where pre-boring may be required for the installation of bridge pile foundations. A description of these cases is presented below:

CASE I: This is the most commonly observed pile installation challenge in southern Louisiana, south of I-10 as shown in Figure 4. This case occurs when cohesive soils overlay a dense/hard soil layer that must be penetrated to achieve the minimum depth requirements or the required capacity. Underlying the dense/hard soil layer the soil is typically cohesive and the pile may terminate in cohesive soils (friction pile) or may be driven into a dense bearing layer. Figure 4 shows the schematic for Case I site.

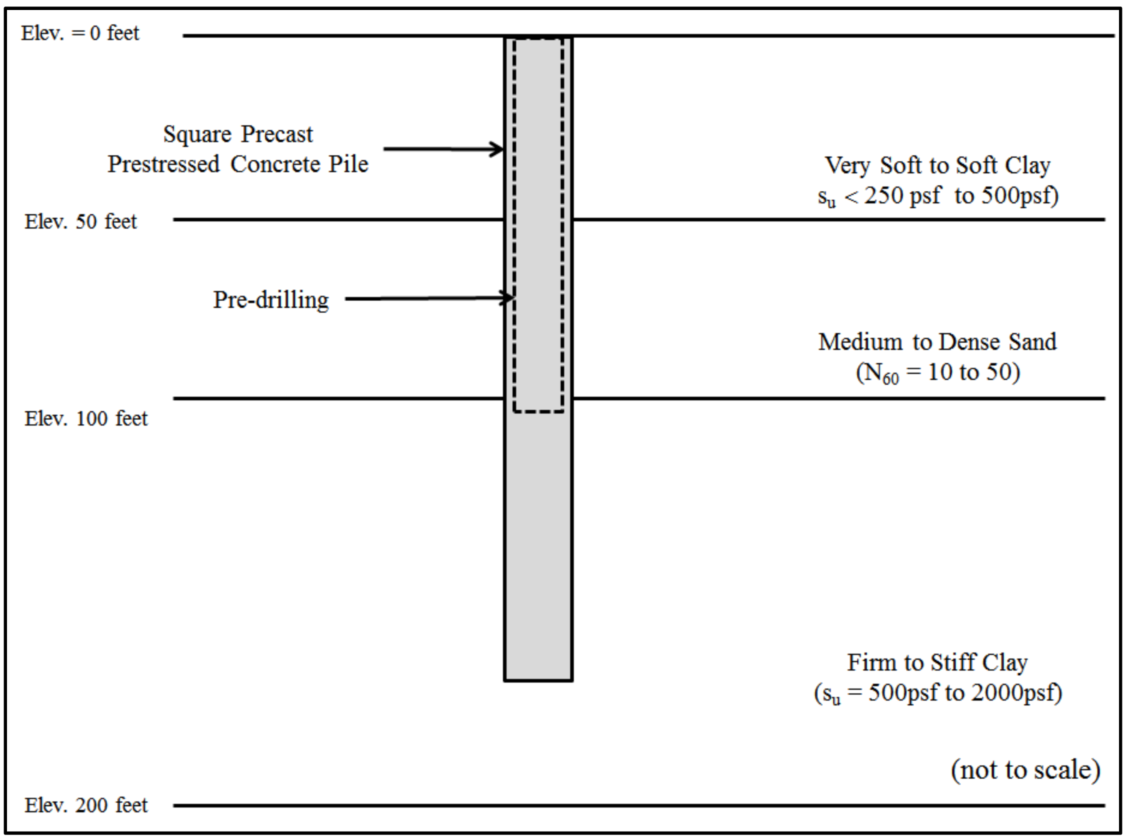

Figure 4
CASE I – pre-boring soil stratigraphy

CASE II: This case (Figure 5) occurs typically north of I-10 within alluvium basins and typically requires driving a pile through granular or cohesive soil near the surface and then penetrating the pile foundation a minimum distance within a very stiff to hard bearing layer.

The minimum penetration is typically required to maintain lateral pile stability during a scour event. Even though cohesionless soils are typically not very good candidate for pre-boring, they are included in Case II since cohesionless soils are abundantly encountered overlying these over-consolidated soils. Cohesionless soils may be candidates for pre-boring if water table does not influence the soils and/or the cohesionless soils have sufficient silt content to have an apparent cohesion during pile installation. In the Case II subsurface stratigraphy, the soils overlying the bearing soils may be of lesser importance to the pile foundation support since the pile bearing and lateral stability is being obtained from the underlying dense/hard bearing strata.

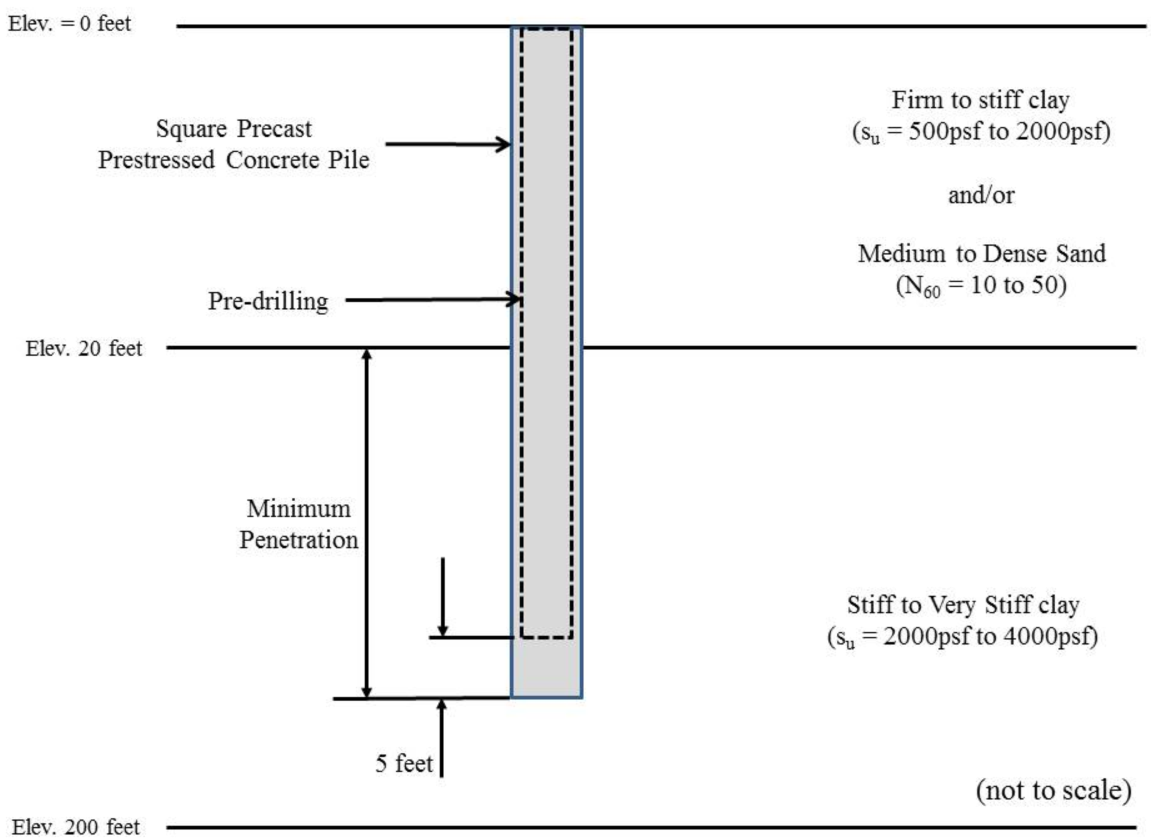

Figure 5
CASE II – pre-boring soil stratigraphy

CASES I and II will be encountered in different geographic locations within the state of Louisiana to cover varying subsurface soil conditions (i.e., soft clay, medium stiff clay, stiff clay, hard clay, medium dense sand, and dense sand).

The sites should contain cohesive soils with varying in-situ soil shear strengths to evaluate the effects of pre-boring on various soil strength using the following consistency clay soil categories:

- Very Soft Clay: $S_u < 250$ psf
- Soft Clay: $250 \leq S_u \leq 500$ psf
- Firm Clay: $500 < S_u \leq 1{,}000$ psf
- Stiff Clay: $1{,}000 < S_u \leq 2{,}000$
- Very Stiff Clay: $2{,}000 < S_u \leq 4{,}000$
- Hard Clay: $S_u > 4{,}000$ psf

It is not anticipated that the density of cohesionless soils will be a major factor since loose soils will remain loose and dense soils will become loose. The main concern with cohesionless soils is caving in of the soil during pile installation and becoming re-compacted. As stated previously pre-boring in cohesionless soils is not ideal but there are cases where pre-boring is required as a result of the underlying stiff to hard cohesive soils.

Subsurface Investigation

It is recommended that an in-depth subsurface investigation be conducted at each test site. The subsurface investigation should consist of soil borings and CPTu soundings. It is recommended that necessary geotechnical laboratory testing be performed on undisturbed and representative disturbed samples to gather additional subsurface soil characteristics and strength parameters. The laboratory testing should be performed to meet the latest requirements of DOTD. Undisturbed samples should be obtained for characterization of the soils by performing laboratory soil index testing and shear strength testing. The laboratory index testing should include Atterberg Limits, Moisture Content, and Hydrometer. The soil shear strength testing that should be considered for both undisturbed samples and remolded samples are Unconsolidated Undrained Triaxial Testing, Consolidated Undrained Triaxial Testing, and Vane Shear.

Investigation Approach to Evaluating Effects of prebored soil on Pile Capacity

The literature review has shown that preboring frequently results in a reduction in axial carrying capacity when compared to piles installed without preboring. It is assumed that long-term end bearing within the pre-bored zone will not be an issue, as current DOTD specifications prohibit predrilling to the pile tip elevation. The primary variables that will affect the pile skin friction capacity are prebore diameter, soil type, and soil strength. Since preboring is known to be more effective in cohesive soils, the evaluation of preboring effects on pile skin friction capacity should be concentrated on cohesive soils of different strengths. The effects of preboring on the pile skin friction capacity should consider the losses observed during pile installation and also the effects of pile capacity setup on its long-term design pile capacity. The test pile instrumentation program should answer the following questions:

1. Ratio of axial pile skin friction capacity installed using preboring to axial pile skin friction capacity without preboring at end-of-initial driving (EOID). This is required to evaluate pile drivability during design and hammer approval.
2. Ratio of axial pile skin friction capacity installed using preboring to axial skin friction pile capacity installed without preboring for the long-term pile capacity obtained from static load tests (SLT), typically performed at 14 days after pile installation. This is required for evaluating the long-term design pile capacity.
3. Evaluate preboring effects on skin friction pile capacity setup. Since pile capacity set-up can play a significant role in the long-term SLT capacity, the losses observed during EOID may be minimized in softer clayey soils with pile capacity set-up. Effects of preboring on the design capacity may be lessened as compared to any permanent reductions in pile capacity when pile capacity set-up cannot overcome the loss in pile capacity due to preboring.

In order to obtain a better understanding of the effects of preboring on pile skin friction capacity, a pile instrumentation program needs to be established that can evaluate trends and ultimately provide design guidance to the geotechnical engineer, who will be designing pile foundations that will use preboring to facilitate pile installation. Instrumenting and evaluating every possible combination of preboring criteria and soil types is impractical and not cost-effective. Therefore, each potential test site should be critically evaluated to determine if pile instrumentation can be used to answer the questions indicated above. To evaluate the effects of preboring, instrumenting all test piles at every test site can be impractical and not cost-effective. Consequently, implementation of a two-tiered instrumentation program is recommended.

Tier 1 test pile instrumentation is the highest tier of instrumentation and has the highest level of complexity and cost. A Tier 1 instrumentation program attempts to provide the maximum insight into the behavior of the prebored pile by increasing the levels of instrumentation to record skin friction directly at discrete locations throughout the length of the pile. The objective is to include sufficient instrumentation for both static load testing (SLT) and dynamic load testing (DLT) and evaluate the pile capacity. This level of instrumentation should be used to provide a higher level of scrutiny. The authors do not anticipate having more than two test sites with Tier 1 test pile instrumentation for each CASE of soil stratigraphy (CASE I and CASE II).

Tier 2 test pile instrumentation is the lowest tier of instrumentation. The level of complexity and cost should be lower than Tier 1, but still will require an in-depth understanding of the objectives of the research and technology being used. A Tier 2 instrumentation program concentrates on evaluating the overall performance within the prebored depths with verification of skin friction (i.e., strains) at selected locations along the pile length. The objective is to include minimal instrumentation for both static load testing (SLT) and dynamic load testing (DLT) and evaluate the pile capacity. This level of instrumentation should be used for verification of results that have been observed from Tier 1 instrumented test piles and to supplement gaps in knowledge. The authors do not anticipate to have more than three test sites with Tier 2 test pile instrumentation for each CASE of soil stratigraphy (CASE I and CASE II).

Pile Instrumentation

It is recommended that a two-tier pile instrumentation program be utilized in order to develop a meaningful database of pre-boring case histories that is both varied and cost-effective. The proposed two-tier instrumentation program is presented below:

Tier 1: This level of test pile instrumentation is the highest tier of instrumentation and has the highest level of complexity and cost. In this tier of instrumentation, all test piles are instrumented with a vibrating wire (VW) strain-gauge along the length of the piles at a 5- to 10-ft. interval depending on soil stratification. If steel pipe piles are being evaluated, the VW strain-gauges can be welded to the pipe piles surface and protected during pile installation with a welded steel angle. Square precast prestressed concrete (PPC) piles should have a minimum side dimension of 18 in. to accommodate the instrumentation and cables that will need to be embedded in the pile. PPC piles should be instrumented with vibrating wire sisterbars cast within reinforcing spiral or ties. VW strain-gauge sensors should be placed in pairs along at each level where instrumentation is being installed. The paired instrumentation will allow for obtaining average strains and will maintain some redundancy in case the instrumentation is damaged. These piles should use embedded data collectors (EDC) to be cast within the PPC piles. Depending on the cost associated with EDC, the strain-gages can be substituted with EDC. If EDC are considered to be used in lieu of strain-gauges, a smaller pile (i.e., 14-in. PPC pile) may be used. When using EDC in solid piles, only one EDC will be needed at each level where strain is being recorded (cast in the center of the pile). When installing EDCs in voided PPC piles, two EDCs will be required at each level.

Tier 2: This level of test pile instrumentation is the lowest tier of instrumentation and should be used for verification of what has been observed and learned from Tier 1 test piles. In this tier, the test piles do not have VW strain-gauge sensors throughout the pile. These piles should use dynamic testing with embedded data collectors (EDC) to be cast within the PPC piles in order to increase the reliability of pile skin friction capacity. As a minimum of three levels of EDC should be installed at the top of the pile, bottom of the pile, and at within the prebored zone.

Pile Installation Records

It is recommended that pile driving be monitored and pertinent data recorded in the field in accordance with the DOTD *Specifications for Construction of Roads and Bridges*. At a minimum, the following data should be collected during pile driving operations:

- Pile type and dimensions
- Pile driving equipment and rated energy
- Pile driving log for the entire pile length
- Pre-bored hole diameter, length, and verticality
- Start and stop time of pile driving

Test Sites

Pre-boring is a method used to facilitate driving of large displacement piles in hard/dense soils. A pilot hole, generally smaller in size than the pile to be installed, is first bored to a specified depth shallower than the intended pile tip elevation. By pre-boring a pilot hole, the "end bearing" and "side friction" within the pre-bore zone are reduced, thus aiding the driving of the pile. It is anticipated that the (1) diameter of the pre-bored hole, (2) depth of the pre-bored hole, (3) type of pile installation method, and (4) relative strength of the soil will all have an effect on the (a) drivability and (b) long-term capacity of driven piles.

As previously discussed, the main parameters that influence the effects of pre-boring on pile capacity are size of pre-bore, pre-bore depth, pile type/size, soil type, and soil shear strength. In order to reduce the large number of combinations, it is recommended that pre-boring criteria be established depending on the subsurface stratigraphy indicated as CASE I and II previously discussed. The results of the test sites should be used to develop pile installation criteria for the production piles.

CASE I: This subsurface soil profile will be encountered mostly in southern Louisiana, south of I-10. The pile size that should be used will depend on the amount of instrumentation that is needed and is dependent on the required pile penetration depth. Consequently, it is anticipated that a minimum pile size of 18-in. square PPC piles with a maximum pile size of a 24-in. PPC pile would be ideal. In order to reduce the effects of pre-boring on pile tip bearing capacity, the standard pre-boring criteria of 5 ft. above pile tip should be maintained that correlates with 3.3 and 2.5 pile diameters for an 18-in. and 24-in. PPC pile, respectively. A "control" pile should be installed above the dense/hard layer to evaluate reduction in pile capacity due to pre-boring. It is recommended that three piles be installed at these test sites as indicated in the following table.

Table 2
Testing matrix for CASE I test sites

Pile No.	Pile Tip	Pre-bore Size	Pile Size	Tier 1 Test Pile	Tier 2 Test Pile
1 (Control)	Stop 3 ft. above Medium to Dense Sand layer	No Pre-bore	18-in. – 24-in. PPC	VW Strain-Gauges and EDC[1] Dynamic Load Test Static Load Test	EDC (minimum 3 Levels) Dynamic Load Test Static Load Test
2	Stop below Firm to Stiff Clay layer	80% of pile side	18-in. – 24-in. PPC		
3	Stop below Firm to Stiff Clay layer	100% of pile diagonal	18-in. – 24-in. PPC		

[1] VW Strain-Gauges may be omitted if embedded data collectors (EDCs) are substituted at all levels.

CASE II: This subsurface soil profile will typically be encountered north of I-10 within alluvium soil deposits in northern part of Louisiana. The foundation design at these sites are typically governed by the minimum pile tip penetration required for lateral stability due to scour. The pile capacity will be primarily obtained from the very stiff to hard bearing soils encountered below the scoured alluvium deposits. Since the control pile cannot be installed within the underlying stiff to hard bearing soils without pre-boring, the control pile will not be used at CASE II test sites. Pile foundations at these sites are generally not as deep as CASE I test sites due to the bearing soils encountered near the surface. It is recommended that 18-in square PPC piles be used at these test sites. In order to reduce the effects of pre-boring on pile tip bearing capacity, the standard pre-boring criteria of 5 ft. above pile tip should be maintained that correlates 3.3 pile diameters for an 18-in PPC pile. It is therefore recommended that two piles be installed at each of these test sites as indicated in the following table.

Table 3
Testing matrix for CASE II test sites

Pile No.	Pile Tip	Pre-bore Size	Pile Size	Tier 1 Test Pile	Tier 2 Test Pile
1	Stop below Firm to Stiff Clay layer	80% of pile side	18-in. PPC	VW Strain-Gauges and EDC[1]	EDC (minimum 3 Levels)
2	Stop below Firm to Stiff Clay layer	100% of pile diagonal	18-in. PPC	Dynamic Load Test Static Load Test	Dynamic Load Test Static Load Test

[1] VW Strain-Gauges may be omitted if embedded data collectors (EDCs) are substituted at all levels.

Pile Installation and Load Testing

It is recommended that all piles be installed in accordance with the current LA standard specifications in order to simulate typical pile installation conditions. To evaluate the effects of the (1) pre-bored hole diameter, (2) pre-bored hole depth, (3) pile installation method, and (4) subsurface soil conditions on the (a) drivability and (b) long-term capacity of driven piles, dynamic load testing (DLT) and static load testing (SLT) are recommended. Test piles (Tier 1 and Tier 2) should be installed full depth and monitored with the pile driving analyzer (PDA) to prevent pile damage from pile driving stresses and to evaluate pile resistance during installation. The PDA results should be compared with instrumented piles (Tier 1) piles by performing pile restrikes to compare with static load test results. The PDA will be the primary method for evaluating Tier 2 test piles. Once confidence has been established from Tier 1 test piles, Tier 2 test piles testing can be implemented.

Static and dynamic load testing should be performed based on the subsurface stratigraphy indicated as CASE I and II previously discussed. The subsurface stratigraphy indicated in CASE I will be subject to greater pile capacity set-up when compared to CASE II test pile sites. Consequently, the number of pile restrikes can be reduced for CASE II test sites when compared to CASE I test sites as indicated in Table 4.

Table 4
Proposed static & dynamic load testing schedule

CASE I	CASE II
DLT - During Pile Installation (EOID)	
DLT – Restrike time interval of 30 minutes	
DLT – Restrike time interval of 2 ½ hours	N/A
DLT – Restrike time interval of 1 day	DLT – Restrike time interval of 1 day
DLT – Restrike time interval of 2 day	N/A
SLT – 14 days after pile installation	SLT – 14 days after pile installation
DLT – ≈14 days after pile installation	DLT – ≈14 days after pile installation

The Static pile load testing should be performed in accordance with ASTM D1143 (Standard Test Methods for Deep Foundations Under Static Axial Compressive Load) under the supervision of a registered professional engineer (P.E.). A Pile Driving Analyzer (PDA) system should be utilized to perform dynamic testing on the driven piles. During the installation of piles, the PDA helps check that driving happens in accordance with the established criterion and gives information on soil resistance at the time of monitoring and on driving system performance. Dynamic Monitoring with a PDA dynamic testing system also calculates driving stresses, helping reduce the risk of pile damage. If stresses indicate a high potential for pile damage, driving can be stopped and alternative installation procedures evaluated. The Case Pile Wave Analysis Program (CAPWAP) should be utilized to estimate the ultimate axial capacity of the piles.

Pile Drivability Analysis

It is recommended that subsurface geotechnical information and the above mentioned field data obtained from Louisiana project test sites be used to simulate pile driving scenarios using GRL Wave Equation Analyses (GRLWEAP) software. The GRLWEAP software (1) calculates driving resistance, dynamic pile stresses, and estimated capacities based on field observed blow count, for a given hammer and pile system; (2) helps select an appropriate hammer and driving system for a job with known piling, soil, pre-boring, and capacity requirements, (3) determines whether a pile will be overstressed at a certain penetration or if refusal will likely occur before a desired pile penetration is reached (drivability analysis), and (4) estimates the total driving time. The results obtained from the analyses can be used to develop pile driving specifications for production piles.

Task 6 –Instrumentation Protocol during Future Data Collection

It is recommended that the following instrumentation be used during pile installation and during dynamic and static load testing of the driven piles.

Strain Gauges

It is recommended that vibrating wire (VW) strain gauges be used to instrument the driven piles during future data collection efforts. The primary purpose of the strain gauges is to measure deformation of the pile under different loading conditions. The strain gauges should be placed at 5-ft. intervals along the length of the driven piles. Closer spacing between strain gauges may be needed near soil stratum change in order to measure strain just above/below a stratum change. VW strain gauges can be welded to the pipe pile surface and protected during pile installation with a welded steel angle. Square precast prestressed concrete (PPC) piles should have a minimum side dimension of 18 in. to accommodate the instrumentation and cables that will need to be embedded in the pile. PPC piles should be instrumented with vibrating wire sisterbars cast within reinforcing spiral or ties. VW strain-gauge sensors should be placed in pairs along each level where instrumentation is being installed. The paired instrumentation will allow for obtaining average strains and will maintain some redundancy in case the instrumentation is damaged. Figure 6 shows the test pile instrumentation plan for Case I sites.

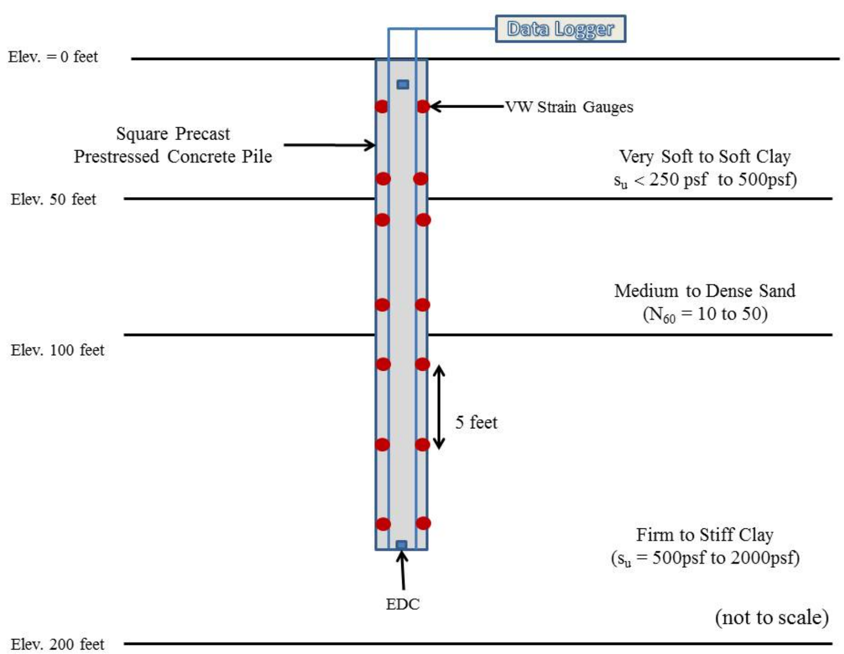

Figure 6
Test pile instrumentation plan for case I sites (Tier 1)

Figure 7 shows the proposed test pile instrumentation plan for Case II sites.

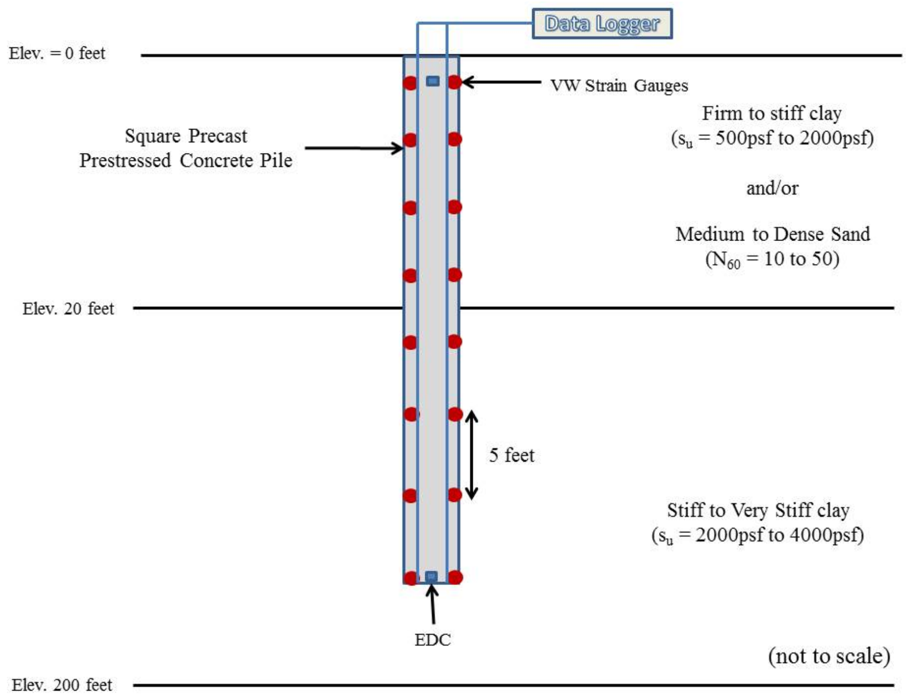

Figure 7
Test pile instrumentation plan for case II sites (Tier 1)

Embedded Data Collector (EDC)

EDC technology can also be used to develop a wireless monitoring and real-time static capacity estimate technology for driven piles. EDC uses two levels of instrumentation embedded in the body of precast prestressed concrete piles near the head and tip. Strain and acceleration measurements obtained at these instrumentation levels during driving can be sent wirelessly to a receiver in the field, and analyzed in real time to provide the operator with estimates of static capacity, stresses in the pile, transfer energy, damping factor, stroke height, and other relevant parameters used to evaluate the pile driving process and the driving system. Concurrent monitoring of piles with EDC instrumentation and the Pile Driving Analyzer (PDA) can provide with adequate data supporting the reliability of PDA. Measurements of strain and particle acceleration converted to force and velocity traces can then be compared between the two systems, along with the corresponding calculated magnitude of downward and upward traveling stress waves as they move along the pile at any point in time.

DISCUSSION OF RESULTS

Pre-boring is a method used to facilitate driving of large displacement piles in hard/dense soils. By pre-boring a pilot hole, the “end bearing” and “side friction” within the pre-bored zone are reduced, thus aiding the driving of the pile. The effects of pre-boring on long term pile capacity (specifically side friction) and pile drivability depend on several factors including pre-bore hole diameter, length of the pre-bored hole, and subsurface soil characteristics.

For this research study, a comprehensive literature survey of published research documents and ongoing research projects related to the effects of pre-bored hole on pile capacity and pile drivability was conducted. A review of standard specifications for construction of bridges and highways revealed that different state highway agencies follow different guidelines regarding the use of pre-bored holes during pile installation.

Subsurface geologic characteristics of Louisiana was used to recommend multiple pile driving sites for future testing of piles to represent different soil strengths and subsurface stratigraphy. A plan was recommended for driving multiple test piles at each site using differently sized pre-bored holes with no pre-boring as control for comparison. An instrumentation and monitoring plan utilizing vibrating wire strain gauges or embedded data collector technology during static load test as well as pile dynamic analyzer (PDA) during initial pile driving and restrikes was suggested to be included in the pile testing protocol.

The field load testing and instrumentation data obtained during the proposed protocol can be used by DOTD and consulting engineers in evaluating the change in “side friction” capacity of piles while utilizing different size pre-bored hole. The database of information generated from the different sites will help reduce uncertainty in long-term pile capacity prediction and constructability issues when using a pre-bored hole for pile installation. This will lead to the design of more cost-effective driven pile foundations and reductions in project costs. Quantifying such an impact will greatly help geotechnical design engineers to understand the interactions among the factors of pre-boring, pile size, soil conditions, pile driving, etc. and improve the design and construction qualities of pile foundations in hard/dense soils.

This research will benefit geotechnical, structural, and construction engineers involved in the design, construction, and installation of pile foundations for DOTD and other private projects. Furthermore, this study will benefit the pile driving contractors industry by advancing the knowledge related to predicting drivability and driven pile behavior within pre-bored soil.

CONCLUSIONS

In this study, state-of-the-art research documents and best practice results available on the subject of pre-bored piles were reviewed and a pile testing and instrumentation plan for field data collection at multiple driving sites representing different soil shear strengths was developed. Based on the results of this study, the following conclusions can be drawn:

- Different state highway agencies follow different guidelines related to the use of pre-bored hole during installation of pile foundations.

- Based on Louisiana's geologic characteristics, a plan was developed for driving multiple test piles at different locations within the state using differently sized pre-bored holes with no pre-boring as control for comparison.

- An instrumentation plan was recommended during test pile driving and restrikes using the pile dynamic analyzer (PDA) and static load tests, as well as vibrating wire strain gauges.

- The data obtained from the field testing and instrumentation plan will benefit DOTD and consulting engineers in reducing uncertainty in long-term pile capacity prediction and constructability issues when using a pre-bored hole for pile installation.

RECOMMENDATIONS

The following initiatives are recommended in order to facilitate the implementation of this study:

- The field testing and instrumentation data collection should be performed by experienced geotechnical engineers or their representatives with adequate knowledge of the procedures.

- The data obtained from the field should be analyzed immediately to determine the effectiveness of the testing protocol and adjust the scope of future testing.

- Implement the results obtained from the recommended field testing and instrumentation study into the design manual for use by DOTD engineers.

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

A_p	area of pile tip
c_a	pile soil adhesion
C_d	effective perimeter of pile
C_f	correction factor for K_δ when $\delta \neq 0$
DOTD	Louisiana Department of Transportation and Development
f_s	ultimate skin resistance per unit area of shaft
ft.	foot (feet)
in.	inch(es)
K_δ	coefficient of lateral stress at depth z
LTRC	Louisiana Transportation Research Center
L	length of pile in contact with soil
m	meter(s)
P_d	effective overburden pressure
Q	Total static pile capcity
Q_s	total skin friction capacity
Q_s	pile shaft resistance
Q_p	pile tip resistance
q_p	bearing capacity at pile tip
σ_h	normal component of stress at pile-soil interface
δ	pile-soil friction angle
ω	angle of pile taper
δ	pile-soil friction angle
z	depth coordinate

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APPENDIX

Survey Questionnaire Response from Private Consultants in Louisiana

Geotechnical Survey Questionnaire

Research Topic: Testing Protocol for Predicting Driven Pile Behavior within Pre-Bored Soil
Funding Agencies: LTRC and LA DOTD

1) When does your agency specify the need for predrilled/prebored holes related to driven pile installation?

   We often recommend predrilling when large-displacement piles are used and when: (1) near-surface debris is present or obstructions are expected, (2) shallow granular deposits exist that are susceptible to vibration-induced settlements, (3) there is a desire/need to reduce vibrations, and/or (4) medium-dense to dense granular soils or very stiff to hard cohesive soils are present. Open-ended steel pipe piles and H-piles often do not require predrilling. We recommend performing the predrilling using wet-rotary drilling methods and a side-discharge drill bit.

2) Using the following table, please indicate your agency's Pre-Boring Criteria

State	Maximum Pre-Bored Hole Diameter	Maximum Pre-Bored Hole Depth from Pile Tip Elevation	Type of Soil in Which Pre-Boring is Typically Recommended
LA (mostly)	About 2/3 of the average pile diameter or width	About 2/3 to 3/4 of the design pile embedment length, depending on the stratigraphy	See response to Question No. 1

3) Does your agency draw the above criteria from any state specifications, research, or other documents?

   Experience, load test results, and published literature.

4) Does your agency have any field data to evaluate the effects of pre-bore hole diameter, pre-boring depth, pile size, soil condition, pile driving methods etc. on the long term "side friction: and "end resistance" capacity of piles?

   Yes, in a general way to form an experienced-based "body of knowledge." However, we evaluate each project on a project- and site-specific basis and make adjustments as needed.

5) Does your agency currently require field-testing protocol for predicting driven pile behavior in prebored soil?

   We recommend the indicator and test pile programs (dynamic and static) be conducted using piles of the same type and size that will be used for construction. We also recommend installing these piles using the same methods, equipment, and techniques as proposed for the production (job) piles.

Please Forward Responses To:

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Geotechnical Survey Questionnaire

Research Topic: Testing Protocol for Predicting Driven Pile Behavior within Pre-Bored Soil
Funding Agencies: LTRC and LA DOTD

1) When does your agency specify the need for predrilled/prebored holes related to driven pile installation?

   Typically, for 2 reasons:
   1). If encounter a sand or hard soil layer that a pile will have difficulty penetrating.
   2). If trying to reduce vibrations.

2) Using the following table, please indicate your agency's Pre-Boring Criteria

State	**Maximum Pre-Bored Hole Diameter**	**Maximum Pre-Bored Hole Depth from Pile Tip Elevation**	**Type of Soil in Which Pre-Boring is Typically Recommended**
LA	75% of pile's side dimension or 85% of pile's tip dia.	Typically, not within 10 feet of design tip depth but have used criteria to within 1 foot of tip depth	Sand or gravel

3) Does your agency draw the above criteria from any state specifications, research, or other documents?

   Not aware of any – mostly experience, common practice, and site specific trial and error.

4) Does your agency have any field data to evaluate the effects of pre-bore hole diameter, pre-boring depth, pile size, soil condition, pile driving methods etc. on the long term "side friction: and "end resistance" capacity of piles?

   Pile load tests where a hole was predrilled prior to load testing. No negative effects of the predrilling were observed.

5) Does your agency currently require field-testing protocol for predicting driven pile behavior in prebored soil?

   Yes, load tests are recommended for every project and the tested pile should be installed with the same methods that are expected for production piles.

Please Forward Responses To:

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Survey Questionnaire Response from DOTs

Geotechnical Survey Questionnaire

Research Topic: Testing Protocol for Predicting Driven Pile Behavior within Pre-Bored Soil
Funding Agencies: LTRC and LA DOTD

1) When does your agency specify the need for predrilled/prebored holes related to driven pile installation? We specify predrilling when having to go through a thin rock lenses to reach the minimum tip elevation due to scour. We also specify predrilling when we need to penetrate rock to get ten feet of embedment after a major scour event to provide enough lateral resistance.

2) Using the following table, please indicate your agency's Pre-Boring Criteria

State	Maximum Pre-Bored Hole Diameter	Maximum Pre-Bored Hole Depth from Pile Tip Elevation	Type of Soil in Which Pre-Boring is Typically Recommended
Alabama	A size smaller than the diameter or diagonal of the pile cross section that is sufficient to allow penetration of the pile to the specified depth.	It varies. Anywhere from 15 to 35 feet. Whatever depth to get through rock lenses or achieve 10 feet of penetration after the maximum scour event.	Rock and whatever soil is above the rock.

3) Does your agency draw the above criteria from any state specifications, research, or other documents? From our Standard Specifications – Section 505 Piling.

4) Does your agency have any field data to evaluate the effects of pre-bore hole diameter, pre-boring depth, pile size, soil condition, pile driving methods etc. on the long term "side friction: and "end resistance" capacity of piles? No.

5) Does your agency currently require field-testing protocol for predicting driven pile behavior in prebored soil? Not usually. We may be doing a dynamic test if we just specified predrilling to get through a thin rock lenses to reach the minimum tip elevation due to scour.

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Geotechnical Survey Questionnaire

Research Topic: Testing Protocol for Predicting Driven Pile Behavior within Pre-Bored Soil
Funding Agencies: LTRC and LA DOTD

1) When does your agency specify the need for predrilled/prebored holes related to driven pile installation? When hard material, refusal, or material that offers a driving resistance higher than the allowable maximum driving resistance specified in the FDOT structures manuals is expected above the minimum penetration requirements/ required minimum tip elevation. Also to minimize vibrations or heave on adjacent structures.

2) Using the following table, please indicate your agency's Pre-Boring Criteria

State	Maximum Pre-Bored Hole Diameter	Maximum Pre-Bored Hole Depth from Pile Tip Elevation	Type of Soil in Which Pre-Boring is Typically Recommended
Florida DOT	Hole to be equal or slightly greater than the largest pile dimension. When preformed holes are to be grouted, they must be at least 2 inches larger than the largest dimension	No rules for land bridges. For water bridges, normally to the scour elevation, but it can be specified deeper as long as lateral confinement is restored	For drivability reasons in rock and cemented sand. For vibration mitigation purposes in all types of soil and rock.

3) Does your agency draw the above criteria from any state specifications, research, or other documents? Yes: FDOT specifications, FDOT Structures Manual and FDOT Soils and Foundation Handbook.

4) Does your agency have any field data to evaluate the effects of pre-bore hole diameter, pre-boring depth, pile size, soil condition, pile driving methods etc. on the long term "side friction: and "end resistance" capacity of piles? No

5) Does your agency currently require field-testing protocol for predicting driven pile behavior in prebored soil? Indirectly yes. All FDOT pile projects require test piles or the first production piles to be dynamically instrumented. Production piles are to be driven in the same way the test piles or the initial piles are.

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Geotechnical Survey Questionnaire

Research Topic: Testing Protocol for Predicting Driven Pile Behavior within Pre-Bored Soil
Funding Agencies: LTRC and LA DOTD

1) When does your agency specify the need for predrilled/prebored holes related to driven pile installation? ODOT limits planned preboring to piles driven through more than 15 feet of new embankment. Preboring is sometimes accepted to pass through a shallow hard layer that may cause pile damage or is not appropriate for bearing.

2) Using the following table, please indicate your agency's Pre-Boring Criteria

State	Maximum Pre-Bored Hole Diameter	Maximum Pre-Bored Hole Depth from Pile Tip Elevation	Type of Soil in Which Pre-Boring is Typically Recommended
Ohio	H-pile: diagonal+2" Pipe: diameter+4"	none	none

3) Does your agency draw the above criteria from any state specifications, research, or other documents? ODOT Bridge Design Manual and Specification Item 507.

4) Does your agency have any field data to evaluate the effects of pre-bore hole diameter, pre-boring depth, pile size, soil condition, pile driving methods etc. on the long term "side friction: and "end resistance" capacity of piles? None collected, because of our application of preboring does not depend on this information.

5) Does your agency currently require field-testing protocol for predicting driven pile behavior in prebored soil? No.

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Geotechnical Survey Questionnaire

Research Topic: Testing Protocol for Predicting Driven Pile Behavior within Pre-Bored Soil
Funding Agencies: LTRC and LA DOTD

1) When does your agency specify the need for predrilled/prebored holes related to driven pile installation?

TDOT Response- TDOT uses preboring of piles generally for two conditions. 1) When the piles will encounter variable layers of rock and soil to get the pile tip down to solid rock and it is determined that driving of piles through the upper rock layers cannot be achieved or it will cause unacceptable pile damage. 2) In West Tennessee where the piles need to go through dense sand or clay layers to achieve minimum tip elevations for either scour or liquefaction requirements.

2) Using the following table, please indicate your agency's Pre-Boring Criteria

State	Maximum Pre-Bored Hole Diameter	Maximum Pre-Bored Hole Depth from Pile Tip Elevation	Type of Soil in Which Pre-Boring is Typically Recommended
TN	*No maximum diameter limitation. It is expected the contractor will pre-bore the pile to a slightly less diameter than the pile. Per spec. the sides/corners of pile are to be in contact with the soil.*	*Depth of pre-boring depends on conditions being encountered. It may be specified to pre-bore just through certain layers or to pre-bore to a certain elevation or to rock refusal for end bearing piles.*	*1) Layers of rock and soil and 2) Dense sand or clay.*

3) Does your agency draw the above criteria from any state specifications, research, or other documents?

TDOT Response- No regarding use of specifications or research. TDOT will adjust the criteria for projects based on results (either good or bad) of previous experience. Pile driving records and/or pile load test may be evaluated to help determine adequacy of recommended practices.
Specification information in section 606.08 and 606.12 of TDOT Standard Specifications http://www.tdot.state.tn.us/construction/specs.htm

4) Does your agency have any field data to evaluate the effects of pre-bore hole diameter, pre-boring depth, pile size, soil condition, pile driving methods etc. on the long term "side friction: and "end resistance" capacity of piles?

TDOT Response- TDOT keeps records of pile driving and pile load test results which could be used for analyzing the effects of pre-boring of piles on capacity but there is currently no formalized evaluation process or engineer assigned to make these type determinations.

5) Does your agency currently require field-testing protocol for predicting driven pile behavior in prebored soil?

TDOT Response- No specific testing required for pre-bored piles other than using prescribed methods for pile driving capacity determination through either blow count data to determine if a particular pile is acceptable on a particular project.

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Geotechnical Survey Questionnaire

Research Topic: Testing Protocol for Predicting Driven Pile Behavior within Pre-Bored Soil
Funding Agencies: LTRC and LA DOTD

1) When does your agency specify the need for predrilled/prebored holes related to driven pile installation? For all integral abutments, sometimes for boulders, and sometimes for fill, if unknown material.

2) Using the following table, please indicate your agency's Pre-Boring Criteria

State	Maximum Pre-Bored Hole Diameter	Maximum Pre-Bored Hole Depth from Pile Tip Elevation	Type of Soil in Which Pre-Boring is Typically Recommended
WV	24 inches	15 ft from bottom of pile cap for integral abutments	All soil types for integral abutments

3) Does your agency draw the above criteria from any state specifications, research, or other documents? Not to my knowledge

4) Does your agency have any field data to evaluate the effects of pre-bore hole diameter, pre-boring depth, pile size, soil condition, pile driving methods etc. on the long term "side friction: and "end resistance" capacity of piles? Yes, most contractors have a 24 inch auger and our standard pile sizes (HP 10x42, 12x53, and 14x73) all fit in this borehole.

5) Does your agency currently require field-testing protocol for predicting driven pile behavior in prebored soil? No

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State DOT Specifications related to pre-bored pile installation

Alabama (2002)

2. HAMMER CUSHION.

Where required by the hammer manufacturer, impact pile driving equipment, except gravity hammers, shall be equipped with a suitable thickness of hammer cushion material to prevent damage to the hammer or pile and to insure uniform driving behavior. Hammer cushions shall be made of durable, manufactured materials, provided in accordance with the hammer manufacturer's guidelines except that all wood, wire rope, and asbestos hammer cushions are specifically disallowed and shall not be used. A striker plate, as recommended by the hammer manufacturer, shall be placed on the hammer cushion to insure uniform compression of the cushion material. The hammer cushion shall be inspected in the presence of the Engineer when beginning pile driving at each structure and after each 100 hours of pile driving. A hammer cushion whose thickness has been reduced to less than 75 percent of the original thickness shall be replaced by the Contractor before driving is permitted to continue.

3. PILE DRIVE HEAD.

Piles driven with impact hammers require an adequate drivehead to distribute the hammer blow to the pile head. The drive head shall be axially aligned with the hammer and the pile. The drive head shall be guided by the leads and not be free-swinging. The drive head shall fit around the pile head in such a manner as to prevent transfer of torsional forces during driving while maintaining proper alignment of hammer and pile.

For steel piling, the pile heads shall be cut squarely and a drive head, as recommended by the hammer manufacturer, shall be provided to hold the axis of the pile in line with the axis of the hammer.

For prestressed concrete piles, the pile head shall be plane and perpendicular to the longitudinal axis of the pile to prevent eccentric impacts from the drive head.

For special types of piles, appropriate driving heads, mandrels or other devices shall be provided in accordance with the manufacturer's recommendations so that the piles may be driven without damage.

4. PILE CUSHION.

A concrete pile's head shall be protected by a wooden pile cushion. The minimum thickness placed on the pile head prior to driving shall not be less than 4 inches {100 mm}. A new pile cushion shall be provided for each pile. In addition the pile cushion shall be replaced if during the driving of any pile, the cushion is either compressed more than one-half the original thickness or begins to burn to the extent that flame is visible. The pile cushion dimensions shall equal or exceed the cross sectional area of the pile top, and shall be appropriately sized to fit the dimensions of the pile cap.

5. LEADS.

Piles shall be supported in line and position with leads while being driven. Pile driver leads shall be constructed in a manner that affords freedom of movement of the hammer while maintaining alignment of the hammer and the pile to insure concentric impact for each blow. Leads may be either fixed or swinging type. Swinging leads, when used, shall be fitted with a pile gate at the bottom of the leads. The pile section being driven shall not extend above the leads. The leads shall be adequately embedded in the ground or the pile constrained in a structural frame such as a template to maintain alignment. The leads shall be of sufficient length to make the use of a follower unnecessary and shall be so designed as to permit proper alignment of batter piles.

(c) DRIVING AIDS.

1. GENERAL.

Driving aids such as jets, pilot holes and followers shall not be used unless either specifically permitted in writing by the Engineer or stated in the contract documents. When permitted, driving aids shall be used for installing production piles only after the pile tip elevation for safe support of the pile load is established by load testing and/or test piles driven with the same aids and methods. The Contractor shall perform, at his cost, any extra load tests and/or extra work required to drive test piles as determined by the Engineer as a condition of approval of the driving aids.

2. JETTING.

Jetting shall only be permitted if approved in writing by the Engineer or when specifically stated in the contract documents. The Contractor shall determine the number of jets and the volume and pressure of water at the jet nozzles necessary to freely erode the material adjacent to the pile without affecting the lateral stability of the final in-place pile. The jetting plant shall have sufficient capacity to permit installation to the required elevation, location, and alignment within specification tolerances. The Contractor shall decide when the jet pipes will be removed above the prescribed tip elevation so that the pile will attain the required capacity at the required tip elevation established in the plans when driven with the approved hammer.

The Contractor shall control, treat if necessary, and dispose of all jet water in a manner satisfactory to the Engineer and in compliance with all regulatory guidelines.

Upon completion of jetting a pile, any voids around the pile shall be filled with clean sand and saturated with water (unless driven under water). The Contractor shall be responsible for all damage to the site caused by unapproved or improper jetting operations.

When driving concrete piles, if 240 blows per foot {300 mm} (20 blows per inch {25 mm}) is reached before the concrete pile reaches the required minimum tip elevation, then jetting may be used, when approved in writing by the Engineer, to facilitate the advancement of the concrete pile. Jetting shall be performed in a manner that allows the pile to continue on the previously established linear path of advancement by eroding the material adjacent to the concrete pile. This may require jetting through a steel pipe previously cast inside the concrete pile presently being driven, using a collar jet or jetting symmetrically with multiple jets.

Once driving of the concrete pile resumes, the lowest stroke of the hammer shall be used until the Contractor and Engineer are satisfied that the original driving resistance has resumed. Under no circumstances shall driving and jetting concrete piling be allowed simultaneously.

3. PILOT HOLES.

Augering, wet-rotary drilling or other methods of boring pilot holes shall be used only when approved by the Engineer or shown on the plans. When permitted, such procedures shall be carried out in a manner which will not impair the load bearing capacity of the piles already in place or the safety of existing adjacent structures. Pilot holes shall be of a size smaller than the diameter or diagonal of the pile cross section that is sufficient to allow penetration of the pile to the specified depth. If subsurface obstructions, such as boulders or rock layers are encountered, the hole diameter may be increased to the least dimension which is adequate for pile installation. The use of spuds, a short strong driven member which is removed to make a hole for inserting a pile, shall not be permitted in lieu of pilot holes.

After a pile is placed in a pilot hole the voids around the pile shall be filled with clean sand before the pile is driven. After driving, additional sand shall be added to the hole to fill the voids left by the settlement of the sand during driving. Water shall then be added to the hole to saturate the final placement of sand. Pilot holes that terminate in rock shall be backfilled to the top of the rock with substructure concrete after seating the pile. The remainder of the hole may be filled with either sand or concrete.

The Contractor shall decide when the pilot hole will be terminated above the prescribed tip elevation so that the pile will attain the required bearing capacity at the required tip elevation established in the plans when driven with the approved hammer. Where piles are to be end-bearing on rock or hardpan, pilot holes may be carried to the surface of the rock or hardpan unless otherwise noted on the plans. The piles shall then be driven with an impact hammer to insure proper seating.

If the Engineer determines that pre-excavation has disturbed the load bearing capacities of previously installed piles, those piles that have been disturbed shall be restored to conditions meeting the requirements of this specification by redriving or by other methods acceptable to the Engineer. Redriving or other remedial measures shall be instituted after pilot hole excavation operations in the area have been completed. The Contractor shall be responsible for the costs of any necessary remedial measures unless the pilot hole excavation method was specifically included in the contract documents and properly executed by the Contractor.

4. FOLLOWERS.

Followers shall only be used when approved in writing by the Engineer or when specifically stated in the contract documents. In cases where a follower is permitted, the first pile in each bent and every tenth pile driven thereafter shall be driven full length, without a follower, to verify that adequate pile length is being attained to develop the desired pile capacity. The follower and pile shall be held and maintained in equal and proper alignment during driving. The follower shall be of such material and dimensions to permit the piles to be driven to the length determined necessary from the driving of the full-length piles. The final position and alignment of the first two piles installed with followers in each substructure unit shall be verified to be in accordance with the location tolerances given in this Section before additional piles are installed.

Alaska (2004)

Provide driving heads, mandrels, or other devices according to the manufacturer's recommendations so that the pile may be driven without damage. Use cast steel combination driving heads and pilots with suitable cushion blocks. Ensure that the driving heads closely fit the top of a steel H-pile or steel pipe pile, and cut the steel piles squarely. Provide a driving cap to hold the axis of the pile in line with the axis of the hammer.

Use full-length piles where practical. Where splices are required, follow the provisions of Subsection 505-3.07.

Use metal shoes or reinforced tips of the design shown on the Plans or as ordered in writing.

Use impact hammers or a combination of hammers to drive piles. However, with written permission, use gravity hammers to drive timber piles. The Department will consider the use of vibratory hammers when requested by the Contractor and when circumstances permit the determination of bearing capacity and required penetration by means other than a dynamic driving formula. Remove inefficient hammers from the work. Do not use followers to drive piles.

Use pile driver leads that allow the hammer to move freely. To ensure rigid lateral support to the pile during driving, hold the pile driver leads in position at the top and bottom by using guys or steel braces or by securely fastening them to the ground. Except where piles are driven through water, use leads that are long enough to avoid using a follower. The design of the leads must permit proper placing of batter piles.

If you cannot obtain the desirable penetration shown on the Plans by using the specified driving methods and equipment, or if the Engineer believes structural damage to the piling is likely to result from continuing these methods, attempt other methods (as approved in writing) to obtain penetration. These methods may include, but are not necessarily limited to:

1. Pre-boring
2. Blasting
3. Spudding
4. Jetting
5. Using a heavier or faster striking hammer

Attempt all approved methods before starting work on more than 5 piles or 50% of the piles, whichever is lesser, in any one substructure unit (such as pier or abutment), or within a 30 foot length of retaining wall.

After exhausting all practicable means to obtain the desired penetration but without success, the Engineer may consider accepting the piling at a lesser penetration if the Engineer believes the adequacy and safety of the resulting structure will not be jeopardized by such acceptance.

Obtain written approval before employing any alternative methods of pile driving or variations from the desirable tip elevation accepted.

When driving piles through new embankment and the depth of the embankment at the pile location is in excess of 5 feet, drive the pile in a hole made through the embankment. Make the hole diameter not less than the nominal size of the pile plus 6 inches. After driving the pile, fill the annular space around the pile with dry sand or pea gravel. Dispose of excess excavated material as provided in Subsection 203-3.01.

505-3.10 DEFECTIVE PILES. Use a pile driving method which does not subject the piles to excessive and undue abuse producing crushing and spalling of the concrete, injurious splitting, splintering, and brooming of the wood or deformation of the steel. Do not manipulate the piles to force them into proper position. Correct damaged or improperly driven piles by one of the following approved methods:

Arizona (2008)

pine, Douglas fir or Larch. All piles for permanent structures shall be cleaned.

Timber piles requiring treatment shall be pressure treated in accordance with the requirements of AASHTO M 133.

Treated piles will be inspected for grade and quality before treatment and each piece accepted for treatment will be hammer-marked on the butt end with the registered brand of the inspector.

603-2.05 Paint:

Paint for steel piles or metal shells shall be of the type shown on the project plans and shall conform to the requirements of Section 1002.

603-2.06 Certificates:

Certificates of Analysis conforming to the requirements of Subsection 106.05 shall be furnished for all steel piling and steel shells used.

603-3 Construction Requirements:

603-3.01 General:

When the project plans or specifications permit the use of more than one type of pile, the same type of pile shall be used for all piles within each individual footing, unless otherwise permitted by the Engineer. The contractor shall be responsible for furnishing piling of sufficient length to obtain the penetration and bearing value required.

603-3.02 Predrilled Holes:

Piles to be driven through embankment constructed by the contractor shall be driven in holes drilled or spudded through the embankment when shown on the project plans or ordered by the Engineer. The hole shall have a diameter of not less than the greatest dimension of the pile cross section plus six inches. After driving the pile the space around the pile shall be filled to ground surface with dry sand or pea gravel, or as specified on the plans.

603-3.03 Equipment:

(A) General:

Steam or air hammers shall be furnished with boiler or air capacity at least equal to that specified by the manufacturer of the hammers to be used. The boiler or compressor shall be equipped with an accurate pressure gauge at all times. The valve mechanism and other parts of steam, air, or diesel hammers shall be maintained in first class condition so that the length of stroke and number of blows per minute

Arkansas (2003)

The following hammer efficiencies will be used in the Wave Equation Analysis:

Hammer Type	Efficiency in Percent
Single acting air/steam	67
Double acting air/steam	50
Diesel	72

The criteria that the Engineer will use to evaluate the acceptability of the driving equipment shall consist of: 1) the required number of hammer blows per 1 inch (25 mm); and 2) the pile stresses at both the required ultimate pile capacity and at a hammer blow count of 20 blows per 1 inch (25 mm). The required number of hammer blows indicated by wave equation analysis calculations and, as applicable, pile driving analyzer measurements at the required ultimate bearing capacity shall be between 3 and 12 per 1 inch (25 mm) for the driving equipment to be acceptable. In addition, the pile stresses to be generated by the driving equipment shall not exceed the values where pile damage impends. The point of impending damage is defined as follows:

- For steel piles, a compressive driving stress of 90% of the yield point, f_y, of the pile material ($0.90f_y$).
- For prestressed concrete piles, tensile stresses shall not exceed 912 psi (6.3 MPa) and compressive stresses shall not exceed 3550 psi (24.9 MPa).
- For non-prestressed concrete piles, tensile stresses shall not exceed 190 psi (1.3 MPa) and compressive stresses shall not exceed 3400 psi (23.8 MPa).

805.08 Driving. Unless otherwise specified, the use of pilot holes or other driving procedures not covered above will be permitted only when approved by the Engineer.

(a) Preboring. When specified, the Contractor shall prebore holes at pile locations and to depths shown on the plans or as directed by the Engineer. Prebored holes shall be smaller than the diameter or diagonal of the pile cross section and sufficient to allow penetration of the pile to the specified depth. If subsurface obstructions, such as boulders or rock layers, are encountered, the hole diameter may be increased to the least dimension that is adequate for pile installation. Any void space remaining around the pile after completion of driving shall be filled with sand, sand grout mixture, or other approved material. Material resulting from drilled holes shall be disposed of under Section 210. The use of spuds (a short strong driven member that is removed to make a hole for inserting a pile) will not be permitted in lieu of boring, unless specifically authorized by the Engineer. When preboring is not specified, the Contractor may, with the approval of the Engineer, use preboring for his own convenience and at no cost to the Department.

(b) Protection of Concrete. No piles shall be driven within 20' (6 m) of a concrete placement, including placement in a steel shell, for a period of seven calendar days after placement.

(c) Splicing Piles. Concrete piles shall be furnished full length without splices.

Steel and steel shell piles shall be furnished full length with not more than one splice prior to driving. The full length is considered to be the length as may reasonable be expected to develop the required bearing resistance and the minimum specified depth of penetration. Two additional splices for build-up will be permitted in order to satisfy all conditions required to cease driving. A minimum length of 5′ (1.5 m) between splices shall be maintained. The sections shall be properly aligned to form a straight axis and shall be welded together in compliance with the plans and in a manner that will fully develop the section. Splices of steel shell piles shall form a watertight joint.

The splicing of steel piles and steel shell piles shall be accomplished by welding according to Subsection 805.03(f).

(d) Accuracy of Driving. Piles shall be driven with a variation of not more than 1/4" per foot (20 mm/m) from the vertical or from the batter shown on the plans, except that for pile bents the top of the completed pile shall be no more than 3" (75 mm) from the true position as shown on the plans. Foundation piles shall not be out of the position shown on the plans more than 4" (100 mm) after driving.

(e) Penetration. Piles shall be driven to the required depths of penetration shown on the plans and to greater depths if necessary to secure the bearing resistance specified.

If penetration requirements are not specified, piling shall have a minimum penetration of 20' (6 m) or be driven into the material shown on the plans or boring logs as rock. Penetration will be measured from the natural ground line for pile bents and from the bottom of footing or seal for foundation piles.

(f) Driving Inspection. Piling shall be driven under the observation of the Engineer or his representative so that data may be

California (2010)

49-2.01C(4) Predrilled Holes

For piles to be driven through embankments constructed under the Contract, drive piles through predrilled holes where the depth of the new embankment at the pile location is in excess of 5 feet.

The hole diameter must be at least 6 inches larger than the greatest dimension of the pile cross section. After driving the pile, fill the space around the pile to the ground surface with dry sand or pea gravel.

49-2.01C(5) Driving

Use driving heads or driving blocks that hold the pile in position directly under the hammer when driving.

Protect the heads of driven piles from direct impact of the hammer with a cushion driving block. Maintain the cushion in good condition during the entire driving operation. Arrange the cushion driving block such that any reinforcing bars projecting above the pile are not displaced or damaged during driving.

Provide special driving tips or heavier pile sections or take other authorized measures to prevent damage to steel piles, steel shells, or steel casings during installation.

If you encounter obstructions to driving, provide special driving tips or heavier pile sections, or subexcavate below the bottom of footing, or take other measures to prevent damage to the pile during driving. This is change order work.

Drive piles to the position and line shown. The Engineer rejects piles materially out of line. Dispose of rejected piles that interfere with the work. Rejected piles that do not interfere with the work may be removed or cut off and abandoned in place.

49-2.01C(6) Pile Cutoff

Cut off driven piles at the elevations shown and anchor them to the structure. Do not damage the pile below cutoff.

Dispose of all cutoff lengths of piles.

49-2.01D Payment

Driven piling is paid for as furnish piling and drive pile of the class, type, size, or alternative shown in the Bid Item List.

Furnish piling is measured from the specified tip elevation shown to the plane of pile cutoff.

Payment for furnish piling includes:

1. Furnishing piles to the job site
2. Splicing piles
3. Furnishing and installing pile anchors and lugs

Payment for drive pile includes:

1. Driving and cutting the piles off at the elevations shown
2. Furnishing special driving tips or heavier sections of steel piles
3. Drilling holes or predrilling holes through embankments
4. Disposing of material resulting from drilling holes or predrilling holes

49-2.02 STEEL PIPE PILING

49-2.02A General

49-2.02A(1) Summary

Section 49-2.02 includes specifications for constructing steel pipe piles.

49-2.02A(2) Definitions

shop welding: Welding performed at a permanent plant.

field welding: Welding performed at the job site.

Colorado (2005)

approval criteria for wave equation analysis will consist of (1) the pile stress at the required ultimate pile capacity and (2) pile driveability.

The driving stresses in the pile indicated by the Wave Equation Analysis shall not exceed 90 percent of the yield stress of the steel.

Once approved, changes in the pile driving equipment shall not be made without additional approval, and will be considered only after the Contractor has submitted the necessary information for a revised Wave Equation Analysis. The approval process outlined above shall be applied to the revised driving equipment.

All pile hammers delivered to the job site which the Engineer determines, either by observation or by pile driving analyzer, are not in good working condition will be rejected.

502.05 Driving Piles. Foundation piles shall not be driven until the excavation is complete unless authorized by the Engineer. After driving is complete, all loose and displaced material shall be removed from around the piling before pouring any concrete.

Piles shall be driven with a variation of not more than ¼ inch per foot from the vertical or from the batter shown in the Contract. Foundation piles shall not be out of the position shown in the Contract more than 6 inches after driving.

A minimum pile penetration of 10 feet in natural ground is required for all piles. This requirement may be waived by the Engineer if the subsurface material at the pile tip location is bedrock or other acceptable bearing material provided that the bearing elevation is below scour depth.

If a minimum pile tip elevation is specified in the Contract, all piles shall be driven to or below this elevation unless otherwise approved in writing. If the pile cannot be driven to the minimum tip elevation, the Engineer will determine if predrilling is required. Any predrilling not required by the Contract and ordered by the Engineer will be paid for in accordance with subsection 109.04. The depth of the predrilling will be determined by the Engineer.

Piles shall be driven to virtual refusal in natural ground at or below the estimated tip elevations specified on the plans. Virtual refusal is defined as a penetration of 1 inch or less for the final ten blows unless modified by the Engineer based on the pile driving analyzer results as described below. If virtual refusal has been reached in natural ground and piles have not been driven to the estimated tip elevation but have been driven below minimum tip elevation, the Engineer may order the driving to be continued for 40 additional blows.

Water jets may be used in conjunction with the hammer to obtain the specified penetration only with approval. The last 3 feet of penetration shall be obtained by driving without the use of water jets. Test blows to determine average penetration shall be applied after the jets have been removed. The use of water jets will not modify any of the requirements of this section.

The Engineer may monitor the pile driving by using a Pile Driving Analyzer (PDA) to determine the condition of the pile, the efficiency of the hammer and the static bearing capacity of the piles, and to verify or modify the pile driving criteria specified in this Section. Modifications may include relaxing or stiffening the refusal criteria. The monitoring will be conducted by the Engineer. It is estimated that the Engineer will need approximately one hour per pile to install the PDA measurement equipment. Not more than two piles per project will be monitored unless specified in the Contract. All necessary work performed by the Contractor associated with the dynamic monitoring_will not be paid for separately but shall be included in the work. If the Engineer requests additional piles to be monitored, or requests the Contractor to monitor the pile or piles, all necessary time required and work performed by the Contractor will be paid for in accordance with subsection 109.04.

502.06 Drilling Holes to Facilitate Pile Driving. Holes to facilitate pile driving shall be drilled at all locations shown on the plans and to elevations shown.

When test piles are shown on the plans they shall be used to determine if drilling holes to facilitate pile driving is required.

If the test pile or piles do not reach the estimated tip elevation as specified in subsection 502.05, holes shall be drilled to facilitate pile driving.

If the test pile or piles reach the estimated tip elevation shown on the plans and develop the required bearing capacity as determined in subsection 502.05, drilling holes will not be required and the remainder of the piles shall be driven in the normal manner.

The drilling of holes shall be done in such manner that the piling will stand accurately positioned as shown on the plans.

The diameter of the drilled holes and the material used to fill oversize holes shall be as stipulated herein unless otherwise designated on the plans.

The minimum diameter of the drilled holes shall be 1 inch larger than the outside diameter of steel pipe piles. The minimum diameter of the drilled holes shall be 2 inches larger than the web depth for H piles.

The maximum diameter of the drilled holes shall be 2 inches larger than the minimum diameter specified above. If the maximum diameter of the drilled hole is exceeded due to sloughing, drifting, over-drilling, or other causes, the void area between the driven pile and the edge of the hole shall be filled with sand or pea gravel at the Contractor's expense.

The Engineer will determine if shooting holes with explosives or redesign is necessary when piles cannot be driven or holes drilled.

502.07 Capping Piles. Steel pipe or shell piles will be inspected after all adjacent piles within a 5 foot radius have been driven. The Contractor shall supply suitable

Delaware (2001)

The results of the survey shall be furnished to the Engineer. In the event that one or more of the piles are damaged by improper driving, or driven outside the allowable tolerance specified herein, the Engineer will analyze the pile group. If the analysis indicates that any pile is overstressed as a result of the damaged or out of tolerance piles, the Contractor shall remove the rejected pile or drive additional piles as directed by the Engineer. In addition, the Contractor shall modify the pile cap or abutment as required by the Engineer to accommodate the out of tolerance or added piles. All piles damaged by improper driving, or driven out of their proper location or alignment shall be rejected.

(7) Any driving splices determined necessary by the Engineer shall be made in accordance with the Plans or other details submitted by the Contractor to the Engineer for review and approval. Following the required curing time for the splice, the spliced pile shall be driven to the required bearing capacity and/or tip elevation. If it becomes necessary to splice timber piles, the method for splicing and driving shall be submitted to the Engineer for written approval.

(8) Any build-ups (non-driving splices) shall be constructed in accordance with the requirements of Subsection 619.15.

(9) If the piles are driven to a tip elevation, as shown on the Plans or directed by the Engineer, and "Bearing Achieved by Freeze" is being used to achieve the desired bearing, the Engineer may direct the Contractor to restrike selected production piles in a particular footing, bent, or structural element. If this direction is given, the production pile restrikes shall be performed in accordance with the requirements of Subsection 619.14.

(10) Cut-offs, as necessary, shall be performed in accordance with the requirements of Subsection 619.16.

(11) After driving, prestressed concrete piles shall have their tops covered with plastic to prevent dirt and water from entering holes/sleeves provided for grouting in bar reinforcement for anchorage into the pier caps or the abutment footings. Prior to grouting in bar reinforcement, such holes/sleeves shall be blasted out with air to remove any dirt and/or water.

619.13 Augering.

(a) *General.* When specifically indicated on the Plans or specifically approved by the Engineer, augering shall be used to facilitate pile driving. The Contractor shall submit its proposed equipment and augering procedures to the Engineer for approval prior to beginning pile driving operations.

When round piles are used, the auger diameter shall not be greater than 2″ (50 mm) less than the pile diameter. The auger diameters listed below shall be used for square concrete piles unless otherwise shown on the Plans:

Hole Diameter	*Pile Size*
10″ (250 mm)	12 by 12″ (300 by 300 mm)
12″ (300 mm)	14 by 14″ (350 by 350 mm)
14″ (350 mm)	18 by 18″ (450 by 450 mm)
20″ (500 mm)	24 by 24″ (600 by 600 mm)
24″ (600 mm)	30 by 30″ (750 by 750 mm)
30″ (750 mm)	36 by 36″ (900 by 900 mm)

For other pile sizes, the diameter of the augers shall be as shown on the Plans, or approved by the Engineer. The pile holes shall be accurately augered with the hole centered over the plan location of the piling. The location and vertical alignment shall be maintained within the tolerances allowed for the piling.

For an augered hole which is required through rock material or a very dense layer that may damage the pile during driving, the augered hole diameter shall be approximately 2″ (50 mm) larger than the largest dimensions across the pile′s cross-section. When required by the Plans or Project subsurface conditions, the Contractor shall maintain augered holes open both before and during pile driving operations. Bentonite slurry or an equivalent method shall be employed, if necessary, to maintain the holes in an open condition.

(b) *Augering Through Compacted Fill.*

(1) When steel H or other low displacement piles are used, piles shall be driven through the compacted fill without augering holes through the fill, except when the requirements for augering are shown on the Plans. When concrete or other high displacement piles are used, pile holes shall be augered through the fill to at least the elevation of the original ground surface.

(2) For an augered hole which is required through material that caves during driving, to the extent that the augered hole does not serve its intended purpose, the hole shall be cased from the embankment surface to the approximate elevation of the original ground surface. After the pile is driven, annular spaces between the casing and pile shall be filled with concrete sand or other approved clean sand in a manner approved by the Engineer. Unless otherwise shown on the Plans, the casing shall be removed after the pile is driven and accepted.

Any voids between the pile and soil remaining after driving through an augered hole, cased or uncased, shall be filled with concrete sand or other approved clean sand in an approved manner. The use of spuds (a spud is a short, strong driven member that is removed to make a hole for inserting a pile) will not be permitted in lieu of augering.

619.14 Pile Restrike. After initial driving of production and/or test piles, the Engineer may order, within two working days after completion of the initial driving, a pile restrike. The restrike shall be performed within seven days of initial driving unless otherwise noted in the Contract. After the directed waiting time has elapsed, the pile restrike shall be performed as follows:

(1) Dynamic pile testing equipment shall be connected, if indicated on the Plans or directed by the Engineer, in accordance with Special Provision 621502.

(2) The pile hammer used during initial driving must be used for the Restrike.

(3) The hammer shall be warmed-up by striking another pile or pile cut-off at least 20 blows at full stoke.

(4) The elevation of the top of pile shall be established prior to performing the restrike.

(5) The hammer shall be carefully lowered and positioned on the pile. The hammer shall strike the pile 20 blows at the required stroke height.

(6) The hammer shall be removed from the pile, and the new top of pile elevation shall be established.

(7) After completion of the pile restrike, the Engineer will review the driving records and make a recommendation, within two working days, on how to proceed.

On contracts requiring dynamic pile testing, all piles to receive dynamic pile testing shall be subject to restrikes as described in Special Provision 621502.

On contracts requiring static load testing, test pile restrikes shall be performed, on each pile to be load tested, after a minimum of three but before five calendar days after completion of the pile load

Florida (2013)

455-4 Classification.

The Department classifies piling as follows:

(1) Treated timber piling.
(2) Prestressed concrete piling.
(3) Steel piling.
(4) Test piling.
(5) Sheet piling.
  (a) Concrete sheet piling.
  (b) Steel sheet piling.
(6) Polymeric Piles (see Section 471 for requirements).

455-5 General Requirements.

455-5.1 Site Preparation:

455-5.1.1 Predrilling of Pile Holes: Predrilled pile holes are either starter holes to the depth described in this section or holes drilled through embankment/fill material down to the natural ground surface. When using low displacement steel piling such as structural shapes, drive them through the compacted fill without the necessity of drilling holes through the fill except when the requirements for predrilling are shown in the Plans. When using concrete or other high displacement piles, drill pile holes through fill, new or existing, to at least the elevation of the natural ground surface. Use the range of drill diameters listed below for square concrete piles.

12 inch square piles	15 to 17 inches
14 inch square piles	18 to 20 inches
18 inch square piles	22 to 26 inches
20 inch square piles	24 to 29 inches
24 inch square piles	30 to 34 inches
30 inch square piles	36 to 43 inches

For other pile sizes, use the diameter of the drills shown in the Plans or approved by the Engineer. Accurately drill the pile holes with the hole centered over the Plan location of the piling. Maintain the location and vertical alignment within the tolerances allowed for the piling.

For predrilled holes required through rock or other hard (i.e. debris, obstructions, etc.) materials that may damage the pile during installation, predrill hole diameters approximately 2 inches larger than the largest dimension across the pile cross-section. Fill the annular space around the piles as described in 455-5.9.1 with clean A-3 sand or sand meeting the requirements of 902-3.3.

In the setting of permanent and test piling, the Contractor may initially predrill holes to a depth up to 10 feet or 20% of the pile length whichever is greater, except that, where installing piles in compacted fill, predrill the holes to the elevation of the natural ground surface. With prior written authorization from the Engineer, the Contractor may predrill holes to greater depths to minimize the effects of vibrations on existing structures adjacent to the work and/or for other reasons the Contractor proposes. Perform such work the Engineer allows but does not require at no expense to the Department. When the Engineer requires such work, the Department will pay for such work as Preformed Pile Holes as described in 455-5.9.

Hawaii (2005)

installed with followers as specified in Subsection 505.03(H)(5) - Accuracy of Driving. Do not install additional piles until verification is made for each substructure unit. Submit pile location data for each substructure unit.

(2) Water Jets. Jetting will be allowed only if acceptable to the Engineer as part of the Contractor's driving system, or when specified in the contract documents.

Determine number of jets and volume and pressure of water at jet nozzle necessary to erode material next to the pile without affecting lateral stability of the final in-place pile. Cease jetting when project site, stability of embankment, and improvements are endangered by jetting operation. Restore damage to project site and improvements at no increase in contract price or contract time. Acceptance of proposed method does not relieve the Contractor of the responsibility to install piles free of defects to the required pile tip elevation and bearing capacity.

Ensure jetting plant has sufficient capacity to deliver consistent pressure equivalent to at least 100 pounds per square inch at two 3/4-inch jet nozzles. Stop jetting and remove pipes when pile tip is a minimum of 5 feet above prescribed tip elevation. Drive pile to required pile bearing capacity with impact hammer. Control, treat if necessary, and dispose of jet water.

(3) Drilling. Drill in locations where piles will be driven through embankments that are more than 5 feet deep or when required in the contract documents.

Make hole diameter equal to pile diameter plus 6 inches.

Unless otherwise specified, use auger or wet-rotary drill . Use same drilling method for test piles and production piles. Construct drilled holes such that finished holes will allow piles to stand accurately in positions shown in the contract documents.

Drill in a manner that will not impair carrying capacity of piles already in place or safety of existing adjacent structures.

If the Engineer concludes that drilling has disturbed load bearing capacities of previously installed piles, restore those piles to conditions conforming to the contract documents. Redrive or perform other remedial measures acceptable to the Engineer, at no increase in contract price or contract time. Begin remedial measures after completing drilling operations in the area.

Drive piles in holes drilled through embankments. After driving pile, fill space around pile to the ground surface with dry, calcareous sand. Sand shall have a minimum sand equivalent (SE) value of 70 or coarse aggregate conforming to AASHTO M 43 size number 8. Dispose of material resulting from drilling holes.

Drill holes through natural ground only when required in the contract documents. For piles driven through natural ground, make drilled holes sufficiently large to allow penetration of piles to specified depth, but not larger than diameter or diagonal of pile cross-section. If subsurface obstructions are encountered, such as boulders or rock layers, hole diameter may be increased to the least dimension adequate for pile installation.

Except for piles specified in the contract documents as end-bearing, stop drilling at least 5 feet above pile tip elevation, or as ordered by the Engineer. Drive pile with impact hammer to specified blow count. For end-bearing piles on rock or hardpan, drill to surface of rock or hardpan. Tap planted piles with impact hammer. Do not use spud (short, strong, driven member that is removed) to make hole for inserting pile.

(F) Preparation for Driving.

(1) Excavation. Do not drill holes for piles or drive piles until after foundation excavation has been completed and accepted in writing by the Engineer. Remove materials forced up between piles to the correct elevation, at no increase in contract price or contract time, before placing foundation concrete.

(2) Concrete Pile Splices. Piles shown on plans are full-length piles. Piles longer than 100 feet may be spliced not more than once, to suit the Contractor's operation, provided piles are mechanically spliced. Design strengths of splice shall be no less than strengths of unspliced pile in tension, compression, bending, and torsion. Use metal with minimum corrosion life of 100 years. Provide splices at no additional increase in contract price or contract time.

(3) Pile Shoes. When specified in the contract documents, provide and install pile shoes of the type and dimensions indicated. Prefabricate shoes for steel piles from cast steel conforming to AASHTO M 103M.

(4) Collars. Provide collar bands to protect timber piles against splitting and brooming, where necessary.

(5) Compressive Strength of Concrete Piles. Do not drive prestressed concrete piles until concrete has reached the minimum compressive strength , as determined by test cylinders, and not earlier

Indiana (2012)

the pile hammer, improper construction methods, etc. Piles damaged for such reasons will be rejected and shall be replaced if the Engineer determines that the damage impairs the strength of the pile.

(a) Pilot Holes

Pilot holes are prebored, predrilled, or cored. After a pile is driven thru a pilot hole, all voids around the pile shall be filled with B borrow. Water shall be added to the hole to saturate the final placement of B borrow.

If the Engineer determines that preboring or predrilling has disturbed the nominal driving resistance of previously installed piles, those piles that have been disturbed shall be restored by means of redriving or other approved remedial measures. Redriving or other remedial measures shall be instituted after the preboring or predrilling operations in the area have been completed.

1. Preboring

When shown in the plans, the Contractor shall prebore holes at the locations shown and to the depth specified. Prebored holes shall be 2 in. smaller than the diameter or diagonal of the pile cross section that is sufficient to allow penetration of the pile to the specified penetration depth. If subsurface obstructions, such as boulders or rock layers, are encountered, the hole diameter may be increased to the least dimension which is adequate for pile installation.

Augering, wet-rotary drilling, spudding, or other methods of preboring shall be used only when specified or approved in writing by the Engineer. The procedures shall be carried out so as not to impair the nominal driving resistance of the piles already in place or the safety of existing adjacent structures.

Except for end bearing piles, preboring shall be stopped at least 5 ft (1.5 m) above the pile tip elevation shown on the plans. The pile shall be driven with an impact hammer to the specified penetration resistance. Where piles are to be end-bearing on rock or hardpan, preboring may be carried to the surface of the rock or hardpan. The piles shall then be driven with an impact hammer to ensure proper seating.

2. Predrilling

The hole shall have a minimum diameter of not less than the greatest dimension of the pile cross section plus 4 in. (100 mm). The holes shall be drilled to the elevations shown on the plans.

Before driving piles for end bents, holes to receive piling shall be predrilled or spudded through new embankment to the original ground elevation if the new embankment is 10 ft (3 m) or more in height. If the new embankment is less than 10 ft (3 m) in height, predrilling is not required. If new embankment in the area of the end bents is to be constructed of sand, gravel, or other permeable material in which a predrilled hole would not remain open, the piling shall be driven before the embankment is constructed.

Pilot holes for end bent piles for structures with integral end bents shall be predrilled to the depth specified in the plans, regardless of the height of new embankment.

If pile sleeves are shown on the plans, the drilled holes shall be sleeved to maintain the opening during the driving of the piles.

If bentonite grout is shown on the plans, it shall be used to fill the annular space around the pile. The grout shall be placed at the depths shown on the plans or as directed. The entire annular space shall be filled from the bottom upwards to the top of the pile in 1 pumping operation using a tremie pipe.

Tremie-pipe construction shall include side discharge ports. The tremie pipe can be terminated by means of a tee connection. Tremie-pipe may be polyvinyl chloride, however, joints shall not be glued or cemented.

3. Cored Hole in Rock

When specified, holes shall be cored into rock to accommodate pile placement. The approach grade shall be completed before coring is begun. Holes of the diameter shown on the plans shall then be predrilled through the embankment into solid rock to the elevations shown on the plans or as otherwise directed. The piles shall be driven to practical refusal at the bottom of the cored holes. The holes in cored rock shall then be filled with concrete.

(b) Location and Alignment Tolerance

A maximum deviation of 1 1/2 in. (38 mm) in any direction from the plan position will be permissible in pile trestle bents and exposed pile bents. A maximum deviation of 6 in. (150 mm) in any direction will be permitted for a foundation pile in footings for piers or abutments. The tendency of concrete or steel piles to twist or rotate shall be prevented and corrected. Piles to be swaybraced shall be aligned as necessary so that the swaybracing may be properly welded to the piles by a welder qualified in accordance with 711.32. No pile shall be closer than 4 in. (100 mm) from an edge of the pile cap. Pulling laterally on installed piles to correct misalignment, or splicing a properly aligned section on a misaligned section shall not be done unless approved by the Engineer. The pile head at cutoff elevation shall be within 2 in. (50 mm) of plan elevation for bent caps supported by piles.

Piles driven at integral end bents shall be installed so that the axial alignment of the top 10 ft (3 m) of the pile is within 2% of the specified alignment.

Battered piles shall be installed so that the alignment of the top 10 ft (3 m) of the pile does not vary by more than 3% from the batter rate shown in the plans.

Iowa (2012)

e. Use the same quality concrete for the extension used to cast the original pile.

f. Just prior to placing concrete for the extension, prepare the joint according to Article 2403.03, I. Coat with a creamy mixture composed of 1 part of water and 1.5 parts of dry cement. The grout may be poured in at the top of the form, depositing it as nearly as possible in the center of the pile.

g. After placement, the forms may be removed after 24 hours, and the extension cured by wrapping with two thicknesses of burlap kept wet for 4 calendar days. Finish the entire surface of the exposed pile to present a uniform color and texture. Splice piles that require further driving as specified in the contract documents or as directed by the Engineer.

2. Steel Piles.

a. For extensions of steel H-piles and steel pipe piles, neatly weld the entire cross section after removing all damaged metal. Ensure the axis of the extension coincides with the axis of the original pile. Perform welding of all steel piles according to Article 2408.03, B.

b. Allow only welders qualified according to Material I.M. 560 to make field extensions of steel piles. Ensure they use an approved welding procedure involving the use of backing plates according to Article 2408.03, B.

c. When designated in the contract documents, the Contractor has the option of extending steel piles by means of mechanical splices approved by the Engineer.

3. Wood Piles.

Splice wood piles as directed by the Engineer.

Q. Prebored Holes as per Plan.

1. When required by the contract documents, bore holes greater than the maximum cross sectional dimension of the pile. Bore holes to the elevations shown and to a minimum diameter 4 inches (100 mm) greater than the maximum cross sectional dimension of the pile 3 feet (1 m) from the butt. Drive piles through the holes to at least the specified design bearing.

2. Use natural bentonite slurry when piling is to be advanced in prebored holes. For holes drilled in noncollapsing soils, the bentonite slurry may be placed after piles are driven. In collapsing soils, place the bentonite slurry at the time the hole is drilled. Cover holes to prevent footing concrete from entering the holes.

3. Use prebored hole filling materials consisting of polymer free sodium bentonite designed for sealing wells and bored holes. Materials may consist of American Petroleum Institute Specification 13A, sodium bentonites, high solids bentonite grout mixes, or granular bentonites composed of approximately 1/4 inch (6 mm) or larger particles.

4. For collapsing soils, make a slurry by thoroughly mixing the bentonite with water according to the manufacturer's recommendation for the product used. In no case use more than 100 gallons (500 L) of water per 80 pounds (50 kg) of bentonite. Place slurry materials by pumping or other applicable methods that assure the hole is filled from the bottom up.

5. For noncollapsing dry holes, coarse 1/4 inch (6 mm) or larger bentonite particles may be poured directly into the hole and hydrated with water after placement.

6. Completely stabilize the hole and fill with bentonite prior to placing footing concrete.

2501.04 METHOD OF MEASUREMENT.

Measurement for the quantities of Wood Piles, Steel HP-Piles (either encased or not), Steel Pipe Piles, Concrete Piles, and Steel Sheet Piles, will be the plan quantity. The quantity may be modified by Article 2501.04, D, F, or G.

A. Wood Piles.
When a wood pile is broken in driving, through no fault of the Contractor, the length measured for payment will be the plan length.

B. Sheet Piles.
The area of walls of sheet piles will be determined from the plan length and the horizontal center line length measured to the nearest 0.1 foot (0.1 m) of wall.

C. Concrete Encasement.
The length of concrete encasement of steel HP-piles constructed will be measured to the nearest 0.1 foot (0.1 m).

D. Extension and Splices.

1. **Wood and Steel Piling.**
   a. For Measurement for extensions of wood, steel HP (either encased or not), or steel pipe piles will be the length of the extension specified by the Engineer. Portions of pile cut-offs used as extensions on the same contract will not be remeasured as additional plan quantity.
   b. Splices (welded or mechanical) are measured by count. Only splices specified by the Engineer to extend piles beyond plan length will be counted.

2. **Concrete Piling.**
   a. Measurement for extensions of concrete piles will be the length of the extension specified by the Engineer, plus the additional length required to be removed for splicing the reinforcement.
   b. Splices are not measured separately.

Kansas (2007)

c. Driving Piles. Drive the piles with a gravity hammer, a diesel hammer, an air/steam hammer or a combination of pre-drilled holes or water jetting and a hammer. Use equipment that complies with **subsection 157.2.**

Drive the piles at the locations and to the vertical or battered lines shown in the Contract Documents. Use leads of sufficient length to allow them to be spiked into the ground at the onset of driving the pile.

Do not drive piles until the footing, webwall or abutment excavation is completed. Drive all of the piles required for the footing or abutment before placing any concrete in the footing or abutment, unless the foundation is a minimum of 20 feet away or has cured a minimum of 24 hours.

When specified, drill pile holes before driving the piles. Drill the holes accurately so that the piles are set as shown in the Contract Documents. The maximum size of the pre-drilled holes is equal to the diameter of the pile plus 3 inches. The depth of pre-drilled pile holes is shown in the Contract Documents. If pre-drilled pile holes are not specified, the Contractor may choose to pre-drill pile holes, provided the Engineer approves the Contractor's method and limits. After the piles are driven to their final positions in the pre-drilled holes, fill the holes with loose sand or material specified in the Contract Documents. If concrete is specified, allow sufficient concrete slump and provide vibration to fill all voids around the pile.

Drive all pile heads perpendicular to the longitudinal axis of the piles to prevent eccentric impacts from the drive head of the hammer. Use pile caps on all piles during the pile driving operations. For pile caps of concrete piles and prestressed concrete piles, use a suitable cushion next to the pile head that fits into a casting that supports a timber shock block. On pile caps for steel piles and steel sheet piles, provide grooves in the bottom of the cap to accommodate the shape of the piles to hold the axis of piles in line with the axis of the hammer.

If specified, use the type of cast steel pile points shown in the Contract Documents. Use pile points that provide full bearing for the piles. Provide an experienced welder to attach the cast steel pile points to the piles.

Use full-length piles where practicable. It is preferred that steel piling is not spliced. Splices may be made with the permission of the Engineer, or when shown in the Contract Documents. Make splices as shown in the Contract Documents. Use an approved welding process as provided in **DIVISION 700** to make the splices. Provide an experienced welder to make the welded splices for structural steel piling and shell piling. Correct or replace any failure in the splice at own expense.

Avoid extensions, splices or build-ups on prestressed concrete piles whenever possible. When splicing is necessary, make them as shown in the Contract Documents.

If the pile driving procedure causes crushing or spalling of the prestressed concrete piles, or deformation of the steel piles, remove and replace the damaged piles with new, longer piles. A second pile may be driven adjacent to the damaged pile, when approved by the Engineer and can be accomplished without detriment to the structure.

Do not force misaligned piles into proper position. Remove and replace piles driven out of their proper location with new, longer piles.

- If the driven pile is 35 feet or less in length, the maximum allowable variation from the vertical or battered lines shown in the Contract Documents is ¼ inch per foot of length.
- If the driven pile is greater than 35 feet in length, the maximum allowable variation from the vertical or battered lines shown in the Contract Documents is ⅛ inch per foot of length.
- The maximum allowable variation on the head of the driven pile from the position shown on the Contract Documents is 2 inches for piles used in bents, and 6 inches for foundation piles.

Re-drive all piles pushed up by the driving of adjacent piles, or by any other cause.

d. Bearing Values and Required Penetration. Drive the piling to attain, as a minimum, the specified bearing value, penetration and pile tip elevation. Stop driving the piling (regardless of the penetration) if 1½ times the specified minimum driving resistance is attained. Stop driving the piling if, in the opinion of the Engineer, the specified minimum driving resistance, penetration and pile tip elevation can not be attained without damage to the piling. If the specified minimum driving resistance is not attained with the specified number and length of piling, the Engineer may allow additional piling be driven so that the maximum load on any pile does not exceed its safe carrying capacity.

In the absence of loading tests, determine the safe bearing values of piles by the formulas in **TABLE 704-1.**

Kentucky (2008)

order to obtain penetration. Use pile points of the type specified in the Contract or by the Engineer. Weld pile points to the pile with a minimum 5/16 inch groove weld along the full outside width of each flange on the pile. Install pile points in the shop or in the field. Furnish a mill test report according to Subsection 607.03.13 C). Furnish the Engineer with the manufacturer's specifications.

D) Extensions, Build-Ups, and Splices. The Engineer may allow extensions, splices, or build ups when necessary as follows:

1) Precast and Prestressed Concrete Piles. Perform extension or build-ups according to the Standard Drawings. If alternate methods for extensions or build-up is desired submit proposal to the Engineer for consideration.
2) Cast-in-Place Piles. Make extensions, splices, or build-ups on steel shells as specified in the Plans or as directed.
3) Steel Piles. Make extensions or splices according to the standard drawings or the Division of Construction's Guidance Manual. Weld according to Subsection 607.03.07. Never begin driving with a spliced pile. When splicing is necessary, use a length that will reasonably assure that bearing will be attained without additional splicing.

604.03.05 Methods of Driving and Placing. With the Engineer's written permission, water jet or core holes for prestressed, precast, or cast-in-place concrete piles, and then place piles in the holes and drive them to secure the last few feet of their penetration. Do not jet or core holes for steel piles unless the Engineer directs. Unless otherwise specified in the Plans or directed, prepare jetted or cored holes in compacted fills as necessary to secure the required penetration. Core holes to a maximum diameter equal to the least cross sectional dimension of the piles driven. Fill all voids that occur around a driven pile with free flowing sand.

Do not drive piles in the vicinity of recently placed concrete until the concrete is sufficiently cured to prevent damage, in the judgment of the Engineer.

For cast-in-place piles, drive the shells using steel heads having a projecting ring fitting inside the shell. Provide a 1/4 inch clearance between the ring and the shell. The Department will allow the use of other types of driving heads if the Engineer approves. The Department will not require painting the steel shells. Provide an inspection light before and during the shell filling operation. Remove and replace improperly driven, broken, or otherwise defective shells, or otherwise correct them to the Engineer's satisfaction by driving an additional pile. The Engineer will inspect all driven shells. When the Engineer approves the driven shells, cut them off to a horizontal plane at the required elevation.

Before placing concrete, remove all water or debris from the shell. Place concrete in an approved manner that will ensure against segregation. Do not place concrete until completely driving all piles within a radius of 16 feet of the shell to be filled or until completely driving all the shells for any one bent or foundation. Continuously place the concrete in each pile, and exercise proper care to fill every part of the shell and to ensure a dense, homogeneous mixture.

The Engineer will not require steel reinforcement in cast-in-place piles unless specified in the Plans. When specified, use the type and design of reinforcement specified in the Plans.

Ensure that the finished tops of piles are at the elevation specified in the Contract or directed by the Engineer and that they project no less than 6 inches into pier footings and no less than 3 feet into end bents.

604.03.06 Test Piles. Drive test piles of a length and at the location designated on the plans or determined by the Engineer. These piles shall be of greater length than the length assumed in the design in order to provide for any variation in soil conditions.

Test Piles are for the Engineer's use in determining capability of the Contractor's equipment and adequacy of design. The Engineer will determine when an adequate

Maine (2002)

vibratory hammers shall be based on the driving resistance recorded during impact driving after the vibratory equipment has been removed. Vibrated piles not attaining the ultimate pile capacity at the ordered length shall be spliced, as required, at the Contractors cost, and driven with an impact hammer until the ultimate pile capacity is achieved as indicated by the appropriate criteria in Section 501.07. When the ultimate pile capacity is attained, the remaining piles shall be installed to similar depth with similar vibratory hammer power consumption and rate of penetration as the first pile.

Preaugering When necessary to obtain the specified pile penetration and when authorized by the Resident, the Contractor shall furnish the necessary drilling apparatus and drill holes, not greater that the least dimension of the pile top, to the proper depth and drive the piles therein. When specified in the contract documents, the Contractor shall prebore holes at pile locations and to the depths shown on the plans. Preaugered holes shall be of a size smaller than the diameter of diagonal of the pile cross section. If subsurface obstructions, such as boulders or rock layers are encountered, the hole diameter may be increase to the least dimension needed for pile installation. Any void space remaining around any type pile after driving shall be completely filled with sand or other approved material. The used of spuds, which are driven and removed to make a hole for inserting a pile, shall not be permitted in lieu of preboring.

Concrete shall not be placed in pipe piles until pile driving has progressed beyond a radius of 5 m [15 ft] from the pile to be concreted. If pile heave is detected for pipe piles that have been filled with concrete, the piles shall be redriven to the original position after the concrete has attained sufficient strength and a proper hammer-pile cushion system, is in place as is satisfactory to the Resident.

Heaved Piles Piles that have heaved more than 5 mm [¼ in] during the driving of other piles in a group shall be reseated to the required penetration or bearing capacity at the Contractor's expense.

Location and Alignment Tolerance The Contractor will be responsible to hold the piles in place to allowable tolerances. Piles shall be driven with a variation of not more than 20 mm/m [¼ in/ft] from the vertical or from the batter shown on the plans. For piles that cannot be inspected for axial alignment internally after installation, an alignment check shall be made before installing the last 1.5 m [5 ft] of pile, or after installation is completed provided the exposed portion of the piles is not less than 1.5 m [5 ft] in length. The Resident may require that driving be stopped in order to check the pile alignment. Pulling laterally on piles to correct misalignment, or splicing a properly aligned section of a misaligned section shall not be permitted.

The cutoff elevation of piles for trestle bents shall not be out of position by more than 50 mm [2 in] from the dimensions shown on the plans. The cutoff elevation of piles, other than for trestle bents, shall not be out of position by more than 150 mm [6 in]. Actual embedment of the piles in the concrete shall be within 150 mm [6 in] of that shown on the plans. The as-driven centroid of load of any group at cutoff elevation shall be within 5% of the plan location of the designated centroid of load. No pile shall be nearer than 100 mm [4 in] from any edge of the

Maryland (2001)

When considering the hammer for approval, the ratio of the weight of the pile to the weight of the striking unit will be evaluated to determine the adequacy of the hammer.

Leads or spuds shall be constructed to afford freedom of movement of the hammer during the driving phases. The Contractor shall drive the piles within the tolerance as specified without injury to the piles. Any leads that do not produce satisfactory end results in the driving of piling shall be removed from the work.

Driving with the hammer out of the leads is prohibited.

On all special, marine or water projects and pile bents, the leads shall be of sufficient length so that the use of a follower will not be necessary. Long piles and batter piles may require guides at intervals and additional support to prevent excessive bending or buckling under the hammer blow. Piles shall be held in place and alignment by templates or other means approved by the Engineer.

External jetting of any piles is prohibited. If it is necessary to remove material from within a pile shell to advance the pile tip or merely to obtain room for concreting, a minimum of 10 ft soil plug shall be left undisturbed at the tip of the pile. Turbidity curtains shall be installed around the piles being cleaned.

Where piling must perforate strata which resists driving, the Contractor shall auger or drill holes through the strata. The size of the auger or drill to be used shall not be larger than the nominal diameter of a round pile or the minimum diameter of a circle in which an H pile will fit and shall be approved by the Engineer before use. After the hole is completed, the pile shall be inserted and dry sand shall be used to completely fill any voids between the pile and the walls of the hole. Driving shall then be completed, after which any remaining voids shall be completely filled with dry sand.

410.03.07 Pile Driving Tolerances.

(a) **General.** Foundation piles shall not be used out of the position specified in the Contract Documents by more than 6 in. in any direction after driving, regardless of the length of piles. Variation from the vertical or from the batter shall not be more than 1/4 in./ft.

(b) **H Piles.** Rotation of the pile in excess of 25 degrees from the as planned axis is prohibited.

Massachusetts (1995)

The hammer cushion shall be inspected in the presence of the Engineer when beginning pile driving at each substructure element or after each 100 hours of pile driving, whichever is less. Any reduction of hammer cushion thickness shall be replaced by the Contractor before driving is permitted to continue.

D. Pile Cushion.

The heads of concrete piles shall be protected by a pile cushion made of plywood or other similar material approved by the Engineer. The minimum plywood thickness placed on the pile head prior to driving shall not be less than 100 millimeters. A new pile cushion shall be provided for each pile. In addition during the driving of each pile, the pile cushion shall be replaced if during the driving the cushion is either compressed more than one-half the original thickness or begins to burn. The pile cushion dimensions shall match the cross-sectional area of the pile top.

E. Leads.

The pile driver shall be equipped with fixed leads that are an integral part of the machine. The pile driving hammer shall ride in the ways of the leads. Fixed leads shall be used for driving all piles unless written approval to the contrary is obtained from the Engineer.

F. Followers.

Followers shall only be used when approved in writing by the Engineer, or when specifically stated in the contract documents. The follower shall be of such material and dimensions to permit the piles to be driven to the length determined necessary from the driving of the full length piles. The final position and alignment of the first two piles installed with followers in each substructure unit shall be verified to be in accordance with the location tolerances in this specification before additional piles are installed.

G. Jets.

Jetting shall only be permitted if approved in writing by the Engineer or when specifically stated in the contract documents.

Jetting will not be allowed when driving through newly placed embankment.

The use of water jets will be permitted only when excess of water will not affect adjacent structures. In general, jetting will not be permitted near railroad tracks.

When jetting is permitted, the Contractor shall determine the number of jets and the volume and pressure of water at the jet nozzles necessary to freely erode the material adjacent to the pile without affecting the lateral stability of the final in-place pile. The Contractor shall control, treat if necessary, and dispose of all jet water such as to meet environmental considerations. The Contractor shall be responsible for all damage to the site caused by jetting operations. The jetting plant shall have sufficient capacity to deliver at all times a pressure equivalent to at least 700 kiloPascals at two 20 millimeter jet nozzles. Unless otherwise indicated, jet pipes shall be removed when the pile tip is a minimum of 1.5 meters above prescribed tip elevation and the pile shall be driven to the required bearing capacity with an impact hammer.

H. Preaugering.

Preaugering shall only be permitted if approved in writing by the Engineer or when specifically stated in the Contract documents. When permitted, the Contractor shall provide the necessary equipment such as augers, well drilling machines, etc. to preauger holes at pile locations and to the depths required by the Engineer.

PILE INSTALLATION

940.60 Preparation for Driving.

A. Excavation.

When piles are located in an area where excavation is to be made or in an area where embankment is to be placed, the piles shall not be driven until the excavation has been made or the embankment has been placed. For either of the foregoing, the grade shall be brought to such an elevation as to compensate for possible uplift or subsidence of the surrounding earth. Adjustments in the grade shall be made after all the piles at the location have been driven. Additional excavation or embankment will be considered as part of the process of pile driving and will not be included in the payment for either excavation or borrow.

B. Preaugering.

Where timber, cast-in place, precast-prestressed concrete piles, or steel piles are to be driven through an embankment, and the depth of the embankment at the pile location is in excess of 1.5 meters, the Contractor shall make a hole for the full depth of the embankment for each pile with an auger or by other approved methods. The hole shall have a diameter of not less than the butt diameter of the pile. After driving, the annular space around the pile shall be filled to the ground surface with dry sand, fine gravel or pea stone. Material resulting from drilling holes shall be disposed of in accordance with Section 120, Excavation.

Michigan (2003)

705.03 Construction.

A. **Equipment.** Support pile hammers in leads. Allow the hammer free movement in the leads, rigged to hold the pile and hammer in alignment during driving. Drive piles with equipment that will ensure an evenly distributed hammer blow on the pile and prevent damage while driving.

Do not use drop hammers for driving permanent piling.

Use pile hammers with a minimum rated energy of not less than 13,000 foot-pounds per blow. Furnish an operator's manual and manufacturer's specifications for the hammer proposed for use.

Equip pile hammers with a bonnet or cap that will accurately and securely hold the top of the pile in the correct position relative to the hammer and distribute the blow from the ram over the entire top area of the pile.

B. **Test Piles.** Test piles are not required when the plans show the design pile length.

When test piles are required, determine the ordered pile lengths from the test pile results. The Engineer will evaluate test pile results and determine the ordered pile lengths for timber piles. Furnish cast-in-place concrete pile shells and steel piles of sufficient lengths to obtain the specified bearing capacity and penetration.

Before driving test piles, complete the excavation or embankment to within 2 feet of the proposed grade at the test pile locations. Drive the test piles to the minimum pile length or to practical refusal, whichever penetration is greater.

C. **Load Testing.** Perform load tests when specified by the contract documents. Refer to contract documents for load testing details.

D. **Pile Preboring.** When specified, prebore holes to the elevation shown. Provide a finished hole with a diameter equal to or slightly greater than the diameter of the pile.

Maintain a stable open hole until the pile has been installed and advanced to the bottom of the bore. Do not begin final drive for bearing until the pile reaches the prebore elevation. Control caving or unstable soil layers by using temporary casing or non-toxic and non-hazardous drilling slurry. Handle and dispose of drilling slurry according to the

Sedimentation and Erosion Control Act, Act 347 of 1972 as amended either on the site or at an off site location where existing or proposed structures will not be affected. Obtain approval from the Engineer for on site disposal.

Remove or clear boulders, cobbles, or other obstructions. Provide rock chisels, extractors, core barrels, or other equipment necessary to clear obstructions. The removal of obstructions that require this special equipment will be paid for as extra work.

To the extent possible, complete all preboring within a foundation unit and advance all piles to the prebore elevation, before beginning the final drive. When preboring occurs within 20 feet of a completed pile, recheck the pile capacity by restriking the pile. The Engineer will select the piles for restrike. Restrike with the same driving equipment used in the initial installation. If any reduction in capacity occurs, redrive all piles to design bearing.

Backfill all voids remaining after the final drive with granular material Class II or approved equal.

Prebore pile holes with a variation of not more than ¼ inch per foot from the vertical or from the batter line shown on the plans. Upon completion, the center of the hole at cutoff elevation must be within 6 inches of the position shown on the plans.

E. **Driving Methods.**

1. **General.** Drive piles after the excavation is complete. Where piles are to be driven through fills, compact the embankment to the bottom of the concrete substructure unit. Do not drive piles within a radius of 25 feet of newly placed concrete until the concrete has attained at least 75 percent of its specified minimum strength. Drive all piles for a given foundation unit with the same hammer, under the same operating conditions, and with the same cushion material used to drive the test piles.

   Provide watertight shells for cast-in-place piles. Always have available a mirror and a light suitable for illuminating the interior of the pile shells for their full length after driving. Replace all pile shells showing bends, kinks, or other deformations incurred during the process of driving, that the Engineer determines would impair the strength of the completed pile. Pull the damaged shell and drive a new shell in the same location or drive a new shell near the dam-

Minnesota (2014)

(1) Capable of holding the pile and the pile hammer in alignment during driving operations,
(2) Long enough to preclude the use of punches or chasers, and
(3) Meeting the requirements of the pile hammer manufacturer.

C.4 Water Jets

Provide jets capable of delivering water in the volume and pressure required to freely erode the material adjacent to the pile. Provide a water source capable of maintaining at least 100 psi [690 kPa] of pressure at two jet nozzles, ¾ in [19 mm] in diameter.

D Pile Driving

Notify the Engineer at least 24 h before beginning pile driving operations. The Engineer will reestablish the working points for each substructure unit after the Contractor completes the excavation for that unit. Stake the pile locations.

Excavate to the bottom of footing elevation as shown on the plans before driving foundation piles or test piles in any substructure. During pile driving operations, keep the water level in the excavation below the top of the pile. Do not perform underwater pile driving unless a concrete foundation seal is required to dewater cofferdam.

For each foundation pile, perform continuous pile driving operations unless otherwise directed by the Engineer.

Sharpen timber piles to a square point with dimensions at least 5 in [127 mm] at the tip. Provide timber piles with blunt ends for soils with SPT below counts less than 20 as shown in plan borings or for piles having point bearing on hard stratum.

Do not use punches or chasers for pile driving if the contract requires a concrete foundation seal in a cofferdam. If driving piles in a cofferdam, provide the extra length of piling to drive the piles to the cutoff elevation, at no additional cost to the Department. Accurately locate and space the piling as shown in the bridge plans with tolerances per 2452.3.D.4, "Foundation Piles," 2452.3.D.5, "Pile Bents," and 2452.3.F.2, "Pile Bents."

Provide pile material and appurtenances capable of withstanding driving to substantial refusal defined in accordance with 2452.3.E.1, "General." The Department considers failure of piles during pile driving operations to include buckling, bending, kinking, splitting, or rupturing that will impair the strength of the pile or reduce the effectiveness of the energy delivered by the pile hammer, as determined by the Engineer.

If the Engineer determines that the piling material and appurtenances cannot withstand driving to substantial refusal, discontinue pile driving and correct or change the pile driving operations, equipment, or material as approved by the Engineer.

If failure of the pile occurs after the Engineer directs the Contractor to continue driving after obtaining substantial refusal, the Department will pay for the cost of the failure.

D.1 Jetting and Preboring

The Contractor may perform water jetting if needed, or as required by the contract, to aid in driving displacement type piles. Do not perform jetting in embankments or in areas where the jetting may damage the existing soils. Before reaching a preset depth approved by the engineer but not less than 5 ft [2 m] of the final tip elevation, withdraw the jets and drive the piles with the hammer to secure the final penetration. Control and dispose of jet water, as approved by the Engineer.

Perform preboring for displacement type piles driven through embankments if the embankment depth, measured below the bottom of the footing, is greater than 8 ft [2.4 m]. Perform preboring through the depth of the embankment. Continue preboring through shallow, dense crust at the surface of the original ground as directed by the Engineer.

Perform preboring through embankments less than 8 ft [2.4 m] if the material may damage the piles during driving, as directed by the Engineer. Perform preboring for displacement type piles if the material below the bottom of a footing precludes driving to a penetration of 10 ft [3.0 m] below the bottom of the footing without damaging the piles, as directed by the Engineer. If the pile does not penetrate greater than 0.03 in [0.75 mm] per blow for each 1000 foot pounds [1,356 J] of rated energy, the Engineer will consider this, the weight of the ram, and the type and size of the piles to determine the probability of damage.

Make prebored holes of a diameter that will admit the largest cross-sectional diameter of the pile without creating friction between the faces of the pile and the prebored hole.

D.2 Test Piles

Provide test piles as required by the contract. Drive test piles at the locations shown on the plans unless otherwise approved or directed by the Engineer.

Place full lengths of test piles in the leads and continuously drive, unless otherwise approved by the Engineer. The Contractor may perform sectional driving if the Engineer determines from the survey sheet or from previous pile driving in the area that the test piles can be driven in sections without the danger of "set-up" during the splicing period.

Assist the Engineer in obtaining data (examples: lay pile in a safe location, marking pile with 10 blow count, attach gauges as instructed) for bearing for the full length of the pile driving. Redrive the test piles as required by the Engineer and in accordance with 2452.3.D.8, "Pile Redriving."

If the Engineer determines that steel test piles have not developed adequate bearing capacity per 2452.3.E.1, "Penetration and Bearing, General," provide additional lengths and splice as directed by the Engineer.

D.3 Static Pile Load Tests

Provide Axial Static Compressive Load Testing (ASTM D1143M) , Axial Static Tension Load Testing (ASTM D3689), Lateral Static Load Testing (ASTM D3966), Quasi-Static Load Testing (ASTM D7383), O-Cell Load Testing, or similar testing for evaluation of either axial or lateral compressive or tensile load and deformation analysis.

a) Coordinate test program with Construction, Bridge, and Materials offices.
b) Provide materials, furnish labor, and conduct the test program as required by the contract. Install temporary and permanent instrumentation as required by the contract or as directed by the Engineer.
c) Analyze and report data both in hard-copy format and electronic format in a timely manner.
d) Adjust test program as directed by the Engineer based on conditions encountered in the field.
e) If the test program is used for construction control, provide appropriate analysis and field inspectors' charts, as described in section K, for assessment of the capacity of foundation piling.

D.4 Foundation Piles

Guide piles during driving. Complete pile driving with piles having the required batter or plumbness within ½ in per ft [40 mm per m], and having a final position within 6 in [150 mm] of plan location within the footing area. The Engineer may reject or reduce payment for improperly positioned piles, as determined by the Engineer.

If the Engineer determines that some piles in a unit have heaved during the driving of other piles in the unit, redrive the piles as directed by the Engineer to complete the pile driving.

D.5 Pile Bents

The Department defines pile bents as piles meeting the following characteristics and requirements:

(1) Driven in single rows,
(2) Capped with timber, steel, or concrete caps, and
(3) Driven to closer tolerances than for general pile driving, as described below.

Mississippi (2004)

protect the pile top during driving and shall be constructed such that the hammer energy is uniformly distributed to the pile top. The pile cushion shall be changed prior to driving each pile. In addition, if the cushion material becomes highly compressed, or chars or burns during the driving operations or damage occurs at the pile top, it shall be replaced. The type of material and dimensions of the pile cushion shall be included in the appropriate place on the *Pile and Driving Equipment Data Form.*

803.03.1.7.4.3--Water Jets. Water jets may be used in conjunction with the pile hammer to install piles to the required depth or penetration called for in the plans. The use of water jets, where the stability of embankments or other improvements would be endangered, will not be permitted. When water jets are used, the number of jets and the volume and pressure of water shall be sufficient to adequately facilitate driving without undue damage to the pile or the soil adjacent to or below the pile. Unless otherwise specified, water jets shall not be used within five feet of the final tip elevation of the pile. In addition, it shall be the Contractor's responsibility to withdraw the water jets sufficiently above the five foot requirement to obtain the specified bearing at the required cut off elevation.

In the event a jetted pile fails to obtain the specified bearing at the required penetration and a determination is made by the Engineer that the Contractor has failed to properly control the jetting operation, the Contractor should submit detailed corrective measures for founding the pile to the Engineer for approval. Any required corrective measures to the pile due to the Contractor's operation shall be performed at no additional cost to the State.

803.03.1.7.4.4--Followers. Followers are considered to be part of the Driving System and should be included for approval with the *Pile and Driving Equipment Data Form.* Included with the submittal should be a dimensioned sketch of the follower. Also, the type(s) of materials that the follower is made of and the weight of the follower should be included as well as cushion information.

803.03.1.7.4.5--Pre-formed Pile Holes. The Bridge Engineer will make all determinations as to the necessity for pre-formed pile holes and the size and maximum depth of each hole required or permitted.

If it is determined from the Geotechnical Investigation or from the site survey that pre-formed pile holes are necessary, a pay item and estimated quantities will be included on the plans, and the Bridge Engineer will furnish the Contractor with an itemized list showing the location, size and bottom elevation of each hole.

If the plans do not specify pre-formed pile holes and the Bridge Engineer, with the concurrence of the Construction Engineer, determines during construction that subsurface conditions are encountered that necessitate pre-formed pile holes, at certain locations, an adjustment in the contract unit price for furnishing and driving piling at these locations may be made under the provisions of Subsection 104.02.

If in the judgment of the Engineer pre-formed pile holes are not required and the Contractor desires to use them, the Contractor may be permitted to do so under conditions prescribed by the Bridge Engineer and at no additional cost to the State.

803.03.1.7.4.6--Additional Equipment. When a minimum penetration is indicated on the plans and is not obtained by the use of an approved hammer, the Contractor shall submit to the Engineer for approval a completed *Pile and Driving Equipment Data* Form for a heavier hammer or resort to jetting at no additional cost to the State.

803.03.1.8--Defective Piles. Prior to driving, piles shall not be subjected to handling that causes damage either through bending, crushing or spalling of concrete, or deformation of the steel. All piles damaged because of internal defects or by improper driving, driven out of the proper location or driven below the specified elevation shall be corrected at the Contractor's expense by one of the following methods approved by the Engineer for the pile in question:

1) The pile shall be withdrawn and replaced by a new and, if necessary, a longer pile.
2) A second pile shall be driven adjacent to the defective or low pile.
3) The pile shall be spliced or built up or a sufficient portion of the footing shall be extended to properly embed the pile. All piles pushed up by the driving of adjacent piles or by any other cause shall be driven down to grade.

803.03.1.9--Determination of Bearing Value of Piling.

803.03.1.9.1--General. The ability of the pile to transfer load to the ground will be determined to the satisfaction of the Bridge Engineer. Such determination will be made by the Geotechnical Engineer and Foundation Engineer from a subsurface investigation conducted by the Geotechnical Branch of Materials Division and test piles that are driven out-of-position or driven to be incorporated in the structure as permanent piles.

803.03.1.9.2--Determination of Bearing Value by Pile Hammer Formulas. When load testing, either static or dynamic, is not called for in the plans, the safe bearing values will be determined by the following formulas or as directed by the Engineer.

$$P = \frac{2WH}{S+0.2}$$ for single-acting steam/air hammers and open cylinder diesel hammers

Missouri (2011)

702.4 Construction Requirements.

702.4.1 Test Piles. The contractor shall furnish and drive test piles at locations specified. Where required, test piles shall be driven to refusal or to a capacity 50 percent greater than that shown on the plans. In all cases, test piles shall be driven to at least the minimum tip elevation shown on the plans for permanent piles. If no minimum tip elevation is shown on the plans, piles shall have a tip elevation at least 10 feet below the bottom of the supported footing or 10 feet below the natural ground line, whichever is lower, unless specifically authorized otherwise by the engineer. Test piles shall be driven with the same type of equipment as will be used for driving the permanent piles. Before driving test piles, the excavation shall be completed to an elevation no more than 2 feet above the proposed grade at the point where a test pile is to be driven. Test piles not driven in a permanent location shall be cut off, or pulled and backfilled as approved by the engineer.

702.4.2 Load-Bearing Piles. Load-bearing piles shall not be driven until after the excavation for the footing has been substantially completed. The heads of piles shall be protected against damage during driving. The procedure incident to the driving of piles shall not subject piles to excessive and undue abuse. Any pile broken or damaged by reason of internal defects, by improper driving, or driven outside of the pile's proper location, shall be removed and replaced, or a second adjacent pile may be driven if this can be done without detriment to the structure, as determined by the engineer.

702.4.3 Preboring. Where piles are to be driven through more than 5 feet of compacted embankment that has been in place for less than five years, holes shall be prebored entirely through the embankment to the lowest elevation of the natural ground line adjacent to the embankment, or as shown on the plans. The holes shall have a diameter no less than that of the pile. After the pile is placed in the hole and before driving begins, the space remaining around the pile shall be filled with sand or other approved material before and maintained full during the driving of the pile.

702.4.3.1 Other locations where preboring for piles will be required will be shown on the plans. At such locations, holes shall be prebored to the elevation specified prior to pile placement. The holes shall have a diameter no less than that of the pile and shall be large enough to avoid damage to the pile being driven through the hole in hard material. The size of the hole shall be approved by the engineer before preboring is started. Pilot holes of lesser diameter than the pile shall not extend below the pile tip. Either prior to or after placement of the pile, the hole shall be filled with sand or other approved materials. The hole shall be maintained full with sand or other approved material during the driving of the pile. The pile shall then be driven in accordance with Sec 702.4.11.

702.4.4 Pile Placement Tolerances. Final position of piles shall be no more than 1/4 inch per foot from the vertical or from the batter line shown on the plans. The maximum variation of the head of the pile from the position shown on the plans shall be no more than 2 inches, except that piles in footings entirely below the finished ground line may not vary more than 6 inches. All piles forced upward by the driving of adjacent piles or by any other cause shall be redriven to the required minimum nominal axial compressive resistance and penetration.

702.4.5 Pile Point Reinforcement. Each point shall be manufactured in one piece of cast steel. Pile points furnished for cast-in-place concrete piles shall be attached to the pile in accordance with the manufacturer's recommendations and as specified herein. Pile points for structural steel piles shall be furnished with the minimum point web and flange thickness at the location of attachment to the pile equal to the thickness of that portion of the pile being attached thereto multiplied by the factor (t) shown below with additional requirements as described herein.

Montana (2006)

the hammer are at least 1/3 the weight of the helmet and the pile being driven or 2,750 lbs. (1,250 kg), whichever is greater.

Provide open-end (single-acting) diesel hammers with rings or other indicators on the ram that permit visual determination of the hammer stroke as the pile is driven. Submit a copy of the hammer manufacturer's chart that equates the stroke and blows per minute for the hammer being used.

Provide closed-end (double-acting) hammers with an accurate bounce chamber pressure gauge that is easily read from ground level. Submit a copy of a chart, calibrated to the actual hammer performance that equates the bounce chamber pressure to the equivalent energy or stroke of the hammer.

Provide equipment for hydraulic hammers that are sized to maintain the manufacturer's specified volume and pressure during driving. Provide equipment with accurate pressure gauges that are easily read from ground level.

Delays and additional costs resulting from load tests or other extra work required to verify approval of the vibratory hammer or driving aids is at Contractor's expense. If a vibratory hammer is used, re-drive each pile with an impact hammer having the energy to verify the ultimate pile capacity, as required in Subsection 559.03.3.

B. **Pile Driving Aides and Accessories.**

1. **Followers.** Do not use followers.
2. **Helmet.** Provide metal helmets for pile to be driven by impact drivers. Helmets must fit around the pile top, align axially with the hammer and pile, distribute the hammer energy to the total pile head cross section and have leads to guide them.
3. **Hammer Cushion.** When driving pile with an impact hammer, use a cushion to prevent damage to the pile and hammer. Use a cushion recommended and approved by the hammer manufacturer. Use a striker plate recommended by the hammer manufacturer on the hammer cushion to provide uniform compression of the cushion material.
4. **Leads.** Support the piles in line and position during driving. Use pile hammer leads that permit free movement of the hammer, maintain hammer and pile alignment and provide concentric impact for each blow.
5. **Jets.** Do not use water jets.
6. **Caps.** Follow the pile manufacturer's recommendations regarding caps, driving heads, mandrels or other required devices.

C. **Pile Pre-drilling.** When specified in the plans, use the prescribed drilling methods discussed in this specification. Do not impair the capacity of previously installed pile or the safety of adjacent structures. If drilling reduces the capacity of previously placed pile, restore the disturbed pile to conditions meeting this specification by re-driving after drilling operations in the area have been completed.

1. **Pile Pre-bore.** When pile pre-bore is specified, use an auger, wet-rotary drill or other approved method. Drill pre-bore holes to the specified diameter and depth. Drive the pile in the pre-bore hole, starting from the bottom of the hole, with an impact hammer evaluated in accordance with Subsection 559.03.2. Continue driving the pile to the ultimate pile capacity and the depth specified. After driving, fill the annular void around the pile with dry, fine concrete aggregate meeting the requirements of Subsection 701.01.1 and Table 701-2.
2. **Pile Drill and Socket.** At each pile location, drill pilot holes a maximum of one inch (25 mm) in diameter less than the outside diameter of the round pile and a maximum of 4 inches (100 mm) less than the outside diagonal cross sectional measurement of square or H-pile, to the elevation specified. Drive the pile into the pre-drilled pilot hole

to the bottom of the hole with an impact hammer evaluated in accordance with Subsection 559.03.2. Continue driving the pile below the bottom of the drilled hole to the design tip elevation specified in the plans, or deeper if directed by the Project Manager.

559.03.2 Evaluation of Pile Driving Equipment

The Department will evaluate pile-driving equipment provided by the Contractor. The equipment must have the capability to drive the project pile to the design pile tip elevation and required ultimate pile capacity without damage to the pile. When dynamic load tests are required by the contract, submit a wave equation analysis performed by a pile specialty consultant meeting the requirements of Subsection 559.03.3(B)(2). The Department will base hammer evaluations on wave equation analysis. Submit the pile driving equipment information on Form CSB559_03_2. Provide pile-driving equipment that produces the following results from the wave equation analysis:

- 35 to 120 blows per one foot (0.3 meter) at ultimate capacity; and
- Maximum compressive driving stress less than 90 percent of the minimum pile material yield strength.

The Project Manager will notify the Contractor of results of the pile driving equipment evaluation within 14 calendar days after receipt of the Pile and Driving Equipment Data form. If the wave equation analysis indicates that pile damage may occur or that the proposed pile driving equipment cannot drive the pile to the specified ultimate capacity, re-submit a plan that modifies the equipment or the method to ensure the ability to drive pile to the specified ultimate capacity without pile damage. The Project Manager will notify the Contractor of results of the revised pile driving submission within seven calendar days after receipt of the re-submittal.

Do not vary from the evaluated driving system without prior written approval. The Department will consider proposed changes to the pile driving equipment or method only after submittal of revised information for a new wave equation analysis. The Project Manager will notify the Contractor of evaluation results of the pile driving system changes within seven calendar days after receipt of the submittal. Delays and additional costs associated with developing, submitting and obtaining evaluation results for pile driving proposals and resulting changes in the pile driving equipment and work methods are at Contractor's expense.

559.03.3 Pile Capacity

A. **Driven Pile Capacity.** Drive the pile to the design tip elevation shown on the plans or deeper, if necessary, to reach ultimate pile capacity. The Project Manager will use one of the following methods specified to determine ultimate driven pile capacity.

   1. **Wave Equation.** The Department will determine ultimate pile capacity based on a wave equation analysis. Drive piles with the pile driving equipment evaluated in accordance with Subsection 559.03.2 to the depths necessary to obtain ultimate pile capacity. Do not use other methods to aid pile penetration, unless specified or approved after a revised driving resistance is established from the wave equation analysis. Unless otherwise specified, adequate pile penetration consists of reaching the specified wave equation resistance criteria within 1 foot (0.3 meter) of the pile tip elevation. Drive pile not achieving the specified resistance within these limits to penetrations established by the Project Manager.
   2. **Dynamic Formula.** The Department will determine ultimate pile capacity based on a dynamic formula. Drive pile to obtain the ultimate pile capacity determined by the following formula:

Nebraska (2007)

(1) The minimum weight of gravity hammers which may be used for driving shells for cast-in-place concrete, pipe piles, and steel bearing piles shall be as shown in Table 703.02.

Table 703.02

Minimum Gravity Hammer Weight	
Design Bearing Capacity of Pile in Tons (kN)	**Gravity Hammer Weight in Pounds (kg)**
8 – 12 (70-105)	2,000 (900)
More than 12 – 15 (105-135)	2,500 (1100)
More than 15 – 22 (135-195)	2,800 (1250)
More than 22 – 28 (195-250)	3,000 (1350)
More than 28 – 37 (250-330)	3,500 (1600)
More than 37 – 50 (330-445)	4,000 (1800)

(2) The weight of the gravity hammer for driving precast concrete bearing piles shall not be less than 30 percent of the weight of the pile and never less than 2,000 pounds (900 kg).

d. The fall of gravity hammers shall be regulated so as to avoid damage to the piles.

e. (1) No pile shall be driven without the use of leads. Pile driver leads shall be designed to afford free movement of the hammer and shall support the pile and hammer in proper position during driving. The stroke of the hammer shall be accurately in line with the axis of the pile. Leads, pile, and hammer shall be held in proper vertical or battered alignment to place the piles within the tolerances allowed.

(2) Swinging leads may be used with steam, air, or diesel hammers if the results obtained meet all requirements of these *Specifications*.

(3) Pile driver leads used with gravity hammers shall be guyed, braced, or fixed.

f. When water or air jets are used, the number of jets and the volume and pressure at the jet nozzles shall be sufficient to freely erode the material adjacent to the pile. Before the desired penetration is reached, the jets shall be withdrawn and the piles shall be driven with the hammer to secure the final penetration.

g. (1) The Contractor has the option of starting piling in augured holes.

(2) Augured hole length shall not exceed 30 percent of the below-ground length of the pile.

(3) Augured hole diameters shall not be more than 2 inches (50 mm) larger than the pile.

3. Driving of Bearing and Sheet Piles:

a. Piles shall be driven to the depth and bearing shown in the plans

New Hampshire (2010)

the driving of the full length piles. The final position and alignment of the first two piles installed with followers in each substructure unit shall be verified to be in accordance with the location tolerances in 3.6.4 before additional piles are installed.

2.2.2.6 Jets. Jetting shall only be permitted if approved in writing by the Engineer or when specifically stated in the Contract documents. When jetting is permitted, the Contractor shall determine the number of jets and the volume and pressure of water at the jet nozzles necessary to freely erode the material adjacent to the pile without affecting the lateral stability of the final in-place jetted pile and adjacent piles. The Contractor shall control, treat if necessary, and dispose of all jet water in a manner satisfactory to the Engineer. The Contractor shall be responsible for all damage to the site caused by unapproved or improper jetting operations. When jetting is specifically required in the Contract documents, the jetting plant shall have sufficient capacity to deliver at all times a pressure equivalent to at least 100 psi (690 kPa) at two 3/4 in. (19 mm) jet nozzles. In either case, unless otherwise indicated, jet pipes shall be removed when the pile tip is a minimum of 5 ft. (1.5 m) above prescribed tip elevation and the pile shall be driven to the required ultimate resistance with an impact hammer.

2.2.2.7 Preboring. When specified in the Contract documents, the Contractor shall prebore holes at pile locations and to the depths shown on the plans. Prebored holes shall be of a size smaller than the diameter or diagonal of the pile cross section that is sufficient to allow penetration of pile to the specified depth. If subsurface obstructions, such as boulders or rock layers are encountered, the hole diameter may be increased to the least dimension which is adequate for pile installation. Any void space remaining around any type pile after driving shall be completely filled with sand or other approved material. The use of spuds, a short strong driven member which is removed to make a hole for inserting a pile, shall not be permitted in lieu of preboring.

2.2.3 Approval of pile driving equipment. All pile driving equipment furnished by the Contractor shall be subject to the approval of the Engineer. All pile driving equipment shall be sized to meet the requirements in 2.2.1. Approval of pile driving equipment by the Engineer will be based on wave equation analysis and/or other judgments. In no case shall the driving equipment be transported to the project site until approval of the Engineer is received in writing. Prerequisite to such approval, the Contractor shall submit to the Engineer the necessary pile driving equipment information at least 30 days prior to driving piles. The form for the above information is shown in Figure 1. A full size form will be included in the Contract documents or supplied by the Engineer.

2.2.3.1 Wave equation analysis. The criteria, which the Engineer will use to evaluate the driving equipment from the wave equation results, consist of both the required number of hammer blows per in. (25 mm) and the pile stresses at the ultimate pile resistance. The required number of hammer blows indicated by the wave equation at the ultimate pile resistance shall be between 3 and 15 per in. (25 mm) for the driving equipment to be acceptable. The pile stresses which are indicated by the wave equation to be generated by the driving equipment shall not exceed the values where pile damage impends, if the equipment is to be acceptable.

2.2.3.1.1 The point of impending damage in steel piles is defined herein as a compressive driving stress of 90 percent of the yield point of the pile material.

For concrete piles, tensile stresses shall not exceed the following:

In ENGLISH units:

3 multiplied by the square root of the concrete compressive strength, f ' c, in pounds per square inch, plus the effective prestress value, in pounds per square inch, $3\sqrt{f'c} + \text{prestress}$.

In METRIC units:

0.25 multiplied by the square root of the concrete compressive strength, f ' c, in megapascals, plus the effective prestress value, in megapascals, $0.25\sqrt{f'c} + \text{prestress}$.

Compressive stresses shall not exceed 85 percent of the compressive strength minus the effective prestress value (0.85 f ' c - prestress).

These criteria will be used in evaluating wave equation results to determine acceptability of the Contractor's proposed driving system.

New Jersey (2007)

Round Timber Piling 915.02
Timber Treatment 915.05

502.02.02 Equipment

Provide equipment as specified:

Impact Hammers 1004.01
Vibratory Hammers 1004.02
Leads and Followers 1004.03

502.03 CONSTRUCTION

502.03.01 Furnishing Pile Driving Equipment

Perform a wave equation analysis program (WEAP) for each pile type and hammer combination. Ensure that the number of required hammer blows at the ultimate pile resistance indicated by the WEAP analysis is between 3 and 10 blows per inch. Also ensure that the compressive and tensile pile stresses are within the allowable limits.

Submit 4 copies of the WEAP analysis, signed and sealed by a Professional Engineer, and 4 copies of the NJDOT Pile and Driving Equipment Data Form to the Department for approval 30 days before delivery of the equipment to the Project Limits. Submit a separate WEAP analysis and NJDOT Pile and Driving Equipment Data Form for each pile type and hammer combination.

502.03.02 Preboring Holes

When preboring holes for round piles, use an auger with a diameter that is between 2 inches smaller than the average nominal diameter of piles. When preboring holes for steel H-piles, use an auger with a diameter that is 4 to 6 inches less than the nominal diagonal dimension of the piles. Backfill the void between the piles and the prebored holes with granular material.

502.03.03 Driving Piles

A. Wave Equation Analysis Program (WEAP). When Dynamic Pile Load Tests will not be performed, the RE will determine the ultimate bearing capacity of the pile, the anticipated number of hammer blows per inch, and the anticipated compressive and tensile pile stresses at the required ultimate pile capacity using the wave equation analysis.

B. Methods of Driving. Do not drive piles in embankments until the embankment work, including placement, compaction, and removal of surcharge has been completed. Do not drive piles within 200 feet of concrete that is being placed or has been placed within the previous 24 hours unless approved by the RE. When driving piles in groups, start from the center of the group and proceed outward in both directions, or start from the end of the group and proceed to the opposite end of the group.

When using followers in driving, drive 1 long pile in each group of 10 without a follower as a test pile to determine the average bearing capacity of the group.

Do not install precast and prestressed concrete piles for at least 21 days after fabrication. If at any point precast and prestressed concrete piles are cured at 40 °F or below, the RE may require additional curing time before the installation of the piles. Additionally, do not install precast and prestressed concrete piles in seawater, brackish water, or sulfate soils for at least 30 days after fabrication.

The Contractor may use vibratory pile drivers, with the approval of the RE, to advance steel bearing piles. Obtain RE approval before jetting piles. The RE will require use of an impact pile driver for at least the final 10 feet of penetration.

Drive piles as follows:

1. **Accuracy of Driving.** Ensure that piles are driven within 1/4 inch per foot from the vertical or batter. Ensure that the driven piles are within 6 inches of the specified position. Ensure that piles for trestle bents are driven

New Mexico (2014)

501.3.3 Preparation for Driving

501.3.3.1 Abutment Piles

Unless otherwise shown, and before driving the abutment bearing piles, place and compact the approach Embankment Material underneath and adjacent to the abutment to the required density. After compaction, ensure that the surface of the approach Embankment is not lower than the elevation of the bottom of the abutment.

501.3.3.2 Pre-Boring

If specified, pre-bore holes at pile locations to the depths and size in accordance with the Plans. If the Contract does not specify pre-bored, but the Foundation Engineer approves the use of pre-bored holes, drill the holes to the depth established by the Foundation Engineer. Ensure that the depth permits the piles to be driven to the minimum penetration elevation and required bearing capacity without overstress or damage to the piles. Pre-bore holes in the presence of the Inspector. After placing pile, fill voids remaining around the pile with sand or other approved material.

501.3.3.2.1 Application of Pre-Bored Holes

Only use pre-bored holes as specified, or when demonstrated to the satisfaction of the Foundation Engineer that a pile cannot be driven to the minimum penetration elevation in accordance with Section 501.3.5.2, "Minimum Penetration Elevation."

The Department will determine the need for pre-bored pile holes based on the following driving resistances:

1. Steel piles: when, in ten (10) blows, the set is less than 3/4 inch with the hammer delivering the minimum energy required;
2. Pre-cast concrete piles: when, in ten (10) blows, the set is less than one (1) inch with the hammer delivering the minimum energy as required in the Contract;
3. All piles: if the resistance is sufficient to overstress the pile as indicated by the Wave Equation Analysis Field Acceptance Chart for the approved hammer system.

501.3.3.2.2 Diameter of Pre-bored Holes

The Foundation Engineer will establish the diameter of pre-bored holes. In general, the diameter established will be as shown in Table 501.3.3.2.5:1, "Diameter of Pre-Bored Holes in Soil," or Table 501.3.3.2.5:2, "Diameter of Pre-Bored Holes in Rock, Shale, or Conglomerate."

501.3.3.2.3 Obstructions

If the Contractor encounters subsurface obstructions, the Contractor may increase the borehole diameter to the smallest dimension adequate for pile installation. Penetrate obstructions in accordance with Section 502.3.4.2.2, "Obstructions."

501.3.3.2.4 Rock Sockets

If the Contract requires the Contractor to drive a pile in a rock socket and the bore hole is larger than the diameter of the pile, fill around that part of the pile in solid material with Class G concrete. Place concrete in accordance with Section 502.3, "Construction Requirements." Fill the part of the pile above the rock socket with sand or other suitable material.

501.3.3.2.5 Temporary Casing

Temporary casing may be required if the soil sloughs or caves into the hole or if a hole is required to be kept dry from groundwater, such as socketed holes into shale. Increase the diameter of the drilled hole as necessary to place the temporary casing. Pull the casing after driving the pile and after the hole is backfilled with the appropriate Material.

Table 501.3.3.2.5:1
Diameter of Pre-Bored Holes in Soil

Pile type	Diameter
Cylindrical concrete piles	two (2) inch smaller than the outside pile diameter
Square concrete piles	Minimum pile width
H-piles	two (2) inch smaller than the diagonal measurement of pile

Table 501.3.3.2.5:2
Diameter of Pre-Bored Holes in Rock, Shale, or Conglomerate

Pile type	Diameter
Cylindrical concrete and pipe piles	Outside pile diameter
Square concrete piles and H-piles	Diagonal measurement of pile

501.3.3.3 Pile and Hammer Cushion Preparation

Before the drive head is attached, make the pile heads plane and perpendicular to the longitudinal axis of the pile. Protect pre-cast concrete pile heads with a pile cushion in accordance with Section 501.3.1.2.3, "Pile Cushion." Provide a new pile cushion for each pre-cast concrete pile. Replace the pile cushion if it is either compressed more than one-half of the original thickness or begins to burn during driving.

Inspect the hammer cushion with the Inspector present when beginning pile driving at each Structure or after each 100 h of pile driving, whichever is less. If the hammer cushion thickness is reduced by more than 25% of the original thickness, replace the cushion before proceeding with driving.

501.3.3.4 Conditions to Proceed

The Contractor shall not drive production piles until it meets the following conditions:

1. The Foundation Engineer approves the driving system in accordance with Section 501.3.1.4, "Approval of Driving System;"
2. The Inspector completes the *Pile Driving Field Inspection Form* and the form is then approved by the Project Manager;
3. All required load testing is complete as specified and in accordance with Section 504, "Load Testing of Bearing Piles;"
4. The *Pile Driving Acceptance Chart* is completed and stamped with New Mexico P.E. seal by the Foundation Engineer and approved by the State Geotechnical Engineer and submitted to the Project Manager;
5. The hammer and leads are aligned with the pile plan in vertical or battered position; and
6. The Inspector is present before beginning operations.

501.3.4 Variations of Approved Driving Systems

Only use the approved pile driving system. Submit a new *Pile and Driving Equipment Data Form* to the Project Manager for variations to the approved driving system. The Project Manager will notify the Contractor of Acceptance or rejection within 72 h of the receipt of the data form. The time required for submission, review, and approval of a variation in the driving system will not constitute a basis for a Contract Time extension.

501.3.4.1 Variations Due to Dynamic Testing

The Foundation Engineer will reject the hammer if the hammer is unable to transfer sufficient energy to perform the dynamic testing in accordance with Section 504, "Load Testing

North Dakota (2008)

a. The gravity hammer has a free fall.

b. The head of the pile is free from broomed or crushed fiber.

c. The penetration of the pile is at a reasonably uniform rate.

d. There is no noticeable bounce after the blow. When there is a noticeable bounce, twice the height of the bounce shall be deducted from "H" to determine the value of "H" in the formula.

The bearing value of timber piles, as determined from formulas, shall be considered effective only when they are less than the safe working stresses for the materials of which the piles are made. When water jets are used with the driving, the bearing value shall be determined by the formulas from the results of driving after the jets have been withdrawn.

B. **Pile Driving.** Piling shall not be driven unless the Engineer is present and was given at least 24 hours advance notice of any pile driving operations.

Pile shall not be driven within 80 feet of concrete which has cured less than 3 days, or a greater distance if determined necessary by the Engineer.

Before driving foundation piles, the excavation shall be completed to the bottom of the footing elevation.

Any excess excavation and voids remaining after pile driving is completed shall be backfilled and compacted to the bottom of the footing elevation with foundation fill, at the Contractor's expense.

Timber piles may be sharpened at the tip.

A steel head block or cap fitted to the pile head shall be used to prevent damage to the pile head. The head block or cap shall be provided with a shock block or cushion. Where necessary, bands shall be used to prevent splitting in the body of timber pile.

Pile driver leads shall be used for all types of hammers. They shall allow free movement of the hammer and rigidly hold the pile in correct alignment during the driving operation.

The driving of piling with followers is not permitted.

When specified penetration cannot be obtained without damaging the pile, the Engineer may approve the use of jetting, preboring, or spudding to secure the required penetration. The final driving shall be with the hammer for determining bearing.

When pilings are driven through a constructed embankment, having a thickness of 5 feet or more below the bottom of footing, the embankment shall be prebored for each pile. All pilot holes not completely filled by piles shall be backfilled with sand or fine gravel before the substructure is built.

Sawing or cutting the body of a pile to assist in springing it to proper location is not permitted. If a pile vibrates excessively or shows signs of buckling during driving, it shall be braced or guyed to assure satisfactory results.

<u>Ohio (2005)</u>

507.11 Prebored Holes. Locate prebored holes as shown on the plans. Provide augured hole diameters:

A. For round piles, from 2 inches (50 mm) less to 4 inches (100 mm) more than the pile diameter.

B. For steel H-piles, from 6 inches (150 mm) less to 2 inches (50 mm) more than the pile's diagonal dimension but shall be such as to produce satisfactory pile driving results. Backfill voids between the pile and the prebored hole with a granular material satisfactory to the Engineer.

507.12 Method of Measurement. The Department will measure piles driven by the number of feet (meters). The Department will determine the sum as the lengths of all non-defective piles measured along the axis of each pile from the bottom of each pile to the elevation of cutoff. Unless a separate pay item is specified in the Contract, the Department will include Steel Points or Shoes in the measured length of driven piles. If a separate pay item is specified in the Contract, the Department will measure Steel Points or Shoes by the number of each.

The Department will measure piles furnished by the number of feet (meters) of plan specified order length plus any additional order length specified by the Engineer. The Engineer will include the length of undriven piles as furnished, but the Contractor will not receive additional compensation for hauling the piles off the project.

For plan specified prebored holes, the Department will measure Prebored Holes by the number of feet (meters) of prebored hole lengths for non-defective piles measured from the surface of ground at the time of boring to the bottom of the hole. The Department will not measure preboring to facilitate the pile driving operation.

The Department will measure steel pile splices by the number of splices authorized by the Engineer to lengthen non-defective piles beyond the plan specified length. Instead of plan specified steel pile splices, the Contractor may choose to furnish steel piles longer or shorter than the plan specified pile order lengths.

507.13 Basis of Payment. Preboring to facilitate the pile driving operation is included in the unit price bid for piles driven.

The Department will not pay for any splices due to the Contractor furnishing pile lengths shorter than plan order lengths.

The Department will not pay for increased pile lengths made by the Contractor unless the Engineer determines that the additional lengths are needed to achieve bearing.

If additional penetration is necessary in order to achieve the required bearing, the Department will pay for required splices at a negotiated price.

The Department will pay for accepted quantities at the contract prices as follows:

Item	Unit	Description
507	Foot (Meter)	Steel Piles HP____×____, Furnished
507	Foot (Meter)	Steel Piles HP____×____, Driven
507	Foot (Meter)	___" (___ mm) Cast-In-Place, Reinforced Concrete Piles, Furnished

<u>Oklahoma (1999)</u>

the center of the pile to consolidate the concrete by impact. Vibrate all concrete from at least 5 feet (1.5 m) below the ground surface to the top of the cast-in-place pile. Remove accumulations of water before concrete is placed.

After the concrete has hardened, cut back the top surface to remove laitance and to expose aggregate as specified for construction joints in Subsection 509.04(d)2.

(b) **Preparation for Driving.**

1. *Site Work.*

1.1 *Excavation.* In general, drive piles only after excavation is complete. Remove any material forced up between the pile to the correct elevation before concrete for the foundation is placed.

1.2 *Preboring to Facilitate Driving.* When required by the contract documents, prebore holes at pile locations to the depths specified in the contract documents or by the Engineer. If the depth of preboring is not specified in the contract documents, stop preboring for skin friction piles at least 5 feet (1.5m) above the pile tip elevation and drive the pile with an impact hammer to a specified blow count. Preboring for end bearing piles may extend to the surface of the rock or hardpan where piles are to be end-bearing on rock or hardpan. Seat installed piles into the end-bearing strata.

Use auguring, wet rotary drilling, or other approved methods of preboring. Make prebored holes smaller than the diameter or diagonal of the pile cross-section and sufficient to allow penetration of the pile to the specified depth. If subsurface obstructions, such as boulders or rock layers are encountered, increase the hole diameter to the least dimension that is adequate for pile installation. Fill any void space remaining around the pile after the completion of driving with sand or other approved material. Do not use a spud or punch unless otherwise permitted or specified. (A spud is a short, strong driven member that is removed to make a hole for inserting a pile.) Dispose of material from drilling in a manner approved by the Engineer.

Do not impair the carrying capacity of existing piles or the safety of adjacent structures. If preboring disturbs the load carrying capacities of previously installed piles or structures, restore the required ultimate capacity of piles and structures by approved methods.

1.3 *Predrilled Holes in Embankments.* When the depth of a new embankment is more than 6 feet (2 m) , prebore or spud through the embankment where piles are to be driven. Make the hole diameter not less than the greatest dimension of the pile cross-section plus 6 inches (150 mm) . After driving the pile, fill the space around the pile with dry sand or pea gravel. Dispose of material from drilling in a manner approved by the Engineer.

2. *Preparation of Piling.* In addition to squaring up pile heads before driving, further prepare piles as described below.

2.1 *Collars.* When timber piles are required to be driven to more than 35 tons (310 kN) bearing or when driving condition required it, provide collars, bands, or other devices to protect piles against splitting and brooming.

Oregon (2015)

equipment, in turn, may have significant impacts on the size and capacity of work bridges, shoring required for existing structures or other aspects and elements of construction.

Failure of a previously approved hammer to operate properly during construction will be cause for rejection.

Construction

00520.40 Preparation for Driving:

(a) Excavation - Unless otherwise provided or authorized, do not drive piles until after excavation is complete. Remove to the correct elevation any material forced up by pile driving before concrete for the foundation is placed, at no additional cost to the Agency.

(b) Embankments - Unless otherwise provided or authorized, do not drive piles until the roadway embankment at bridge ends is in place according to 00330.42. Drive piles completely through roadway embankments to the required penetration and bearing in the underlying material.

00520.41 Driving:

(a) General - Drive piles as specified with approved pile driving equipment to the required penetration depth and to the required nominal pile bearing resistance as shown or specified.

(b) Installation Sequence - Unless otherwise shown or specified, install individual piles in pile groups starting from the center of the group and proceeding outward in either direction, or as approved.

(c) Minimum Penetration - Unless otherwise specified or approved, drive piles at least 12 feet below the footing or pile cap, 12 feet below the groundline at trestle pile locations, and completely through embankments at bridge ends. When shown or specified drive piles to a greater minimum penetration. If the required penetration cannot be attained with a hammer complying with 00520.20(d), provide a larger hammer, prebore or jet holes, or use other approved methods as necessary to attain the required penetration.

(d) Preboring - Use augering, wet-rotary drilling or other methods of preboring only when specified or with written approval. When allowed, prebore holes at pile locations and to the depths shown or directed. Make prebored holes smaller than the diameter or diagonal of the pile cross section, but sufficient to allow penetration of the pile to the specified depth. If subsurface obstructions, such as cobbles, boulders or rock layers are encountered, the hole diameter may be increased to the least dimension which is adequate for pile installation. The use of a reinforced section (spud) to loosen the subsurface material at pile locations will not be allowed unless otherwise approved.

Perform preboring in a manner that will not impair the bearing or lateral capacity of the piles already in place or the safety of existing adjacent structures. When it is determined that preboring has disturbed the load bearing resistances of previously installed piles, restore those piles that have been disturbed to conditions meeting the requirements of this Specification by redriving or by other acceptable methods. The Contractor shall be responsible for the costs of any necessary remedial measures unless the preboring method was specifically included in the Contract Documents and properly executed by the Contractor.

(1) End-Bearing Piles - For end-bearing pile as classified by the Engineer, preboring may be carried to the surface of the end-bearing foundation material. Following that, drive pile with an approved impact pile hammer to the specified blow count.

(2) Other Piles - For other piles, extend preboring to the minimum pile penetration depth and then drive pile with an approved impact pile hammer to the specified blow count.

After completion of driving, fill any void space remaining around the pile with sand or other approved material.

(e) Jetting - Jetting may only be used when allowed in the Contract Documents or if approved in writing. When jetting is not required in the Contract Documents, but approved at the Contractor's request, determine and submit for review the number of jets and the volume and pressure of water at the jet nozzles necessary to freely erode the material adjacent to the pile without affecting the lateral stability of the final in-place pile. The Contractor shall be responsible for all damage caused by unapproved or improper jetting operations, unless the jetting method was specifically included in the Contract Documents and properly executed by the Contractor. Control, treat if necessary, and dispose of all jet water in a satisfactory manner. Drive all jetted pile with an approved impact hammer.

(f) Location and Alignment Tolerance - Place the tops of piles at plan cutoff elevation and horizontally within 6 inches of plan locations. No pile shall be nearer than 4 inches from any edge of the cap. Any increase in cap size to meet this edge distance requirement will be at no additional cost to the Agency.

Install piles so the axial alignment of the top 10 feet of the pile is within 5 inches of the specified alignment. For piles that cannot be inspected after installation, make an alignment check before installing the last 5 feet of pile. The Engineer may require that driving be stopped to check the pile alignment. Pulling laterally on piles to correct misalignment or splicing a properly aligned section onto a misaligned section will not be allowed.

If the specified location or alignment tolerances are exceeded, the effect of the pile misalignment on the substructure design will be investigated. If the Engineer determines corrective measures are necessary, implement suitable measures and pay all costs and delays associated with the corrective action.

(g) Heaved Piles - Make elevation readings on piles during pile driving operations to check on pile heave. Take elevation readings after each pile has been driven and again after piles within a radius of 15 feet have been driven. Redrive to the required penetration and resistance all piles that have risen more than 1/2 inch, at no additional cost to the Agency. Continue readings until the Engineer determines that such checking is no longer required. If pipe piles which have been filled with concrete subsequently heave, redrive them to original position, after the concrete has attained specified strength, with an approved hammer-pile cushion system.

(h) Test Piles - When specified, furnish and drive test piles at the locations and to the lengths directed. All test piles shall be of the kind and size specified for the permanent foundation piles unless otherwise directed. Drive all test piles with approved pile driving equipment. The specified length of test piles will be greater than the estimated length of production piles to provide for variation in soil conditions. Drive test piles using driving equipment identical to that which the Contractor proposes to use on the production piling. Excavate to the elevation of the bottom of the footing before driving test piles. (see Section 00510)

Drive test piles to or below the required minimum tip elevation and to a hammer blow count established by the Engineer. Allow test piles which do not attain the hammer blow count specified at the minimum tip elevation shown to "set up" for 24 hours, or less if directed, before being redriven. (see 00520.42(d)) If the tops of test piles reach plan grade without attaining the required pile bearing resistance, splice them and drive until the required bearing resistance is attained.

Rhode Island (2004)

performed under the direction of a Rhode Island Registered Professional Engineer. The Contractor shall adjust his pile driving operations to limit construction vibration peak particle velocities to 1 inch per second, unless a lower limit is warranted based on the preconstruction survey. Daily summaries of peak particle velocities and vibration records shall be submitted to the Engineer on a weekly basis.

b. Layout and Elevation and Location Control. Unless otherwise specified in the Plans or Special Provisions, the Contractor shall be responsible for layout of all pile locations using offsets from the project baselines. The Contractor shall establish ground surface elevation at the proposed driving locations to the nearest 0.1-foot, referenced to the project elevation datum. The Contractor shall set tideboards as needed and as specified in the Plans or Special Provisions when driving piles on water. Mudline elevations shall be determined at each pile location on water prior to starting driving.

The Contractor shall verify the tip elevation of driven piles to the nearest 0.01-foot relative to the project elevation datum. Where foundation or trestle piles are driven in groups, or where piles are to be restruck, the Contractor shall check each pile tip elevation prior to and after restriking as required by the Engineer.

c. Excavations and Sheeting. In general, piles shall not be driven until after excavations are completed. Any material forced up between or around piles as a result of driving shall be removed to the correct elevation and that surface densified before any foundation concrete is placed.

Where sheeting or cofferdams are to be constructed, and piles will be driven within sheeting alignments, unless otherwise specified in the Special Provisions, the Contractor shall submit his proposed sequence of operations for the Engineer's approval prior to beginning any driving of sheeting or piles. The Contractor shall use those methods such that sheeting installation shall not interfere with, obstruct, damage or otherwise impact the function of bearing piles.

d. Preboring. When required by the Special Provisions or as shown in the Plans, the Contractor shall prebore holes at pile locations to the depths shown on the Plans, specified in the Special Provisions, or authorized by the Engineer. Prebored holes shall generally smaller in diameter than the diameter or diagonal of the cross section of the pile, except in the case where preboring is specified where driving vibrations are not permissible. Preboring shall be of sufficient depth to allow penetration of the pile to the specified depth. If subsurface obstructions are encountered, the hole diameter may be increased to the least dimension which is adequate for pile installation. Any void space remaining around the pile after completion of driving or other installation, shall be filled with sand or other approved material. The use of spuds to make a hole for inserting a pile shall not be permitted in lieu of preboring, unless specifically allowed in the Special Provisions or authorized in writing by the Engineer.

Piles to be driven through newly constructed embankments shall be driven in holes drilled or spudded through the embankment when the embankment is in excess of 5 feet in height. The hole shall have a diameter of not less than the greatest dimension of the pile cross section plus 6 inches. After driving the pile, the space around the pile shall be filled to the surface of the embankment with dry sand or fine gravel. Material resulting from drilling holes shall be disposed of as approved by the Engineer.

South Carolina (2007)

ment's failure to comply with the 7 working day requirement is limited to an extension of contract time as the only possible compensation.

2 The Department reserves the rights to add, delete, or shift index piling. Any additional index piling will be paid for at the unit price bid for the specified index piling. The Department also reserves the right to revise the length of any additional index piling after evaluating driving records from earlier index piling.

711.4.4 Pile Load Test

1 In special cases, it will be desirable to load test certain piling in order to determine the relationship between the driving resistance of the pile and the actual load bearing capacity of the driven pile as determined by actual test loading of the pile, taking into consideration the assumed safety factor of the pile. In this case, the Plans and the Special Provisions will outline the work to be done and the method of payment for the portion of work to be done.

711.4.5 Driving of Piling

711.4.5.1 Preparation for Driving

1 Do not drive piling until after the excavation is complete.

711.4.5.2 Methods of Driving

1 Drive piling in accordance with an accepted *Pile Installation Plan* as specified in **Subsection 711.4.1** and with equipment meeting the requirements of **Subsection 711.3**.

2 Do not pre-drill for piling, except where specifically noted in the Plans or approved in writing by the BCE. When pre-drilled holes are allowed, drive the piling by the hammer to its final position and to the required ultimate bearing. If pre-drilled holes are larger than the pile, backfill the space between the pile and the pre-drilled hole with sand, pea-gravel, or an approved material and tamp in an approved manner.

3 Do not use spudding to facilitate pile installation unless specifically approved in writing by the BCE.

4 Build-up prestressed concrete piling driven below grade where necessary as shown in the Plans or directed by the RCE and/or BCE and in accordance with **Subsection 711.4.9**.

5 Splice steel piling driven below grade in accordance with **Subsection 711.4.10**.

6 Remove any material forced up between the piling to the correct elevation before concrete for the foundation is placed.

711.4.5.3 Allowable Variation in Driving

1 Drive piling with a variation of not more than ¼ inch per foot from the vertical or from the batter indicated and a maximum pile head variation of not more than 3 inches from the position shown on the Plans. Drive piling with the head in the proper location without inducing excessive stresses in the pil-

South Dakota (2004)

510.1 DESCRIPTION

This work consists of furnishing, driving and cutting off timber, prestressed and steel piling, and furnishing, driving, cutting off and fastening of sheet piling and steel sheeting designated to be left in place.

510.2 MATERIALS

Materials shall conform to the following requirements:

A. Timber Piles: Section 960.

B. Steel Piles: ASTM A 36.

C. Sheet Piles: Section 1040.

D. Steel Sheeting: Section 1050.

E. Prestressed Piles: Section 560.

510.3 CONSTRUCTION REQUIREMENTS

A. Preparation for Driving Steel and Timber Pile:

1. **Caps:** The heads of timber piles shall be protected by approved caps if driving is likely to damage the pile. When the area of the head of any timber pile is greater than that of the face of the hammer, a suitable cap shall be provided to distribute the hammer blow throughout the cross section of the pile.

   The head shall be cut square and shaped or chamfered to prevent splitting at its periphery.

   The heads of steel piles shall be cut squarely and a driving cap shall be provided to hold the axis of the pile in line with the axis of the hammer.

2. **Collars:** Collars, bands or other devices to protect timber piles against splitting and brooming shall be provided where necessary.

3. **Pointing:** When specified, timber piles shall be shod with metal shoes. The points of the piles shall be carefully shaped to secure an even and uniform bearing on the shoes. After shaping, exposed untreated wood shall be retreated in the field in accordance with Section 510.3.G.

4. **Splicing Piles:** Splices shall be made in accordance with the details. Indiscriminate use and location of splices is prohibited. The proposed location of splices used in conjunction with frame pile bents and integral type abutments will require prior approval. All splices shall be welded by a certified welder in accordance with Section 410.

5. **Preboring:** Preboring shall be done when specified on the plans or directed by the Engineer.

Holes for timber piles shall be a minimum of two inches (50 mm) larger than the nominal diameter of the pile. The nominal diameter shall be measured three feet (1 meter) from the butt of the pile.

Holes for steel piles shall be not less than the following specified diameter:

8 HP (HP200) Piles* .... 12 inches (300 mm)
10 HP (HP250) Piles* .... 15 inches (375 mm)
12 HP (HP310) Piles* .... 18 inches (450 mm)
14 HP (HP360) Piles* .... 21 inches (525 mm)
*All Weights

After the piles are driven, the prebored holes shall be backfilled with coarse dry sand. The sand shall be compacted to prevent bridging.

6. When specified, steel piles shall be equipped with tip reinforcement. Installation shall be per manufacturer recommendation.

B. Method of Driving

1. **General:** Piles may be driven with a steam or air hammer, a gravity hammer, a diesel hammer or a combination of water jets and hammer.

2. **Hammers for Timber and Steel Piles:** Gravity hammers shall weigh not less than 3000 pounds (1360 kg), and the weight of the hammer shall not be less than the combined weight of the driving head and pile. The fall shall be regulated to avoid damage to the piles, and shall not exceed 10 feet (3 meter).

   The total energy, as per manufacturer's rating, developed by mechanically powered hammers shall not be less than that required to achieve design bearing using the equations of Section 510.3.D.2 assuming the following conditions.

Penetration per Blow (S)	=0.10 in/blow (2.54 mm/blow)
Hammer Operating Efficiency	= 85% for diesel hammers
	= 95% for air/steam hammers

3. **Additional Equipment:** If the required penetration is not obtained with a hammer complying with the above requirements, the Contractor shall provide a heavier hammer or resort to jetting at no additional cost.

   Unless otherwise approved, the penetration for any pile shall not be less than eight feet (2.5 meter).

4. **Leads:** Pile leads shall be constructed to afford freedom of movement of the hammer. Inclined leads shall be used in driving battered piles.

Tennessee (2006)

constructed of heavy timbers or steel, which are accurately positioned, securely held in place, and approved by the Engineer. When using water jets, ensure that the number of jets and the nozzle volume and pressure is sufficient to erode the material adjacent to the piling freely. The pump shall have sufficient capacity to deliver at all times a pressure of at least 100 pounds per square inch at two 3/4-inch jet nozzles. Before the required penetration is reached, shut off the jets and drive the piles by hammer to final penetration.

When preformed pile holes are used, construct them by drilling or driving and withdrawing a suitable punch or chisel at or near the locations of the piles. If preformed pile holes are so oversized that the sides of a round pile or the corners of a square pile are not in contact with the soil, restore lateral stability by filling the space between the pile and the sides of the hole with approved clean sand, at no cost to the Department. Terminate preformed holes before the required penetration is reached, and drive the pile by hammer to the final tip elevation to seat the pile and secure the minimum required bearing.

Except when the pile head is fitted into a steel head block, provide every timber pile with a metal collar or wire wrapping. Protect the heads of all concrete piles, and the heads of all other piles when the nature of the driving is such that piles may be unduly damaged, with caps of approved design, having a plywood cushion next to the pile head and fitting into a casting, which, in turn, supports a hammer cushion made from durable, manufactured material. Do not use wire rope and other materials of limited durability. Use an approved pile cushion of sufficient thickness to prevent damage to the pile during driving. Use a minimum initial dimension of 4-inch thick plywood pile cushion for concrete piles. Replace the pile cushion before excessive compression (more than 1/2 the original thickness), burning, or charring takes place. During hard driving, several pile cushions may be necessary for a single pile. Use a new pile cushion for each pile.

For special types of piling, provide driving heads, mandrels, or other devices in accordance with the manufacturer's recommendations so that the pile may be driven without damage.

For steel piling, squarely cut the heads and provide a driving cap to align the axis of the pile with the axis of the hammer. When shown on the Plans, cap steel piles with steel plates or other devices.

Texas (2004)

2. **Foundation Piling.**
   - The top of each pile may be at most 4 in. in any direction from the position shown on the plans.
   - The center of gravity of the piling group may be at most 3 in. from the center of gravity determined from plan location.
   - The minimum edge distance for piling in a footing is 5 in. Additional concrete required to obtain this edge distance and specified reinforcing steel cover will be at the Contractor's expense.

B. Penetration. Piling lengths shown on the plans are the lengths estimated to give required bearing and are for estimating purposes only. Drive piling to within 5 ft. of plan length and to greater depths as necessary to obtain the required bearing resistance shown on the plans, unless other penetration requirements or bearing evaluation methods govern.

When test piling or test loaded piling is used, the Engineer will establish regular pile lengths on the basis of the test data. In these cases, drive regular piling to this approximate elevation and to greater depths as required to obtain the required bearing resistance.

For unusually hard driving conditions, typically less than 0.1 in. of penetration per blow, provide either pilot holes or jetting or a combination of both if plan penetration is not obtained. Penetration may be reduced upon approval if stability requirements are met.

C. Pilot Holes. Except as specified, do not extend pilot holes more than 5 ft. below the bottom of footings for foundation piling or 10 ft. below finished ground line for trestle piling, unless the specified penetration cannot be obtained by using the depth of holes indicated. When deeper pilot holes are required, determine their size and depth from the results of trial operations on the first piling driven or from available test pile data. Obtain approval for any excess depth or size of pilot holes. The maximum hole diameter permitted will be approximately 4 in. less than the diagonal of square piling or steel H-piling and 1 in. less than the diameter of round piling. The Engineer may vary hole size and depth to obtain penetration and bearing resistance.

Extend pilot holes through all embankments to natural ground when driving concrete piling.

Where a pilot hole is required in granular material that cannot be sealed off by ordinary drilling methods, a casing may be required around the boring device deep enough to prevent loose material from falling into the pilot hole.

Drive the piling below the depth of the pilot hole a minimum of 1 ft. or 100 blows but not less than the required bearing resistance shown on the plans. Unless directed otherwise, do not drive piling beyond the point where the penetration per blow is less than 0.1 in. as determined by an average of 10 blows. If damage to the pile is apparent, stop driving.

D. Jetting. Jetting is permitted when the specified penetration cannot be obtained by driving and pilot holes or other methods are not feasible. Before jetting, submit details of the proposed methods for approval. The Engineer may authorize varying depths of jetting to achieve the desired results.

Jet as required in conjunction with driving but only to the approved depth. For jetting operations, use enough power to simultaneously operate at least two 2-1/2-in. diameter pipes equipped with 3/4-in. nozzles at a pressure of 150 psi. Perform the jetting with 1 or 2 jets as determined and approved from results of trial operations.

Drive the piling below the depth of the jetting a minimum of 1 ft. or 100 blows but not less than the required bearing resistance shown on the plans. Unless directed otherwise, do not drive piling beyond the point where the penetration per blow is less than 0.1 in. as determined by an average of 10 blows. If damage to the pile is apparent, stop driving.

E. Hammer Formula Method of Bearing Evaluation. Unless otherwise shown on the plans, determine the dynamic bearing resistance of piling by one of the hammer formulas in this Section. If the Engineer has determined a K factor based on test piling, test-loaded piling, or other methods, the computed resistance will be the driving resistance determined based on the appropriate formula multiplied by the K factor.

1. Single-Acting Power Hammers. Use the following formula:

$$P = \frac{2WH}{S + 0.1}$$

where:

P = dynamic resistance in pounds.
W = weight of ram in pounds.
H = height of fall of ram in feet.
S = average penetration in inches per blow for the last 20 blows.

Utah (2012)

F. Notify the Engineer if any of the remaining piles in the foundation do not meet the established driving criteria before moving the hammer away from bent/abutment area or if driving conditions otherwise change.
   1. The Department may require testing additional piles and reestablishing driving criteria for the remaining piles within the foundation.

3.3 PILE INSTALLATION

A. Pre-drill or pre-auger if the designated pile tip elevation cannot be reached by the approved pile driver.
   1. Do not drill holes greater in diameter than the diameter or other maximum dimension of the pile.

B. Pile Splicing
   1. Use no more than one spliced section less than 6 ft and splice no other section less than 30 ft for any pile.
   2. Inspect the driven pile section before splicing any pile section to determine if it has been distorted from its original shape or otherwise damaged from pile driving operations.
      a. Remove the damaged portion where distortion or damage has occurred before splicing the next segment.
   3. Splice new pile segments parallel with previously driven pile segments.
   4. Butt weld the entire pile cross section using full penetration welds according to AWS D.1.1 for pipe piles and AASHTO/AWS D.1.5 for HP section piles.

C. Keep driven piles within 6 inches of the designated plan location and within 2 percent of vertical (plumb) throughout the total length of the pile (including bending). This is roughly equivalent to ¼ inch in a foot or 0.60 inches in 30 inches.
   1. Receive approval from the Engineer that these criteria have been met at the end of pile driving before proceeding with backfilling or other associated foundation work.
   2. Notify the Department to determine the appropriate resolution if either requirement is not met.
   3. Contractor bears all costs for any measures required to resolve the non-conformance including the price reduction factors shown in Table 1 in this Section, article 3.5.

D. Drive additional piles as required to replace damaged piles and piles driven out of plumb or plan location at locations designated by the Engineer.

E. Drive down piles that were raised due to driving adjacent piles.

Virginia (2008)

face of the hammer, a suitable cap shall be provided to distribute the blow of the hammer throughout the cross section of the pile.

For special types of piles, driving heads, mandrels, or other devices shall be used in accordance with the manufacturer's recommendations so that the pile may be driven without damage.

For steel piles, heads shall be cut squarely and a driving cap provided to hold the axis of the pile in line with the axis of the hammer.

Timber piles that are not enclosed in concrete shall be protected as specified in Section 418.03(d). Collars, bands, or other devices to protect timber piles against splitting and brooming shall be provided when specified by the Engineer.

Tips for timber piles shall be sharpened. When specified, timber piles shall be provided with steel or cast iron points conforming to the requirements of Section 236.02(b). When points are used, the tips of the piles shall be carefully shaped to secure an even and uniform bearing on the points.

When specified, steel H-piles shall be provided with cast steel points. Points shall be welded as recommended by the manufacturer, but the length of the weld shall be not less than twice the width of the flange.

If during the driving of a precast concrete pile a reduction in blow count indicates that the point of the pile has passed from a harder material into a softer material that offers little or no resistance to penetration, the energy per blow shall be reduced to an amount specified by the Engineer. When firm-bearing material is reached, the energy per blow shall be returned to normal.

Steel piles and steel pile shells shall be painted as specified in Section 403.03(d)4.

(d) **Driving:** The capability of the hammer to drive piles properly will be verified from records of the test piles. If the required penetration is not obtained in the driving test by the use of a hammer complying with the requirements, the Contractor shall provide a heavier hammer or use other approved means at his own expense. The method of driving shall not produce deformed piles. Where it is determined necessary by the Engineer in order to obtain the required tip elevation, design bearing capacity, or minimum penetration, driving shall be supplemented by jetting or preboring. After driving is completed, voids existing as a result of preboring, soil consolidation, or movement shall be filled with dry sand and consolidated to provide adequate lateral pile support. Damaged piles shall be removed and replaced.

1. **Hammers for timber and steel H-piles:** Hammers may be either gravity or power hammers. Striking parts of gravity hammers for driving timber piles shall weigh at least 2,000 pounds and for driving steel piles at least 3,000 pounds. In no case shall the weight of the striking parts of gravity hammers be less than the combined weight of the pile and any device used on the pile head for protection during driving. The hammer fall shall be regulated to avoid damage to piles. The fall shall be not more than 15 feet.

   Power hammers shall be capable of developing at least 7,000 foot-pounds of energy per blow when driving timber piles and at least 15,000 foot-pounds of energy per blow when driving steel piles.

2. **Hammers for concrete piles:** Precast concrete piles or shells for cast-in-place piles shall be driven with a power hammer that shall develop an energy per blow of at least 0.2 foot-pound per pound of the design bearing capacity of the pile being driven. Power hammers shall develop an energy (*E*) in foot-pounds per blow of at least 1 foot-pound per pound of pile weight (*W*) for piles weighing up to 25,000 pounds. For piles weighting more than 25,000 pounds, *E* shall be at least 25,000 + 0.6 (W-25,000). The value of *E* shall be at least 15,000 foot-pounds per blow.

3. **Leads:** Pile driver leads shall be constructed in a manner that will afford freedom of movement of the hammer and shall be held in position by guys or stiff braces to ensure support of the pile during driving. Except where piles are driven through water, leads shall be of sufficient length so that a follower will not be necessary.

   Inclined leads shall be used in driving battered piles.

4. **Followers:** Followers shall be used only with the written permission of the Engineer. When followers are used, 1 pile from every group of 10 shall be a long pile driven without a follower and shall be used as a test pile to determine the average bearing capacity of the group.

5. **Water jets:** The volume and pressure of water at the jet nozzles shall be sufficient to erode freely the material adjacent to the pile. A pressure of at least 100 pounds per square inch shall be delivered at the nozzles. At least two jet nozzles, having a diameter of at least 3/4 inch, shall be used and placed symmetrically about the circumference of the pile. Before the desired penetration is reached, the jets shall be withdrawn and the piles driven at least 5 feet or to the depth determined by the Engineer to be necessary to secure the final penetration.

6. **Preboring:** The area of each prebored hole shall be approximately 10 percent more than the area of the pile but not more than 20 percent of the area.

Washington (2014)

So long as the pile is not damaged and the embankment or foundation material being driven through is not permanently damaged, the Contractor shall use normal means necessary to:

1. Secure the minimum depth specified,
2. Penetrate hard material that lies under a soft upper layer,
3. Penetrate through hard material to obtain the specified minimum tip elevation, or
4. Penetrate through a previously placed embankment.

Normal means refer to methods such as preboring, spudding, or jetting piles. Blasting or drilling through obstructions are not considered normal means.

Prebored holes and pile spuds shall have a diameter no larger than the least outside dimension of the pile. After the pile is driven, the Contractor shall fill all open spaces between the pile and the soil caused by the preboring or spudding with dry sand, or pea gravel, or controlled density fill as approved by the Engineer.

If water jets are used, the jets shall be withdrawn before the pile reaches its final penetration, and the pile shall then be driven to its final penetration and ultimate bearing capacity. The pile shall be driven a minimum of 2 feet to obtain the ultimate bearing capacity after the jets are withdrawn, or to refusal, whichever occurs first. If the water jets loosen a pile previously driven, it shall be redriven in place or pulled and replaced by a new pile. To check on pile loosening, the Contractor shall attempt to redrive at least one in every five piles, but no less than one pile per bent or pier.

The various unit Contract prices for driving piles shall cover all costs related to the use of water jets, preboring, or spudding. The Contracting Agency will not pay any costs the Contractor incurs in redriving piles loosened as a result of using water jets, preboring, or spudding.

If the Engineer requires, the Contractor shall overdrive the pile beyond the ultimate bearing capacity and minimum tip elevation shown in the Contract. In this case, the Contractor will not be required to:

1. Use other than normal means to achieve the additional penetration,
2. Bear the expense of removing or replacing any pile damaged by overdriving, or
3. Bear the expense of overdriving the pile more than 3 feet as specified in Section 6-05.5.

In driving piles for footings with seals, the Contractor shall use no method (such as jetting or preboring) that might reduce friction capacity.

6-05.3(11)E Use of Followers for Driving

Followers shall not be used to drive concrete or steel piles. On timber piles, the Contractor may use steel (not wooden) followers if the follower fits snugly over the pile head. If a follower is used, the Contractor shall, in every group of 10 piles, drive one long pile without a follower, but no less than one pile per bent or pier, to the required ultimate bearing capacity and minimum tip elevation. This long pile shall be used to test the bearing capacity of the piles driven with a follower in the group. The tip elevation of the long pile shall be similar to the elevation of the piles driven with the follower. If the tip elevations are significantly different, as determined by the Engineer, the Contractor shall redrive the remaining piles in the group to the tip elevation of the longer pile.

6-05.3(11)F Pile Damage

The Contractor shall remove and replace (and bear the cost of doing so) any pile that is damaged as determined by the Engineer.

After driving a steel casing for a cast-in-place concrete pile, the Contractor shall leave it empty until the Engineer has inspected and approved it. The Contractor shall make available to the Engineer a light suitable for inspecting the entire length of its interior. The Engineer will reject any casing that is improperly driven, that shows partial collapse that would reduce its ultimate bearing capacity, or that has been reduced in diameter, or that will not keep out water. The Contractor shall replace (and bear the cost of replacing) any rejected casing.

West Virginia (2010)

SECTION 614
PILING WALLS

614.1-DESCRIPTION:

This work shall consist of furnishing and placing steel piles in predrilled holes, concrete or grout, backfill and lagging, of the kinds and dimensions designated, in accordance with these provisions and in reasonably close conformity with the lines, grades, dimensions, and locations shown on the Plans or established by the Engineer. Painting of the exposed steel is included.

Careful attention shall be given to assuring the pile wall will tie directly into an existing stable slope. Prior to ordering any materials, the contractor in conjunction with the Engineer shall conduct a project site review in order to verify the limits of the pile wall.

614.2-MATERIALS:

Materials shall conform to the requirements specified in the following Subsections of Division 700:

MATERIAL	SUBSECTION
Steel Piles and Splices	709.12
Steel Lagging and Wales	709.12
Reinforcing Steel	709.1
Prestressing Steel	709.2
Treated Timber Lagging	710
Portland Cement	701.1
Fine Aggregate	702.1
Fly Ash	707.4

614.3-DRILLING:

A drilled hole is required for the buried length of the pile.

A minimum of 1/3 the total pile length or 10 feet (3 m), whichever is greater, is to be placed in bedrock/shale. Deviation from this requirement will be controlled by a Plan note. The total estimated pile length and the depth to the estimated bedrock/shale line are shown on the piling profile. Should the elevation of the actual bedrock/shale vary from the estimated elevation by more than 2.5 feet (0.8 m), the Engineer must approve the hole prior to placement of the pile. The material from the drilled hole shall be removed and disposed of by the Contractor in an approved site.

Particular care must be taken in the drilling operation to avoid deflecting the bit along a sloping bedrock/shale line. To verify proper alignment, the Contractor shall measure and record the vertical alignment of the hole using a plumb bob or other acceptable method.

Preferably, the diameter of the drilled hole shall be a size that will allow the pile, while being slowly lowered into the hole, to reach the bottom of the hole under the impetus of the pile weight. The minimum hole diameter shall be 2 inches (50 mm) larger than the diagonal distance across the pile cross section.

Light tapping (ten blows with at least 3 inches (75 mm) of penetration per blow) with a pile hammer exerting no more than 12,000 ft/lbs (16 kJ) of energy is

Wisconsin (2014)

in the plan length, allow the pile to set up for 24 hours or more, then restrike. Determine the required driving resistance using the first 10 hammer blows during restrike. If required driving resistance is still not obtained, splice on additional length if needed, and drive the pile an additional 10 feet, or to the depth the engineer directs, and restrike after allowing the pile to set up for another 24 hours or more. Repeat this process until the required driving resistance is obtained. After obtaining the required driving resistance, drive the other piles in the substructure to the same tip elevation.

(2) Restrike with the same pile driving system used to drive the production piles. Warm up the hammer by striking another pile a minimum of 20 blows before restriking.

550.3.8 Test Piles

(1) Drive test piles at locations the plans show to both the required driving resistance, and if the plans show, to the required minimum tip elevation. Complete excavation for the associated substructure unit before driving test piles. Use the same driving system as will be used to drive the production piles. Do not drive any production piles for the associated substructure unit until all test piles are driven.

550.3.9 Pre-Boring

550.3.9.1 General

(1) Pre-bore holes to the depth the plans or special provisions require. Submit written requests for pre-boring not required under the contract to the engineer for review and approval. Do not impair the capacity of in-place piles or damage adjacent structures by pre-boring operations.

550.3.9.2 Pre-Boring in Unconsolidated Materials

(1) For round piles, pre-bore holes of approximately the pile diameter. For other shapes, pre-bore holes of a diameter approximately equal to the greatest diagonal pile section dimension. Increase the diameter as necessary for pile installation if subsurface obstructions are encountered.

(2) Maintain an open hole for pile installation using temporary casing if necessary. Do not remove casing until the pile is placed in the pre-bore hole. After driving, backfill around the pile with sand or other engineer-approved material and dispose of excess material.

550.3.9.3 Pre-Boring in Rock or Consolidated Materials

(1) For round piles, pre-bore holes at least one inch larger than the pile outside diameter. For other shapes, pre-bore holes of a diameter at least one inch larger than the greatest diagonal pile section dimension.

(2) Case holes as necessary to prevent introduction of unconsolidated material. Seat the casing firmly into the rock or consolidated material surface. Clear all debris from the pre-bore hole before installing the pile.

(3) Firmly seat piles after preboring and backfill within the rock or consolidated material with a cement grout. Remove the casing, backfill the piles with sand or other engineer-approved material, and dispose of excess material.

(4) Do not blast without the engineer's approval.

550.3.10 Pile Points

(1) Attach pile points conforming to the manufacturer's instructions unless the plans show otherwise.

550.3.11 Finishing Piles

550.3.11.1 General

(1) Cut off piles to a true plane at the plan elevation. Cut off pile shells for cast-in-place concrete piles before placing concrete. Pile cut-offs become the contractor's property.

(2) For steel oil field pipe piles, remove soil, water, and other materials within the pile to the bottom of the footing elevation. Fill any void below this elevation with engineer-approved material or install a barrier acceptable to the engineer at or below this elevation.

550.3.11.2 Cast-in-Place Concrete

(1) Remove water or other foreign material from inside shells before placing concrete. Do not place concrete under freezing conditions without the engineer's approval.

(2) Place steel reinforcement as the plans show ensuring that it is in the correct location when the level of concrete placement reaches the lower limits of that reinforcement.

(3) After the engineer inspects and approves the pile shells, deposit the concrete in each shell in a continuous operation at a rate that causes no air pockets or cold joints. For pile shells with an inside diameter greater than 16 inches, place concrete with a tremie or downspout within the shell. Fill the shell

Wyoming (2010)

specified is an estimate only; the engineer will determine the final length following an investigation of the site.

2 For sheet piling, provide the specified area indicated on the department's "Proposal" (Form E-91), unless site conditions prevent installation to those limits.

504.4.2 Predrilled Holes

1 When specified or approved by the engineer, use predrilled holes. Extend to the elevation specified and obtain the remaining penetration with the pile driver. Do not allow the hole diameter to exceed the pile width. Place the pile in the hole and drive it to set the point firmly into bearing material, and secure full bearing. Fill the space around the pile to the ground surface with dry sand, pea gravel, flowable fill, or other material approved by the engineer. Do not use water or air jets without written approval from the engineer.

504.4.3 Pile Driving

1. **Bearing Piles.** Drive piles using the system approved and without variation, except with the engineer's written approval. The engineer will consider changes in the driving system only after the necessary information for a revised wave equation analysis is submitted. Support long piles to prevent lateral buckling during driving.

   Support pile hammers in leads while driving piles. Maintain hammers to obtain the operating length of the stroke and number of blows per minute for which the hammer is designed. Maintain cushions in good condition. The engineer will observe the hammer's initial operations to verify its adequacy. Repair or replace inadequate hammers.

   Cut the heads of steel piles squarely. Ensure that the helmet closely fits the top of the pile and extends down the sides to maintain alignment of the pile head under hard driving conditions.

   Drive piles to within ¼ in/ft [20 mm/m] of vertical or the specified batter. Drive foundation piles in footings of piers and abutments so that their tops are within 6 in [150 mm] of position in any direction.

   1.1. **Pile Bents.** Drive piles for bents so that the center of each pile's top is within 6 in [150 mm] of that specified when measured parallel to the centerline of the bent.

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