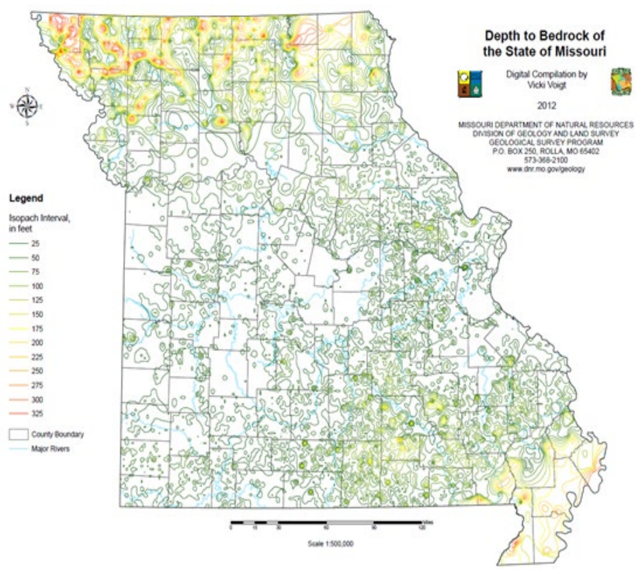
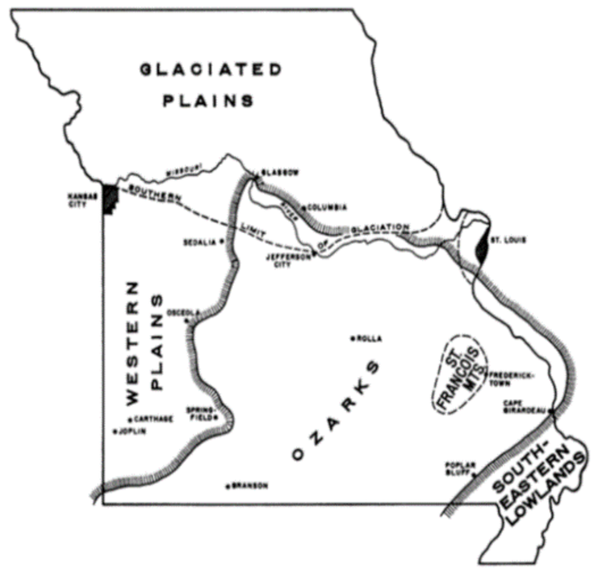
Pile Setup and Restrike Procedures





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16. Abstract

The primary objective of this research is to provide MoDOT with rational procedures and guidelines to incorporate pile setup in MoDOT pile design. Pile setup refers to the time-dependent increase in the capacity of driven piles that occurs after the end of pile driving. High-strain dynamic load test data from end of driving (EOD) and beginning of restrike (BOR) were compiled from sites in Northern Missouri and Southeast Missouri to develop models of pile setup in these regions where the use of friction piles is common. Reliability analysis was performed using the model developed from Northern Missouri data to probabilistically calibrate resistance factors that can be applied to the expected pile setup without the need for restrikes. The application of these resistance factors is shown to produce significant cost benefits over the current common practice of ignoring pile setup. In addition, pile setup factors within the first 24 hrs. of the EOD were examined to provide information on the likelihood of successful restrikes for various levels of required capacity. Data from sites in Southeast Missouri were insufficient to develop a meaningful model of pile setup and associated resistance factors. The limited data that were used showed moderate levels of pile setup, indicating the use of restrike analysis in Southeast Missouri may be cost effective. Additional data collection at sites in Southeast Missouri is recommended.

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Pile Setup and Restrike Procedures

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Executive Summary

Pile setup is the time-dependent increase in capacity that commonly occurs in the days and weeks after piles have been driven. For friction piles (i.e., piles that derive most of their resistance from side shear), it is not unusual for pile capacity to increase by a factor of 1.5 to 3 or more for certain soil conditions. Many factors can contribute to the magnitude of the pile setup, including variations in the soil profile, specific characteristics of the soil, pile diameter, and pile type. Therefore, even in the same geologic region, the observed pile setup can vary significantly, and it is difficult to reliably incorporate in design. One option is to perform restrikes on piles days after installation to measure the increase in capacity. However, this approach requires remobilization of pile driving equipment and often significant construction delays. Therefore, agencies and contractors frequently choose to simply drive a longer pile rather than relying on subsequent pile setup. If pile setup was reliably incorporated into design procedures, the target resistance at the end of driving (EOD) could be reduced resulting in shorter piles and significant cost savings.

The primary objectives of this project are to provide MoDOT with a better understanding of pile setup in Missouri soils and produce reliability-based guidelines and procedures to incorporate pile setup into pile design methods. Load test reports from high-strain dynamic testing (HSDT) and associated soil boring data were compiled from sites in Northern Missouri and Southeast Missouri, where the use of friction piles is common. The load test reports were carefully reviewed and many of the pile test results were removed due to issues including, poor quality signal matching, testing problems, inconsistent pile size or diameter with the rest of the database, outlier soil properties, or piles that reached refusal (i.e., large end bearing capacity). Soil boring information was used to characterize the profile conditions as Sand, Clay, or Mixed based on the percentage of the pile that penetrated through clay layers. In addition, average values of soil properties (pocket penetrometer (PP) values, standard penetration test (SPT) blow counts, and plasticity index (PI)) in the clay layers were computed when these parameters were available. Pile setup factors (ratio of total capacity at restrike time to total capacity at EOD) were calculated and plotted versus time. Finally, resistance factors for pile setup without restrikes were computed for Northern Missouri sites. Insufficient data were available to compute resistance factors for sites in Southeast Missouri. A summary of the findings from these regions and recommendations for incorporating pile setup are presented below. This project also examined very short-term pile setup (<24 hrs.) in Northern Missouri and provided information on the likelihood of a successful short term restrike as a function of the difference in the required and observed capacity.

In Southeast Missouri, data were used from eight piles at four bridge sites, with four of the piles in Sand profile conditions and four in Mixed profile conditions. None of the profiles were classified as Clay. The limited data in Southeast Missouri do not support relying on pile setup without pile restrikes. However, the data also do not suggest that pile setup does not occur in Southeast Missouri. In fact, half of the piles had setup factors between 1.0 and 1.2, one had a setup factor of 1.3, and the pile with the greatest setup had a setup factor of nearly 1.6. Although these data do not support probabilistic

calibration of reliable setup resistance, they do indicate that modest pile setup is likely to occur at least most of the time for friction piles in Southeast Missouri. To rely on the pile setup in Southeast Missouri, restrikes with high-strain dynamic testing with signal matching (HSDT-SM) must be performed. The data from Southeast Missouri do not provide a clear indication of the types of sites where pile setup is more likely. In fact, the two sites with the greatest observed pile setup both had clay embedment ratios of 0; the sites with greater embedment in clay generally had setup factors between 1.0 and 1.2. Although the lack of a clear trend with clay embedment ratio is perhaps unsatisfying, an important conclusion is that the potential for pile setup should not be dismissed simply because a site has a predominately coarse-grained soil profile. Due to limited data, it was not possible to relate pile setup to soil properties in Southeast Missouri.

In Northern Missouri, setup factors versus time were developed from 23 pile tests at nine sites. All piles were closed-ended pipe piles with diameters of 14 or 16 in. Five of the pile tests had short restrike times (<20 hrs.) and were not included in the final model for long-term pile setup. Of the 18 piles considered in the setup model, nine of the piles were in Clay profile conditions and nine in Mixed profile conditions. Setup factors were considered for restrike times after 20 hrs. for the Clay profile conditions and after 60 hrs. for the Mixed profile condition. The lower cutoff time for Clay was necessary so that more sites could be included in the data analysis. Only one of the 18 piles did not show any pile setup (i.e., the setup factor was about 1.0). Among the other 17 piles, five had setup factors in the range of 2.0 to 2.7, 10 had setup factors in the range of 1.5 to 2.0, and two had setup factors in the range of 1.3 to 1.5. Interestingly, the long-term setup up values were significantly higher than those measured by Ng et al. (2011) on piles in similar geology in Iowa, where the setup factors did not exceed 1.5. This is likely due to differences in the pile types, as the data in Iowa were from tests on 10-in. H-piles. For piles in Clay profiles, the pile setup factor correlated well with PP strength values but was poorly correlated with blow counts and PI values. For Mixed profiles, no trends in pile setup were observed for any of the soil parameters considered. For piles in Clay profiles, the average setup was 1.64 and the COV was 0.138, while for piles in Mixed profiles, the average setup was surprisingly higher at 1.91 and the COV was 0.266. The setup data from less than 24 hrs. after EOD driving showed that there was a strong likelihood (80%) of a successful restrike (i.e., meeting the required capacity) when the difference between the required and observed capacity at EOD was less than 15%. For larger differences, the likelihood of success was questionable to unlikely.

Using the model of pile setup in Clay and Mixed profiles, a reliability analysis was performed to probabilistically calibrate resistance factors for the design scenario of relying on pile setup without demonstrating setup through restrikes. Resistance factors of 0.38 and 0.09 were calculated for the setup portion of capacity that are applicable to piles in Clay and Mixed profiles, respectively, considering a 1 in 10,000 probability of failure. A new section in the MoDOT's Engineering Policy Guide (EPG) provisions titled *Friction Piles in Northern Missouri* is proposed that uses these resistance factors to account for pile setup without the need for restrikes. The primary effect of applying the proposed provisions is to reduce the required nominal EOD resistance compared to the current practice of neglecting pile setup unless restrikes are performed. If tip resistance is negligible, the reduction in the nominal EOD resistance is 27% for Clay profiles and

11% in Mixed profiles. The resulting decrease in required pile length is shown to produce significant cost savings as compared to the case of not considering pile setup. In addition, this approach avoids the costs of equipment re-mobilization and construction delays associated with pile restrikes. Situations where the use of restrikes may be preferred to the proposed approach are also described. Examples of four approaches to incorporating pile setup in Northern Missouri are also presented with comparisons of costs.

The importance of pile hammer warmup on measured pile capacity is also demonstrated from the data collected in this study. Proposed revisions to the EPG addressing pile hammer warmup are presented. Recommendations for additional pile load test data collection are presented and the potential benefits are discussed.

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List of Abbreviations

A_p – cross sectional area of pile

ASD – Allowable Stress Design

BOR – Beginning of Restrike

CAPWAP – Case Analysis Program Wave Equation Program

CIP – cast in place

COV – Coefficient of Variation

EOD – End of Driving

EPG – MoDOT's Engineering Policy Guidelines

f_{sndr} – nominal unit side resistance

HSDT – High Strain Dynamic Testing

LRFD – Load and Resistance Factor Design

N_{60} – Blow count at 60% efficiency

PDA – Pile Dynamic Analysis

PI – Plasticity Index

PP – Pocket Penetrometer

R_{BOR} – Observed pile capacity at beginning of restrike

R_{EOD}– Observed pile capacity at end of driving

R_P– Pile tip capacity

R_{ndr} – Required nominal resistance at EOD

$R_{ndr-BOR}$ – Required nominal resistance at BOR

$R_{n-setup}$ – Nominal setup resistance (that occurs in addition to the EOD resistance)

R_P– Pile tip capacity

$R_{setup-i}$ – Setup resistance for each Monte Carlo trial , i

R_{ndr-i}– Nominal resistance for each Monte Carlo trial , i

SM – Signal Matching

SF_n – nominal setup factor

SPT – Standard Penetration Test

s_u – undrained strength

WEAP – Wave Equation Analysis Program

φ_{dyn} – Resistance factor for design based on HSDT-SM

φ_{setup} – Resistance factor for the setup resistance (without restrikes)

γ_{DL} – Dead load factor

γ_{LL} – Live load factor

DL_n – Nominal dead load

LL_n – Nominal live load
μ_{DL} – Mean value of dead load
μ_{LL}– Mean value of live load

1. Introduction

1.1 Motivation and Challenges

During installation of driven piles, driving stresses produce excess pore pressures that reduce soil effective stress. The reduction in effective stresses is primarily beneficial for pile constructability, with attendant reductions in the demand for hammer energy and stress in the pile. However, the reduced effective stresses also generally result in interpretation of geotechnical resistance during driving that is less than the eventual resistance that will develop upon dissipation of the excess pore pressures. For friction piles (i.e., piles that primarily derive geotechnical resistance through skin friction, as opposed to piles bearing on rock), the increase in resistance with time, commonly called *pile setup*, leads to significant differences between dynamic estimates of geotechnical pile resistance at the end of initial pile driving (EOD) and static estimates of pile resistance based on static load tests after at least some pile setup has occurred.

Designers of friction piles can take one of several approaches, all of which have disadvantages. First, the designer may choose to use a static design method that includes pile setup to determine the pile capacity. This approach, however, includes considerable uncertainty and requires that a correspondingly small resistance factor be applied to the estimated capacity. Alternatively, the designer may choose to use dynamic testing at the end of driving (EOD) to produce a more reliable estimate of capacity. This approach allows for use of a larger resistance factor but ignores pile setup, resulting in an uneconomical design. Lastly, the designer may choose to restrike the pile after some pile setup has occurred, resulting in a greater factored resistance than the previous two options. However, this approach requires remobilization of pile driving equipment and often significant construction delays. Because of the construction delays associated with restriking, agencies and contractors frequently choose to simply drive a longer pile rather than relying on subsequent pile setup (Brown and Thompson, 2011).

Currently, Section 751.36.1.7 of the Missouri Department of Transportation (MoDOT) Engineering Policy Guide (EPG) states that “designers should NOT require restrikes unless the Geotechnical Section requires restrike because it delays construction.” MoDOT’s current policy generally follows the second option described above, where dynamic testing may be performed at the EOD, but restrikes are discouraged. This approach, while reasonable and conservative, is likely resulting in uneconomical design of friction piles in Missouri.

As described below, many studies have shown that pile capacity can increase significantly in the days after pile installation. This increase in capacity can be expressed as the ratio of the pile capacity at some time after driving to the capacity measured at the EOD. It is not unusual to have setup factors of 1.5 to 3 or more for certain soil conditions. If this setup was reliably incorporated into the design procedure, pile driving could be stopped short of the required capacity resulting in shorter piles and cost savings. Pile setup phenomena is especially pronounced in clay soils and can be largely attributed to the decrease with time in excess pore pressures generated during pile driving. However, as discussed below, other factors can contribute to the magnitude of the pile setup, including variations in the soil profile, specific characteristics of the soil (e.g., plasticity), pile diameter, and pile type. Therefore, even in the same geologic region, the observed pile setup can vary significantly. Incorporating pile setup into design procedures should be implemented within a probabilistic framework. This project was performed to provide MoDOT with guidance for geotechnical design of friction piles by using the best available data relevant to MoDOT practices and Missouri geology. The guidance presented at the conclusion of this report is based on probabilistically calibrated resistance factors for consideration of pile setup, ensuring that designs are compliant with Load and Resistance Factor Design (LRFD) practices and satisfy appropriate target reliability.

1.2 Project Overview and Objectives

This project has two main objectives. The first objective of this research is to provide MoDOT with a better understanding of pile setup in Missouri soils. Two regions of the state are particularly relevant to this work, the glacial plains in Northern Missouri and the deep alluvial deposits of Southeast Missouri. Bedrock in these regions is deep (often hundreds of feet), so friction piles are commonly used to support bridges in these parts of the state. Pile setup is very important for pile design in these regions, with pile restrikes specified more commonly than in other regions. In other portions of the state, end bearing piles driven to rock are commonly used and pile setup is not an important consideration. This first objective was met by compiling pile test data from Northern Missouri and Southeast Missouri and developing relationships for pile setup in these soils. In addition to this report, a second deliverable from this project is a concise Pile Setup Summary document that identifies regions of the state where setup or relaxation is likely to be encountered, shows the measured magnitude of pile setup in these regions from the compiled load test data, and identifies soil characteristics to look for in a foundation investigation that indicate the potential for setup.

The second and primary objective of this research is to provide MoDOT with rational and economical pile restrike procedures and guidelines to incorporate pile setup in MoDOT pile design. The second objective was accomplished by using the pile setup data collected from Northern Missouri to create a model of pile setup for general soil profiles (e.g., Clay, Mixed). The model informs practitioners of the magnitude of pile setup that can be expected to develop, on average, within three days of initial pile driving. Reliability analysis of the model was performed to probabilistically calibrate resistance factors that can be applied to the expected pile setup.

In the proposed procedures, practitioners have two options for application of the model and resistance factors. The first alternative is to wait and perform restrikes to demonstrate pile setup. This approach is allowed in the status quo, but the model statistics, i.e., average pile setup, variability of pile setup, and range of observed pile setup values for short-term (<24 hrs.) and long-term conditions (>3 days), will lead to more informed decisions regarding restrikes. The second option is to rely on pile setup without restrike testing. In this scenario, the calibrated resistance factors and setup model are used to add factored setup resistance to the EOD resistance demonstrated with high-strain dynamic testing (HSDT) with signal matching (SM). The resulting factored resistance is less than would be achieved by demonstrating the setup with HSDT-SM during a restrike (with a greater resistance factor), but more than the status quo, which neglects setup unless demonstrated with restrikes. The practical outcome of the second option is to reduce the target resistance at EOD compared to the status quo (for the same factored loading) for sites where the model applies.

The proposed model is limited to 14 in.-16 in. closed-ended pipe pile foundations, which are the most common type of driven piles used by MoDOT in Northern Missouri and Southeast Missouri (as reflected in the available data). Design procedures and examples were developed and are presented in this report. There is insufficient data to develop meaningful resistance factors from sites in Southeast Missouri. However, general recommendations on pile setup in these regions are provided.

1.3 Report Organization

Chapter 1 of this report presents an overview of this project along with the motivation, challenges, and project objectives. Chapter 2 provides background material on pile setup including an overview of pile setup, expected setup behavior in different soil types, models of pile setup that have been developed by researchers, the potential for pile setup in Missouri soils, and some of the practices of departments of transportation (DOT) in surrounding states. Chapter 3 presents a summary of the data collected for this study along with details of the procedures used to collect the data, clean the data, characterize soil conditions, develop the pile setup model, and develop the reliability-based resistance factors. Chapter 4 presents the results of the study, including the pile setup models for Northern Missouri and Southeast Missouri regions, relationships between soil properties and pile setup, and the pile setup resistance factors developed in this study. Chapter 5 presents recommendations for practical implementation of the findings from this study along with examples showing how the results can be applied in practice. Lastly, Summary and Conclusions from study are presented in Chapter 6.

2. Background

2.1 Pile Setup Overview

The term, *pile setup*, refers to the increase in pile capacity that often occurs after initial driving of piles in many soil conditions. A related effect, termed *pile relaxation*, refers to the decrease in pile capacity that occurs in rare cases in some soil conditions. When a pile is driven the soil is displaced, sheared, and remolded near the pile, with these effects decreasing in magnitude radially outward from the pile. This remolding of the soil and the associated pore pressure generation is the primary cause of pile setup. In most cases, pore pressures increase significantly, causing an associated decrease in the effective stress and soil strength. Pile driving becomes easier, meaning less energy is required to advance the pile. However, when the pile reaches the expected depth, the measured capacity from dynamic testing may be lower than required. If the pile is allowed to rest, the pore pressures will dissipate with time and the effective stress and strength will continue to increase. The majority of excess pore pressure generation occurs along the pile shaft, so the increase in pile capacity due to setup is primarily associated with an increase in capacity along the pile shaft. The pile capacity will often increase dramatically over hours and days after driving and will continue to increase over months or years in some cases (Skov and Denver, 1988). Even after excess pore pressures have dissipated, the capacity may continue to increase over years due to aging (Long et al., 1999).

Pile setup has been recognized and documented for many years. Incorporating pile setup in design has economic benefits but is challenging for a few reasons. First, as discussed below, the magnitude of pile setup can vary widely depending on several factors, including soil type, soil properties, pile type, pile size, and soil stratigraphy. It is difficult to predict the magnitude of pile setup that can be counted on as part of the pile capacity. Although there are many pile setup models (e.g., Skov and Denver, 1988; Svinkin, 1996; Svinkin and Skov, 2000; Ng, 2013a), the model parameters will depend significantly on local conditions, and the scatter about these models is often significant. Secondly, pile setup can be reliably included in pile design by performing restrike analysis on the pile several days after installation. This approach directly measures the capacity using dynamic analysis. However, the need to remobilize the pile driving equipment days later often delays construction schedules. For these reasons, pile setup is often not considered in pile design. Instead, piles may be driven to greater depths to achieve the needed capacity at the time of driving, resulting in longer piles and greater expense.

2.2 Factors Influencing Pile Setup

2.2.1 Soil Conditions

2.2.1.1 Clay

The magnitude of pile setup is affected by the soil type and profile that the pile is driven into. Greater pile setup is usually observed in piles driven into clay, particularly soft, weaker clay (e.g., Peck, 1958) as compared to sand. As described above, setup is primarily associated with positive excess pore pressure generation due to the shearing and remolding of the soil. Soft, weaker clay will tend to experience greater pore pressure generation and hence greater changes in effective stress and strength. To illustrate the potential variability in pile setup in clay, Figure 1a shows pile setup measured in clay from a database of values compiled and presented by Long et al. (1999). The setup factor (plotted on the y-axis) is defined as the ratio of the capacity measured from a restrike of the pile to the capacity at the end of driving (EOD). The setup factor from this database varies considerably with setup factors from 1 to as high as 6. This illustrates the difficultly in applying a generic factor for setup in clay.

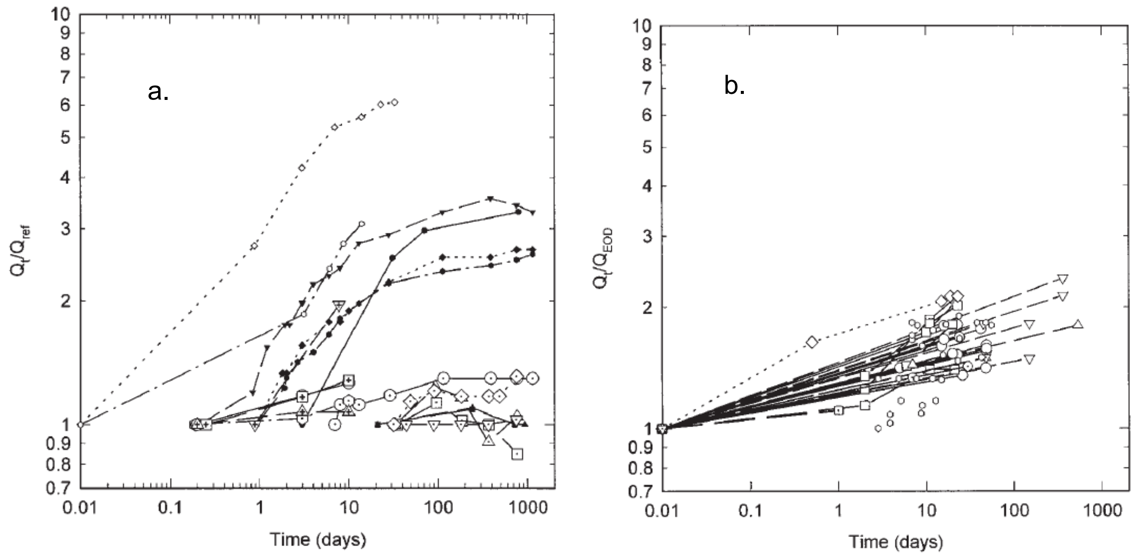


Figure 1 Pile setup in (a) clay versus (b) sand (Long et al., 1999)

2.2.1.2 Sand

As shown in Figure 1b, piles driven in sand may also experience setup. The magnitude of setup is typically lower than what is observed in clay. For the database presented by Long et al. (1999), the setup factor was less than about two in nearly all cases. The explanation for setup in sand is likewise related to pore pressure generation during pile driving in most cases. Although, it should be noted that Parsons (1966) reports pile setup in sand with no significant changes in pore pressure. Piles installed in loose sand will often produce positive pore pressures that temporarily decrease the pile capacity. These pore pressures will dissipate faster due to the higher hydraulic conductivity of the sand. For cases where little or no excess pore pressure is generated, setup factors may remain close to unity. In some cases, pore pressures may become negative during pile driving through dense, fine sand due to dilation of the sand. This will result in higher resistance during driving and subsequent decreases in pile capacity as the negative pore pressures dissipate with time. This time dependent decrease in capacity, called pile relaxation, is unconservative if not accounted for in design. The database of Long et al. (1999) did not show any cases of soil relaxation, however, others have reported evidence of relaxation associated with dilative sand (e.g., Yang, 1970; Parsons, 1966; Zai, 1988). Thompson and Thompson (1985) suggest that some reports of pile relaxation can be attributed to inadequate consideration of the hammer efficiency.

2.2.1.3 Mixed (Sand and Clay)

Mixed soil conditions refer to cases where the profile consists of both clay and sand layers. Since clays are generally associated with larger setup values, the general expectation is that setup factors in mixed soil layers will fall somewhere in between the values for clay and sand, with increasing setup factors as the percentage of clay layer thickness over the drive length increases. Figure 2b shows the setup observed from the database presented by Long et al. (1999). Surprisingly, this data showed little difference in the range of setup factors observed for mixed soil conditions versus clay soil. This again underscores that there are many factors affecting setup and, in this case, other factors may dominate the observed response.

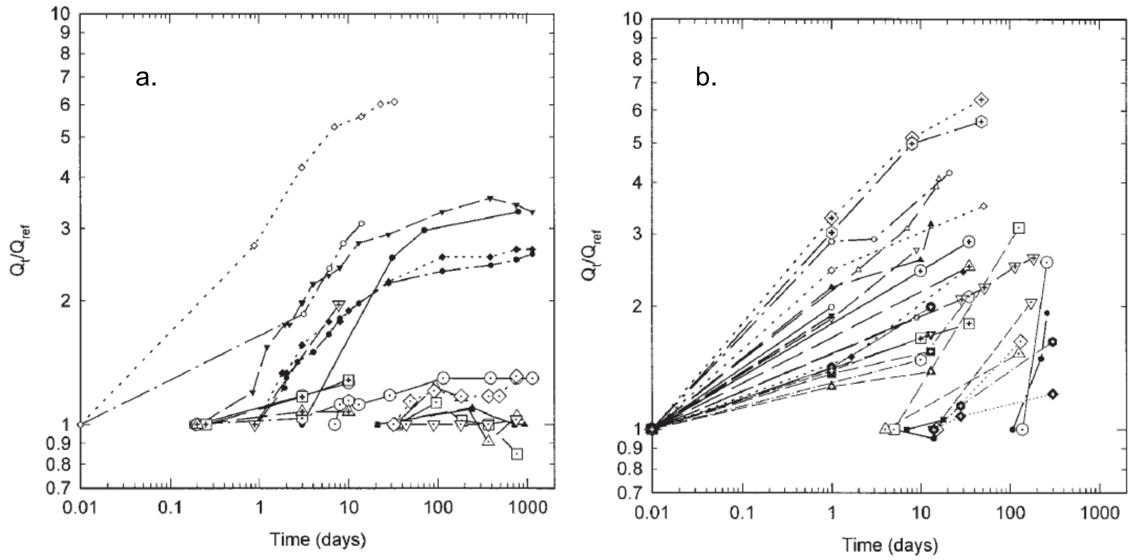


Figure 2 Pile setup in (a) clay versus (b) mixed soil (Long et al., 1999)

2.2.2 Pile Type and Size

It is expected that pile type will influence both the magnitude of setup and rate of pile setup. Since setup is associated with soil displacement during pile installation, it is generally expected that higher displacement piles will produce greater setup (all else being equal). However, Long et al. (1999) noted in their analysis of piles in clay that low displacement piles exhibited setup within the range of all the other piles. Likewise, for mixed soil conditions, they concluded that the data provided no clear difference in the increase in time dependent capacity.

Pile size may also affect the magnitude and rate of pile setup due to the greater zone of disturbed soil around the pile. Pore pressures will tend to dissipate radially, so a larger zone of pore pressure increase will result in a slower rate of setup experienced by the pile. Larger pile diameters, however, will carry more of the load in end bearing, so since pile setup primarily affects side shear, the pile setup, as measured by the total capacity, may be lower.

2.3 Pile Setup Models

A variety of pile capacity models have been developed. Generally, the total capacity of piles (side shear plus end bearing) can be modeled as a linear increase versus the logarithm of time. Some common models that have been developed are discussed below.

2.3.1 Skov and Denver (1988)

One of the early and most common setup models was suggested by Skov and Denver (1988) using a dimensionless setup factor, A, and equation:

$$\frac{Q_t}{Q_0} - 1 = A\log\left(\frac{t}{t_0}\right) \qquad (1)$$

where Q_t is the capacity at time t and Q_0 is the capacity at time t_0, which is the time at the start of the log-linear capacity increase. Application of this equation is limited by the need to establish a time for the start of the log-linear relationship.

2.3.2 Svinkin (1996)

Svinkin (1996) suggested an empirical relationship to estimate the pile setup factor using the EOD as a reference pile resistance:

$$R_t = a\, R_{EOD} t^{0.1} \qquad (2)$$

where R_t is the capacity at time t, R_{EOD} is the capacity at the end of driving, and a is an empirical setup factor.

2.3.3 Svinkin and Skov (2000)

Svinkin and Skov (2000) also developed a relationship with the capacity at the EOD to be used as the reference resistance. Their equation uses a dimensionless setup factor B and is of the form:

$$\frac{R_t}{R_{OED}} = B[\log(t) + 1] + 1 \qquad (3)$$

where R_t is the capacity at time t and R_{EOD} is the capacity at the end of driving.

2.3.4 Mesri et al. (1990)

Mesri et al. (1990) developed a mathematical representation of increasing pile capacity of the form:

$$\frac{Q_t}{Q_R} = \left[\frac{t}{t_0}\right]^{\frac{C_D C_\alpha}{C_c}} \qquad (4)$$

where Q_t is the capacity at time t and Q_{R} is the capacity at time t_0, and C_D, C_α, and C_c are constants. One of the limitations of this equation is that it requires restrike measurements one day after the EOD as the reference value.

2.3.5 Ng et al. (2013a)

Ng et al. (2013a) proposed a complex equation of the form:

$$\frac{R_t}{R_{EOD}} = [(\frac{f_c C_{ha}}{N_a r_p^2} + f_r)\log\left(\frac{t}{t_{EOD}}\right) + 1](\frac{L_t}{L_{EOD}}) \qquad (5)$$

where $\frac{L_t}{L_{EOD}}$ is the normalized embedded length, r_p is the pile radius or the equivalent pile radius based on cross sectional area, C_{ha} is the weighted average value for the coefficient of consolidation in the horizontal direction, f_r is the remolding recovery factor and f_c is the consolidation factor.

In many cases the soil information that is needed to use this relationship is not available. This equation has a similar form as other equations if the $\left(\frac{f_c C_{ha}}{N_a r_p^2} + f_r\right)$ is grouped into a single fitting parameter.

2.4 Pile Setup in Missouri Soils

2.4.1 Missouri Soil, Bedrock Depth, and Foundation Types

The depth of bedrock is quite variable through the state of Missouri, as shown in Figure 3. The deepest bedrock is found in the southeast and northern portions of the state. Throughout much of the rest of Missouri, bedrock is relatively shallow, and the bridge foundation of choice is often H-piles driven to rock. In these cases, pile setup is not an issue as the load is primarily carried by end bearing. However, in regions with deep bedrock, friction piles are common (typically closed-ended pipe piles), and pile setup is an important contributor to pile capacity.

As shown in Figure 4, Missouri is composed of four distinct physiographic regions: the northern plains, western plains, Ozark highlands, and southeast lowlands. Therefore, the regions of primary interest to this study are the northern plains and southeast lowlands. General soil conditions in these regions are described in the sections that follow.

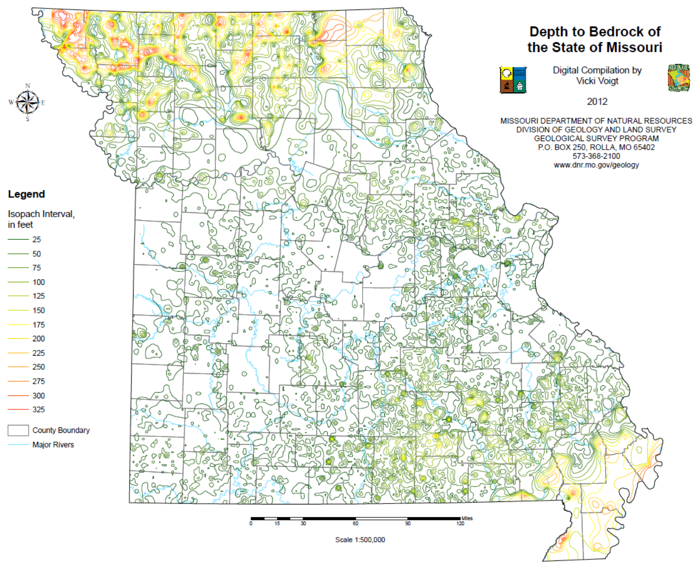


Figure 3 Depth to bedrock in Missouri (Missouri DNR, 2012)

2.4.1.1 Northern Glaciated Plains

Soil conditions in the northern plains generally consist of deep glacial deposits underlain by Pennsylvanian shale along with Mississippian limestone and some sandstone. Bedrock depths are greater than 300 ft. in some parts. The surficial glacial deposits were placed during three glacial advancements in the Pleistocene epoch (Stout and Hoffman, 1973). Deposits of clay, silt, sand, and gravel were accumulated and then overridden by the advancing glaciers, leaving behind an unsorted deposit of till, composed primarily of clay with sand, silt, and boulders. The thickness of these deposits is highly variable, with thickness and continuity of the deposits decreasing southward toward the Missouri River. In parts of this region, the glacial deposits are discontinuous and surficial materials are like the non-glaciated regions of the state (Stout and Hoffman, 1973). During the glacial retreat, wind-blown silt and clay (loess) were deposited over much of the upland areas, with the thickest deposits near the Missouri and Mississippi rivers.

2.4.1.2 Southeast Lowlands

The geographical region known as the Southeast Lowlands encompasses a significant area in the southeastern part of Missouri. The main bedrock formation in this region is Ordovician dolomite and sandstone, which are deeply buried. The surficial material consists mainly of alluvium, although loess and residuum also cover some parts of the area. The upland regions, such as Stoddard County, are typically covered with loess that range from 5 to 30 ft. thick and is mainly composed of silt, with limited amounts of fine-sand clay. In most other areas of the region the surficial materials are predominantly composed of alluvium deposits of stratified gravel, slit, and sand that can reach a thickness of up to 150 ft. in some places.

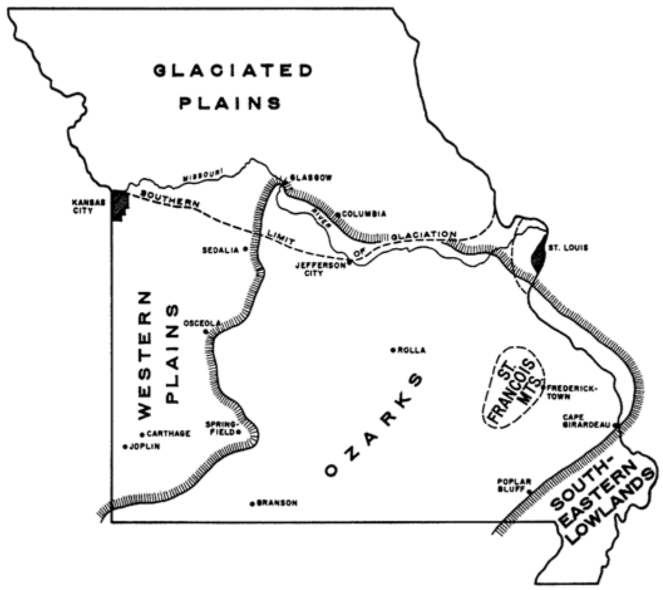


Figure 4 Surficial materials map of Missouri (Saville et al., 1962)

2.4.2 Previous Pile Setup Studies in Missouri and Iowa

Summaries of relevant past studies of pile setup in Missouri soils and similar soils in Iowa are presented below.

2.4.2.1 Kebede (2011)

This study presents results from 64 EOD and 22 beginning of restrike (BOR) tests performed at nine bridge sites. The results are also presented in Kebede (2011). The data were used to develop geotechnical resistance factors calibrated for axial driven piles using the first-order reliability method (FORM). As part of this study, restrike data were collected from several sites, primarily in Southeast Missouri. The results showed negligible pile setup for pile tests performed on H-pile and pipe piles in Southeast Missouri (Figure 5), while significant setup was observed from strikes performed at sites located in the glaciated plains (Figure 6). However, only four piles were tested with restrikes in Northern Missouri. The data from this study were used, when possible, in the present study as described in Section 3.2.

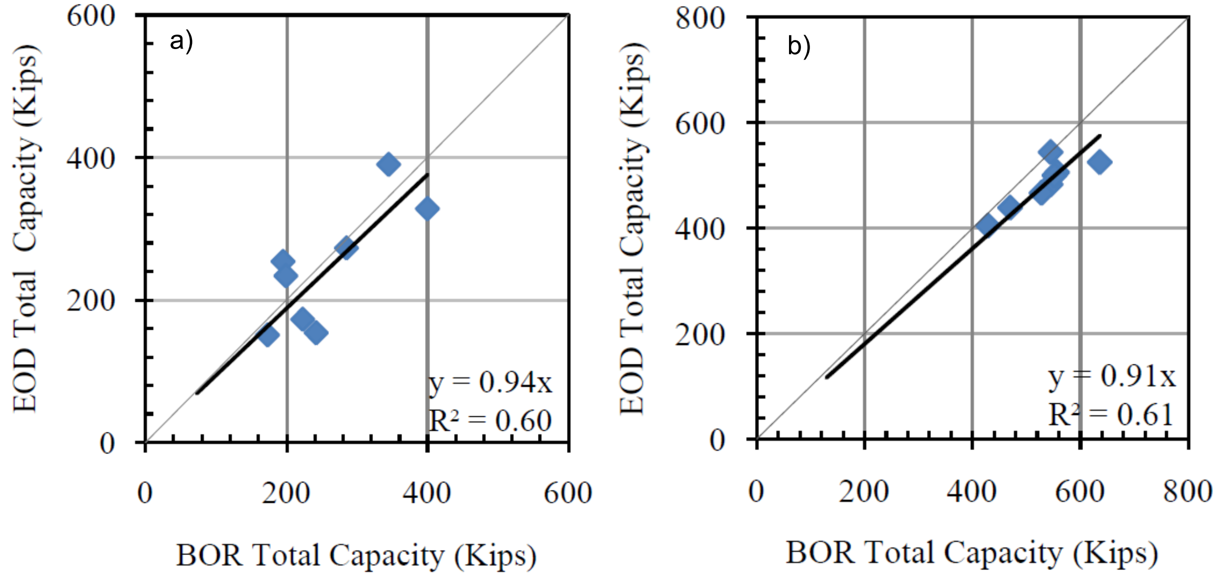


Figure 5 Pile setup in Southeast Missouri for (a) pipe piles and (b) H-piles (Kebebe, 2011)

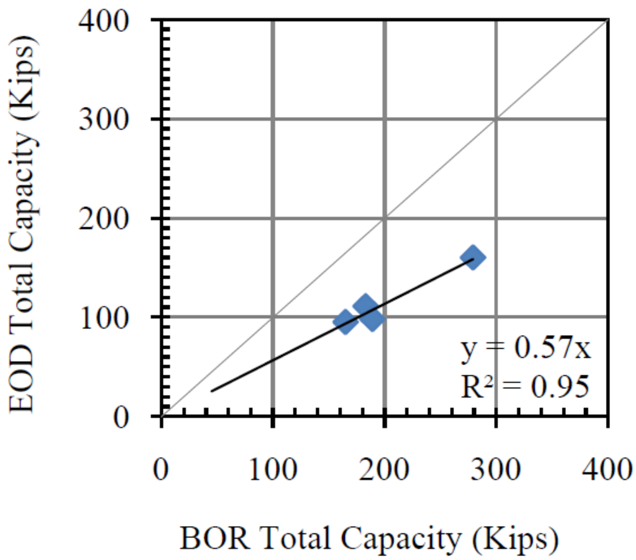
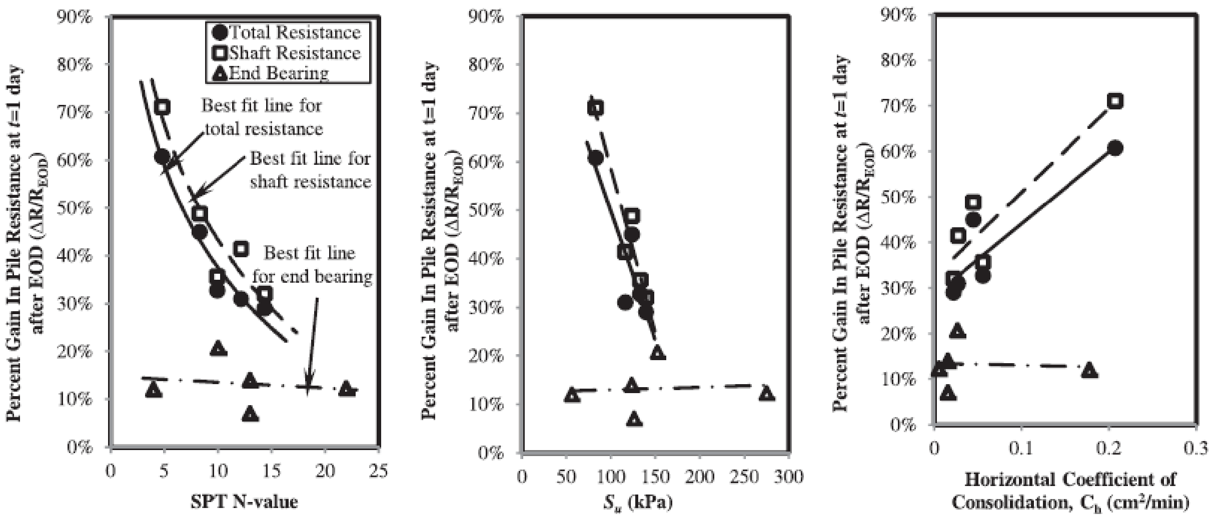


Figure 6 Pile setup in Northern Missouri for pipe piles (Kebebe, 2011)

2.4.2.2 Iowa State University

Iowa State University performed an extensive research project on pile setup in the soils of Iowa (Ng et al., 2011). These tests were performed in glacial soil deposits, like the soil of Northern Missouri described above. In the Iowa State study 10 test piles were installed and load tested using both dynamic testing and static load tests. Only H-piles were used in this study. An extensive program of soil testing was also performed to develop relationships between pile setup and soil properties, such as strength, plasticity, blow counts, and consolidation parameters. Examples of some relationships developed in this work are shown in Figure 7 (Ng et al., 2013a). The data from this study are relevant to the work performed in the present study. As discussed in Section 3.2.3, these data were compiled from Ng et al. (2011) and compared with the results from the Northern Missouri pile load tests in Section 4.4.



(a) Relationship with SPT *N*-value (b) Relationship with *Su* (c) Relationship with C_h

Figure 7 Relationships between percent gain in pile resistance after one day and various soil parameters (Ng et al., 2013a)

2.5 Practices of Neighboring States

The practices of three neighboring states regarding pile setup and restrike analysis are briefly discussed in this section and summarized in Table 1. All three agencies permit restrikes, but with approaches that vary considerably. Kansas DOT simply specifies that restriking is an option if a pile fails to satisfy plan resistance at EOD, with the specification primarily addressing important pile driving procedures for the restrike (e.g., use of a warmed-up hammer, restrictions on disturbing piles). Illinois DOT similarly presents restriking as an option, but also provides guidance regarding the magnitude of pile setup that could be observed. The setup information is for information only to aid the engineer in decisions of restrike versus adding length.

The Iowa DOT procedures include consideration of pile setup even without restriking. During design, the pile length is estimated based on static methods that include the effect of pile setup (and with resistance factors calibrated probabilistically per AbdelSalam et al., 2012). During pile installation, the target pile driving resistance is established as the factored load divided by a target resistance factor. The target resistance factor includes one component for the resistance demonstrated during driving (e.g., via Wave Equation Analysis of Pile Driving (WEAP), Pile Dynamic Analyzer (PDA)) and another component for the resistance anticipated to develop due to pile setup. Setup is only considered for friction piles in clay, with the magnitude of setup dependent on Standard Penetration test (SPT) N value.

Iowa's approach of considering pile setup without demonstrating the setup via restriking is more aggressive than other agencies. However, the setup model is based on real data, and the pile setup is subject to resistance factors based on probabilistic calibrations that conform to American Association of State Highway and Transportation Officials (AASHTO) specifications for local calibrations. This results in resistance factors on the order of 0.2 to 0.3 (e.g., Yang and Liang, 2006; Ng and Sritharan, 2016), relatively low values on par with the least reliable of static prediction methods. The concept of relying on undemonstrated pile setup is sound from an LRFD perspective if resistance factors are appropriately calibrated.

The methodology developed in this research adopts the best aspects of the procedures adopted above, including: incorporation of important pile driving installation considerations as in the Kansas DOT specification (particularly pile warmup as discussed later), and guidance regarding the expected magnitude of pile setup for MoDOT friction piles for both informational purposes (as in Illinois DOT specifications), and as an explicit component of pile resistance to be included in factored resistance (as in Iowa DOT specifications).

Table 1 Pile restrike procedures of neighboring agencies

Agency	Characteristics of Restrike Procedures	Advantages	Limitations
Kansas DOT	• Nominal bearing during driving estimated using KDOT modification of the Engineering News Record (ENR) formula, which is based on Allowable Stress Design (ASD) with presumed safety factor of 5 to 8. PDA can also be used with a resistance factor of 0.65. • If plan resistance is not met at EOD, a restrike may be performed after a minimum of 24 hours. • Includes procedures for warming up hammer and restrictions to prevent disturbance to piles.	• Relatively simple. • Any use of pile setup is demonstrated. • Procedures include beneficial construction considerations.	• Setup neglected without re-strikes. • Not LRFD unless PDA is used.
Illinois DOT	• Nominal bearing during driving estimated using WSDOT formula with resistance factor of 0.55, or any other method per AASHTO Bridge Design Specifications. • If EOD resistance is insufficient, pile can be restruck. Time of restrike not specified. • Standard specifications include estimated increase in nominal bearing for 1 to 5 days of waiting, depending on soil type. The estimates are for information only and cannot be relied upon without demonstrating during restrike.	• Relatively simple. • Any use of pile setup is demonstrated. • Guidance regarding anticipated setup is useful.	• Setup neglected without re-strikes.
Iowa DOT	• Procedures include a model for predicting setup of friction piles in clay from 1 to 7 days. • Factored resistance includes two components, with separate resistance factors for the component of resistance demonstrated during driving or restrike and the component anticipated due to future setup.	• Benefits of setup are included, with or without restrikes. • Probabilistically calibrated resistance factors.	• Procedure is complicated. • Setup is included but not necessarily demonstrated since restrikes not required.

3. Methods and Summary of Data

The major steps involved in this project are described in this chapter. The chapter starts with a discussion of the sources of data before summarizing the collected data. Methods for “cleaning” the data are then discussed before presenting the resulting dataset used for analysis. The chapter closes with a description of the methodology for reliability analysis.

3.1 Data Sources and Data Gathering

As mentioned in Section 2.4.1, the primary areas of interest for this study were Northern Missouri and Southeast Missouri due to the common use of friction piles in these regions. In addition, sites in Iowa located in similar geologic conditions to the Northern Missouri sites were also of interest. The first step performed in this research was to compile all load test data from these locations. Data were sought from sites that included both load tests performed at the end of driving (EOD) and load tests performed after the end of driving, termed beginning of restrike (BOR) in the report. Although either static or dynamic load test data was of interest, all data compiled and used in this study were taken from high-strain dynamic tests (HSDT, also known as the trade name Pile Dynamic Analyzer or PDA) and processed using signal matching (SM), (also known as by the trade name CAPWAP, which stands for Case Pile Wave Analysis Program). In most cases the load test data came from HSDT-SM reports provided to the investigators by MoDOT, as described below. In some cases, the original HDST-SM reports could not be obtained. As described in Section 3.3.3.1, sites without HSDT-SM reports were not included in the model dataset.

In addition to the load test data, information about the subsurface conditions was vital to this study. For most sites, MoDOT provided the associated boring logs at locations near the test piles. However, in cases where load test results had to be obtained from published reports or papers, the subsurface conditions were obtained from tables and descriptions provided in the reports, if available. The data sources used in this study are described in greater detail below.

3.1.1 Pile Test Data

Most pile load test data used in this study came directly from HSDT test reports provided by MoDOT. These reports were the original reports from the company that performed the testing and SM analysis. Information obtained from these reports included:

- Pile installation depths
- Pile type
- Pile driving hammer
- Dates and times of pile load testing
- Details of the testing, including any issue or problems
- Predrilling of piles if performed
- Required axial capacity
- Total, side, and end capacity from SM analysis

- Hammer stroke and set per final blows
- SM parameters and quality of the fit parameter (“CAPWAP match quality”)

The graduate student on the project, overseen by the project PI, performed the work of compiling and sorting through the information provided in these reports. A spreadsheet was developed for the project that contained all pertinent information derived from these reports. The subcontractor on the project also performed their own review of the load test data and made additions and modifications to the work performed by the graduate student. The information provided in these reports was vital to the process of deciding what data could reliably be included in the analyses, as discussed in the data cleaning section below.

3.1.2 Boring Logs

In addition to the PDA reports, MoDOT personnel were very helpful in finding and providing soil boring information from the sites. The soil boring information typically consisted of multiple boring logs from drilling performed near the locations of the pile load tests. The graduate student on this project compiled the boring log information from these locations and identified the borings that were located closest to the individual pile load test locations. The information obtained from the soil borings included:

- Boring location
- Layer thicknesses, soil descriptions, and soil classifications
- Index properties of the soil (liquid limit and plasticity index)
- Standard Penetration Test (SPT) N_{60}-values
- Pocket penetrometer values performed in cohesive soils

The information in the boring logs was important for relating the observed pile setup to soil conditions. Relevant values obtained from the boring logs were entered into the spreadsheet developed for the project. These values are described in Section 3.3.2.

3.1.3 Published Studies

All data used to develop the MoDOT pile setup model are derived from previously unpublished MoDOT project reports. However, reports of pile setup from published studies were used for comparison to evaluate the model developed for MoDOT. For example, all load test results presented from Iowa were obtained from published reports and papers documenting load test research that was performed by Iowa State University (Ng et al., 2011). The Iowa load tests are reportedly stored on an online database (“PIle LOad Tests,” or PILOT), but access to the database was unavailable. Fortunately, the most relevant data to this project is well documented in the literature. Published papers and reports provided the details of the load testing program including:

- Pile types used
- CPT logs
- General stratigraphy and measured soil properties
- Soil profile classification (Sand, Clay, Mixed)

- Measured pile capacities from static and dynamic testing including multiple restrikes
- Correlations of setup to measured soil parameters

Although the pile load test data and boring log information were not directly accessible, the data from the published report is extensive and considered reliable, as this work was performed as part of a research project and included more extensive data collection and analysis than are typically performed on production pile testing.

The second case where published data were predominantly used in this study was for most of the pile load tests performed in Southeast Missouri. The primary source for most of the Southeast Missouri sites is a published thesis by Kebeda (2011). This document provides load test results from nine MoDOT construction sites, with five sites located in the southeastern lowland region. The project numbers and load test data are summarized in tabular form in the document. However, the soil profiles at these sites are not described and attempts to locate the original soil borings and load test reports from MoDOT were not successful for many of these sites. Therefore, details about the soil conditions in the Southeast Missouri sites were lacking, which limited the analyses that could be performed for this region.

3.2 Summary of Data Collected

3.2.1 Northern Missouri Sites

Data were obtained from 14 projects in Northern Missouri, with load test data available from tests performed on 46 piles. The project site locations are shown in Figure 8. All pile load tests compiled from sites in Northern Missouri are listed in Table 2. Most of the piles used in Northern Missouri were 14 in. diameter, closed-ended pipe piles. Pile lengths ranged from 30 ft. to over 100 ft. In the table, piles with significant limitations or errors in the data are highlighted with the limitations described in the final column. Most of the piles with limitations were removed from the data set that was used to calibrate resistance factors, as discussed in Section 3.3.3.

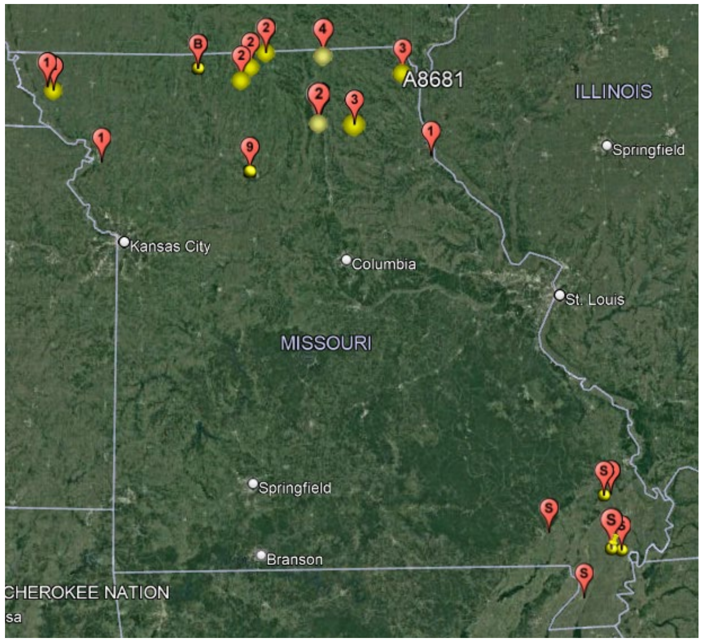


Figure 8 Missouri project sites in Northern Missouri and Southeast Missouri where pile load test data were available

3.2.2 Southeast Missouri Sites

Data were obtained from seven projects in Southeast Missouri with load test data available from tests performed on 24 piles. The locations of the load test sites in Southeast Missouri are also shown in Figure 8. Soil information is only available for four of the seven project sites and eight of the 24 piles, which greatly limits the number of piles that could be used in this study, as discussed below. A summary of the pile data in Southeast Missouri is presented in Table 3, with limitations again highlighted and described.

Table 2 Summary of all pile load test data from sites in Northern Missouri (shading indicates data that were not used)

Bridge	Pile	Type	Pile Length (ft.)	Issues or Limitations of the Data
A7934	1	HP12x53	104.5	No soil report; no signal matching for EOD; H-pile different from other piles
A7934	7	20" CEP	75	No soil report; no restrike data
A7934	16	HP12x53	99	No soil report; no restrike data; H-pile different from other piles
A8320	2	14" CEP	95.25	Poor quality CAPWAP; unreasonable tip resistance; different hammer for restrike
A8320	5	20" CEP	70.25	Very poor quality CAPWAP;
A8320	13	20" CEP	75	Very poor quality CAPWAP;
A8320	15	14" CEP	103.5	Poor quality CAPWAP; unreasonable tip resistance; different hammer for restrike
A8285	10	24" OEP	58.5	No soil report; large diameter open-ended pile is different from other pile types
A8367	1	14" CEP	50	No restrike
A8367	5	14" CEP	43.5	
A8367	14	14" CEP	48.75	
A8371	1a	14" OEP	49.5	Open ended pile inconsistent with majority of other piles -setup likely different
A8371	1b	14" OEP	75	This is redrive of pile 1; hard to interpret setup
A8371	9	14" OEP	48	Open ended pile inconsistent with majority of other piles -setup likely different
A8579	1	16" CEP	91.3	
A8579	7	16" CEP	104.5	
A8043	5	14" CEP	43	
A8043	7	14" CEP	60	Two of three restrikes are unreliable (poor CAPWAP match)
A8043	13	14" CEP	62	
A8043	16	14" CEP	43	
A8743	2a	14" CEP	34	Hammer fueling issues resulting in overprediction of capacity
A8743	2b	14" CEP	43	
A8743	9	14" CEP	42.5	
A8743	14	14" CEP	43.5	
A8743	15a	14" CEP	30	Hammer fueling issues resulting in overprediction of capacity
A8743	15b	14" CEP	34.5	Restrike performed on 20 minutes after driving
A8681	6	14" CEP	51	
A8681	11	24" CEP	50	Large diameter (outside range considered)
A8681	16	24" CEP	65	Large diameter (outside range considered)
A8681	22	14" CEP	55	
A8693	4	14" CEP	38.5	
A8693	6	16" CEP	67	
A8693	12	16" CEP	60	
A8693	21a	14" CEP	40	
A8693	21b	14" CEP	64	
A7077	19	14" CEP	51	At EOD, pile was at practical refusal
A7381	143	14" CEP	37	
A7381	144	14" CEP	37	
A7381	145	14" CEP	37	
A8038	5	14" CEP	40	
A8038	6	14" CEP	60	
A8038	15	14" CEP	58	At EOD, pile was at practical refusal
A8038	16	14" CEP	45	Low strength from pocket pen. (1.25 tsf); inconsistent with other sites (2 to 3 tsf)
A8068	8	14" CEP	61.5	
A8068	18	24" CEP	53	
A8068	30	24" CEP	57	
A8068	48	14" CEP	51.5	

Table 3 Summary of all pile load test data from sites in Southeast Missouri (shading indicates data that were not used)

Bridge	Pile	Type	Pile Length (ft.)	Issues or Limitations of the Data
A8648	6	14” CEP	62	
A8798	4	14” CEP	25	
A8798	8	14” CEP	34	
A8771	1	14” CEP	27	
A5643	7	14” CEP	31	
A5643	17	14” CEP	53	
A5643	23	14” CEP	39	
A5643	28	14” CEP		One strain gage not working; questionable reliability of BOR capacity
A5643	44	14” CEP	26.5	
A7403	-	14” CEP		PDA results not available; errors in spreadsheet; limited soil information
A7403	-	14” CEP		PDA results not available; errors in spreadsheet; limited soil information
A7403	-	14” CEP		PDA results not available; errors in spreadsheet; limited soil information
A7403	-	14” CEP		PDA results not available; errors in spreadsheet; limited soil information
A7403	-	14” CEP		PDA results not available; errors in spreadsheet; limited soil information
A7403	-	14” CEP		PDA results not available; errors in spreadsheet; limited soil information
A7403	-	14” CEP		PDA results not available; errors in spreadsheet; limited soil information
A6443	-	HP14X89		PDA results not available; errors in spreadsheet; limited soil information
A6443	-	HP14X89		PDA results not available; errors in spreadsheet; limited soil information
A6443	-	HP14X89		PDA results not available; errors in spreadsheet; limited soil information
A6443	-	HP14X89		PDA results not available; errors in spreadsheet; limited soil information
A7303	-	HP14X53		PDA results not available; errors in spreadsheet; limited soil information
A6443	-	HP14X89		PDA results not available; errors in spreadsheet; limited soil information
A6443	-	HP14X89		PDA results not available; errors in spreadsheet; limited soil information
A6443	-	HP14X89		PDA results not available; errors in spreadsheet; limited soil information

3.2.3 Iowa Sites

As previously mentioned, a research project investigating pile setup in Iowa soils was performed in 2011 by Iowa State University (ISU). Ten H-piles were installed and tested at sites throughout Iowa, with many of the piles in the southern portion of the state, as shown in Figure 9. The data from this project were obtained from a published report that documented in detail the load test program (Ng et al., 2011). A summary of the piles tested in Iowa is provided in Table 4. Limitations of this data are again highlighted and described.

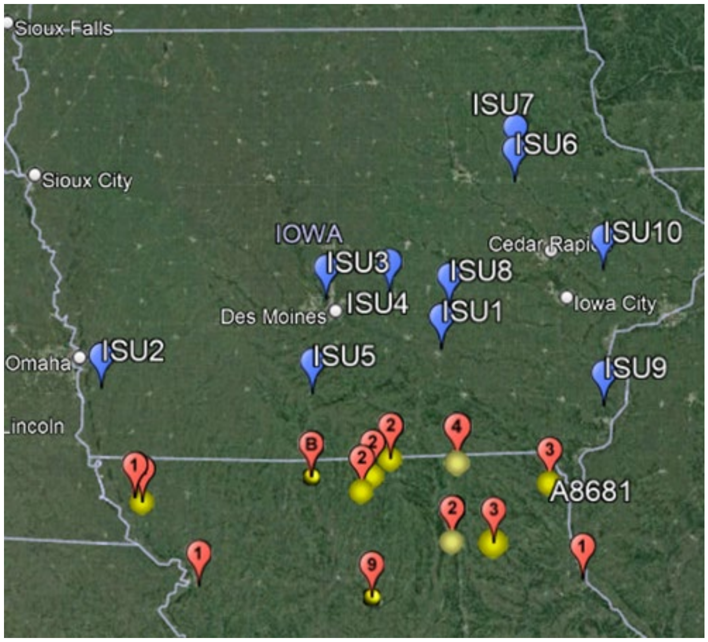


Figure 9 Locations of load tests in Iowa in relation to the Northern Missouri sites

Table 4 Summary of all pile load test data from sites in Iowa (shading indicates data that were not used)

Test Pile	Type	Pile Length (ft.)	Limitations
ISU 1	HP10x57	32.5	No restrikes
ISU 2	HP10X42	55.83	
ISU 3	HP10X42	51	
ISU 4	HP10X42	56.78	
ISU 5	HP10X42	56.67	
ISU 6	HP10X42	57.2	Northern site, far from MO
ISU 7	HP10X42	26.9	Northern site; far from MO; outlier setup factors
ISU 8	HP10X42	57.21	
ISU 9	HP10X42	49.4	
ISU 10	HP10X42	49.5	

3.3 Preliminary Processing and Cleaning of Pile Load Test Data

This section described the procedures and criteria used to identify and remove data ("data cleaning") from the compiled raw dataset. In addition, steps that were performed to calculate soil values from the soil boring information are presented.

3.3.1 Parameters Obtained from Pile Load Test Data

The following parameters were obtained from the pile load test reports:

- **Pile length** - the final depth below grade after driving

- **Driving depth** - the portion of the pile penetration that was obtained from driving the pile. In cases where predrilling was performed the driving depth is less than the pile length
- **Capacity** - the total capacity determined from SM analysis of HSDT data
- **Side resistance** - portion of capacity carried along the side of the pile
- **Tip resistance** - the portion of capacity carried at the base of the pile
- **EOD capacity** - the capacity recorded (total, skin, or toe) recorded at the end of driving
- **BOR capacity** - the capacity recorded at the beginning of a restrike (BOR) performed sometime after EOD
- **Setup factor** - the ratio of the total capacity at BOR to the total capacity at EOD calculated as:

$$\boldsymbol{Setup\ Factor} = \frac{\boldsymbol{Capacity\ at\ BOR}}{\boldsymbol{Capacity\ at\ EOD}} = \frac{\boldsymbol{R_{BOR}}}{\boldsymbol{R_{EOD}}} \quad (6)$$

- **CAPWAP match quality** - a numerical measure of the quality of the fit between the measured and modeled data. This value was used to remove unreliable data, as discussed below

3.3.2 Parameters Obtained from Soil Borings

The soil boring data were used to determine the following parameters:

- **Clay embedment** – the length of the pile driving depth that penetrated through soil that was classified as clay
- **Clay embedment to pile length ratio** – the ratio of the length of pile driven through clay to the pile driving depth. This parameter was used to classify the profile that the pile penetrated through as Sand, Clay, or Mixed, as discussed in greater detail below
- **Average pocket penetrometer value** – this value represents the average pocket penetrometer value (PP_{ave}) recorded in clay layers in the profile. The value was calculated by summing the product of the PP values and the layer thickness they came from and then dividing by the total thickness of clay layers in the profile:

$$\boldsymbol{PP_{ave}} = \frac{\sum(\boldsymbol{PP} \cdot \boldsymbol{t_{clay}})}{\sum \boldsymbol{t_{clay}}} \quad (7)$$

  where PP is the individual pocket penetrometer values and t_{clay} is the thickness of the individual clay layer where the PP value was recorded

- **Average N_{60} values** this value represents the average N_{60} value recorded in clay layers in the profile. The value was calculated by summing the product of the N_{60} value and the layer thickness they came from and then dividing by the total thickness of clay layers in the profile:

$$\boldsymbol{N_{60,ave}} = \frac{\sum(\boldsymbol{N_{60}} \cdot \boldsymbol{t_{clay}})}{\sum \boldsymbol{t_{clay}}} \quad (8)$$

where N_{60} is the value for a given layer and t_{clay} is the thickness of the individual clay layer where the N_{60} value was recorded

- **Average PI -** this value represents the average plasticity index (PI) value recorded in clay layers in the profile. The value was calculated by summing the product of the PI value and the layer thickness it came from and then dividing by the total thickness of clay layers in the profile:

$$\boldsymbol{PI_{ave}} = \frac{\sum(\boldsymbol{PI \cdot t_{clay}})}{\sum \boldsymbol{t_{clay}}} \tag{9}$$

where PI is the value for a given layer and t_{clay} is the thickness of the individual clay layer where PI was recorded

3.3.3 Data Cleaning Criteria

A review of all pile load test data and soil boring information resulted in the identification of major limitations for many of the piles tested. Pile tests where the available information was judged to be either too limited to be reliable or the data were considered potentially erroneous were removed. The reasons for removing data are briefly explained below.

3.3.3.1 Removal due to Limited or No Soil Information

An important part of this study is relating the pile setup behavior to soil stratigraphy and possibly soil parameters, such as strength or plasticity. In addition, soil information is needed to define the site conditions in which the pile setup model is applicable. Therefore, pile test sites where soil information was not available or very limited were excluded from the data that were used in the pile setup model development and subsequent reliability-based calibration of resistance factors.

3.3.3.2 Removal due to Lack of PDA Report

For some sites the original PDA report was not available, and the load test data were obtained secondhand through published reports or papers. For cases where the information in the report or paper was well documented and determined to be reliable, the information was used. However, in cases where the load test data were reported in a table with no additional information it was not used in model development.

3.3.3.3 Removal due to Testing Issues

For some sites the PDA report identified issues that called into question the reliability of the load test results. Examples of testing issues include malfunctioning instrumentation or problems with the pile hammer.

3.3.3.4 Removal due to Pile Type or Size

Pile setup behavior is influenced by many factors, including the size and type of pile used. The piles used in the Northern Missouri sites were predominantly closed-ended pipe piles with a diameter of 14 in. Piles that deviated significantly from this type, such as any open-ended pile or piles with diameters greater than 16 in. were excluded from the Northern Missouri data set. All pile test data from Iowa were performed on 10 in. H-piles. These data were retained and used for comparison purposes to the Missouri data, but due to obvious differences in the resulting setup were not used in the pile model development or reliability-based calibration of resistance factors.

Exclusion of piles outside the range of closed-ended pipe piles considered does not imply that the excluded pile types will not develop significant pile setup. Rather, the decision to only include certain types of piles was made carefully and for two primary reasons. The first reason is to only include the types of piles that are commonly employed on MoDOT bridges in areas where pile setup is significant. The second reason follows from the first - to reduce variability of the pile setup data. Reducing variability of the pile setup data improves the precision of the resulting pile setup model and increases the value to MoDOT upon implementation.

3.3.3.5 Removal due to Pile Refusal

Two piles were removed from consideration in model development because they were at practical refusal at EOD. MoDOT EPG 751.36.5.11 defines practical refusal as 20 blows per in. or greater. At refusal, end bearing likely contributes significantly to geotechnical pile resistance. Because pile setup is understood to primarily derive from increases inside resistance, and because of the strong possibility that piles driven to practical refusal are bearing on rock, it is inappropriate to expect pile setup when piles are driven to refusal.

3.3.3.6 Removal due to Poor Quality Signal Matching

Interpretation of HSDT with SM involves fitting a dynamic model to the observed results from accelerometers and strain gages at the top of the pile. Higher quality datasets generally result in better model fits, with model predictions that more closely match the observed results. The proprietary system used for all HSDT-SM reports evaluated in the MoDOT dataset, CAPWAP, includes a measure of the quality of the signal matching, termed the CAPWAP match quality. Lower values of the CAPWAP match quality indicate better match. The CAPWAP match quality was plotted for each pile test performed in Missouri where this information was available, along with the final penetration rate in blows/in., as shown in Figure 10 and Figure 11. Pile Dynamics reports that for good data a match quality of 5 or lower should be obtained. Therefore, pile tests with match quality indicators greater than 5 were generally excluded from the data used in the model development, especially when other issues were identified.

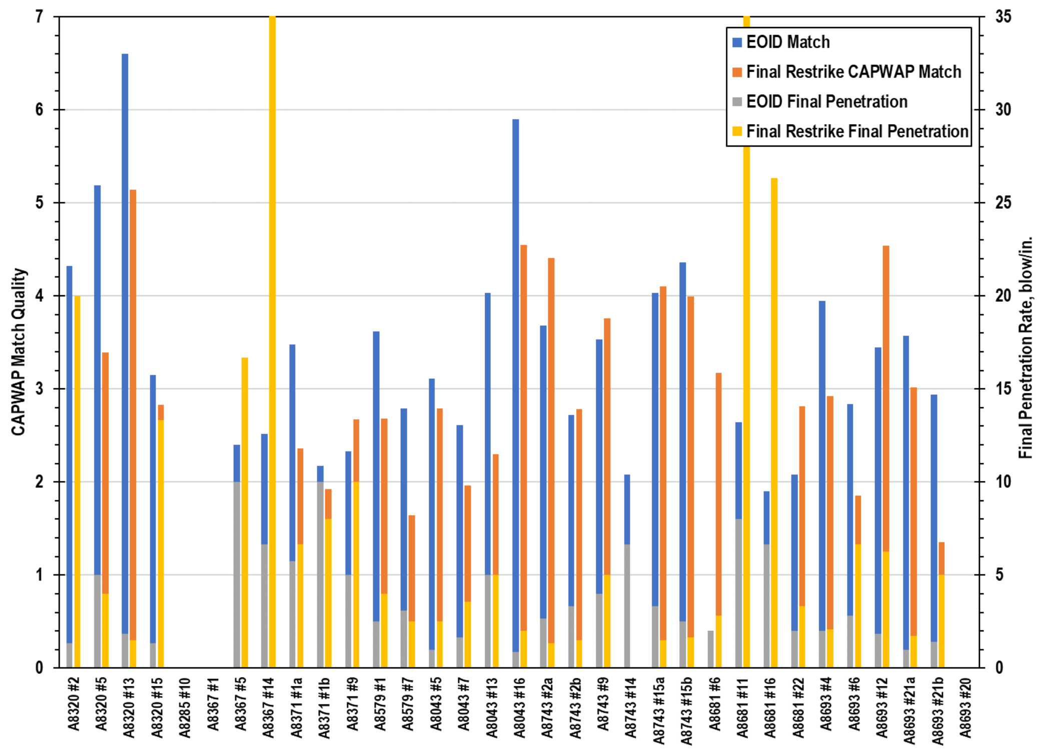


Figure 10 Data quality of pile tests in Northern Missouri

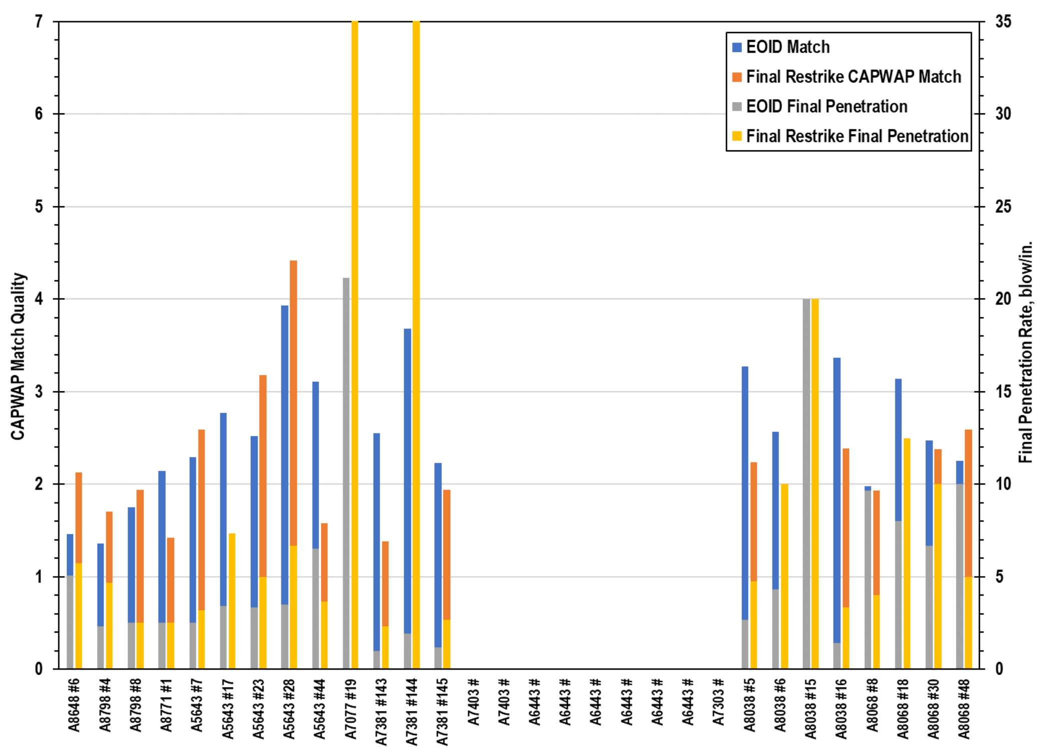


Figure 11 Data quality of pile tests in Southeast Missouri

3.3.3.7 Removal due to Outlier Soil Conditions

Pile 16 from A8038 was removed because the pocket penetrometer indicates a much lower value (1.25 tsf) than values from the other pile locations in clay (generally between 2 and 3 tsf). Further inspection of this profile shows a 20-ft. thick, soft layer that is not present in any of the other profiles. Since there are not enough sites with this condition for Clay profiles (low average PP values) it was excluded from the model development.

3.4 Classification of Piles by Soil Profile

After data cleaning, 23 piles remained from the Northern Missouri sites, as shown in Table 6. Five of these pile tests did not have restrike times that were long enough to be included in the final setup model. These are indicated with shading in Table 6 and Table 7. These data are included in the table because they are later presented in plots of setup versus time. None of the Northern Missouri sites included significant embedment in sand. The soil profiles for the 23 piles were therefore classified as either Clay or Mixed based on the clay embedment to pile length ratio, which is defined in Section 3.3.2. For the 23 piles, the ratio varies from 35 to 100%. The specific value of the ratio used to distinguish between Clay and Mixed is based on statistical evaluation of the effect of cutoff ratio, specifically the effect of the ratio on the average and coefficient of variation (COV) of the setup data for piles classified as Clay and Mixed. Results of the statistical evaluation are presented in Section 4.1. The results support 70% as a rational cutoff definition between Clay and Mixed soil profiles for model development purposes. The basis for 70% is to reduce the variability of datasets for the resulting groups (Clay and Mixed) to support effective model development. Reduced variability is a rational indication that the model groups are based on similar piles; reduced variability also results in corresponding improvement in model precision.

Coincidentally, the Iowa DOT pile setup study (Ng et al., 2011) also used 70% as the cutoff value between Clay and Mixed soil profiles. Although both efforts use the same Clay-Mixed cutoff definition, the piles from Iowa were not included in the Northern Missouri model because all piles in Iowa were H-piles and all piles included in the Northern Missouri model were closed-ended pipe piles. Comparisons between the Iowa and Northern Missouri data sets are presented in Section 4.4.

After data cleaning, eight piles remained in Southeast Missouri. The clay embedment to pile length ratio ranges from 0 to 64%. As discussed in Chapter 4, setup factors for the Southeast Missouri piles are highly variable and generally low. Therefore, no pile setup model for Southeast Missouri was developed.

Definitions of soil profile designations based on the clay embedment ratio are presented in Table 5. The cutoff of 70% between Clay and Mixed soil profiles, as explained above, reduces variability among the two distinct soil profiles in Northern Missouri. The cutoff of 35% between Mixed and Sand soil profiles is based simply on the minimum observed ratio value in Northern Missouri. Soil profiles with a ratio less than 35% are designated as Sand, but the designation is of little practical significance for this work since no model was developed for piles in Sand.

Table 5 Soil profile designation based on pile embedment percentage in clay

Soil Profile Designation	Clay Embedment to Pile Length Ratio, % Pile in Clay
Clay	70% to 100%
Mixed	35% to 70%
Sand	<35%

3.5 Time of Pile Restrike

As discussed in Chapter 2, time is an important factor in pile setup, with setup generally increasing with time as the excess pore pressures generated by driving dissipate. The time between EOD and the final restrike for the piles remaining after data cleaning varies considerably, ranging from 1 to 312 hrs. (13 days). To establish a minimum restrike time to be included in the analysis dataset, two competing interests must be balanced:

- The need for more data to improve model applicability and precision, and
- The need for data from restrikes with significant time for setup to avoid results that considerably underestimate pile setup

Based on evaluation of the data described subsequently (Section 3.7 and Chapter 4), data from piles in Clay were considered if the elapsed time between EOD and BOR was at least 20 hours. For piles in Mixed soil profiles, the cutoff time was 60 hrs. Use of a lower value for Clay sites was necessary to provide a sufficient sample size. If the 60-hr. limit is applied to Clay piles, piles from only two sites are included in the model. By reducing the cutoff to 20 hrs., piles from four sites are included with relatively modest decreases in average pile setup compared to 60 hrs. (setup factors of 1.64 versus 1.74, respectively).

As explained above and presented in greater detail in Chapter 4, no model for piles in Sand was developed because the data do not indicate pile setup can reliably be expected in Sand. Accordingly, a time cutoff values for piles in Sand is not applicable.

3.6 Summary of Data Used in Model Development and Resistance Factor Calibration

3.6.1 Northern Missouri Sites

After removing piles below the minimum time criteria, 18 piles remain in Northern Missouri. The 18 piles used in the Northern Missouri model are listed along with pile length, driving depth, clay embedment, soil type designation, and measured properties in Table 6. The load test results from EOD and BOR used in the Northern Missouri model are summarized in Table 7.

Table 6 Piles from Northern Missouri sites included in the final data model (shading indicates piles with only short (<24 hr restrike times)

Bridge	Pile	Type	Pile Length (ft.)	Driving Depth (ft.)	Clay Embed (ft.)	Clay/ Pile Ratio	Soil Profile Type	Ave PP	Ave N_{60}	Ave PI
A8367	5	14" CEP	43.5	28.5	28.5	1.00	Clay	2.25	16	19
A8367	14	14" CEP	48.75	34	29	0.85	Clay	2.79	20	19
A8579	1	16" CEP	91.3	71	52	0.73	Clay	1.88	15	20
A8579	7	16" CEP	104.5	80	67	0.84	Clay	1.22	11	17
A8043	5	14" CEP	43	43	24	0.56	Mixed	1.7	12	15
A8043	7	14" CEP	60	60	41	0.68	Mixed	2.44	24	16
A8043	13	14" CEP	62	62	33	0.53	Mixed	1.64	14	14
A8043	16	14" CEP	43	43	15	0.35	Mixed	1.1	6	13
A8743	2b	14" CEP	43	43	40	0.93	Clay	3.6	16	-
A8743	9	14" CEP	42.5	42.5	42.5	1.00	Clay	2.6	24	-
A8743	14	14" CEP	43.5	43.5	43.5	1.00	Clay	2.6	25	-
A8681	6	14" CEP	51	51	31	0.61	Mixed	2.3	21	13
A8681	22	14" CEP	55	55	25	0.45	Mixed	2.4	19	-
A8693	4	14" CEP	38.5	38.5	16	0.42	Mixed	1.8	10	22
A8693	6	16" CEP	67	67	45	0.67	Mixed	1.8	16.5	16
A8693	12	16" CEP	60	60	38	0.63	Mixed	2.78	20	17
A8693	21a	14" CEP	40	40	18	0.45	Mixed	0.9	7	23
A8693	21b	14” CEP	64	64	42	0.67	Mixed	2.25	16	20
A7381	143	14" CEP	37	36	36	1.00	Clay	2.4	8	17
A7381	144	14" CEP	37	36	36	1.00	Clay	2.4	8	17
A7381	145	14" CEP	37	36	36	1.00	Clay	2.4	8	17
A8038	5	14" CEP	40	40	40	1.00	Clay	2	14	14
A8038	6	14" CEP	60	60	60	1.00	Clay	3	20	14

Table 7 Load test results from EOD and BOR from Northern Missouri piles (shading indicates piles with only short (<24 hr restrike times)

Bridge	Pile	EOD Total Capacity (kips)	BOR1 Time (hrs.)	BOR1 Total Capacity (kips)	BOR2 Time (hrs.)	BOR2 Total Capacity (kips)	BOR3 Time (hrs.)	BOR3 Total Capacity (kips)
A8367	5	242	1.6	253.5	5.2	262.2	20.1	305
A8367	14	246.8	0.9	276.4	5.4	315.4	22.4	376.4
A8579	1	274	1.4	336.6	24.1	432.7	-	-
A8579	7	257	1.2	303.7	24.2	429.9	-	-
A8043	5	126	1.3	163.5	2.4	165.4	119.5	207.6
A8043	7	211	-	-	-	-	22.7	275.8
A8043	13	222	1.2	253.7	4.9	342.3	22	327.2
A8043	16	71	1.4	102.1	4.8	112.2	168.7	153.2
A8743	2b	165.2	1	225	-	-	-	-
A8743	9	268.7	1.5	320.2	3.5	333	-	-
A8743	14	220.5	1.3	322.3	5.9	327.7	-	-
A8681	6	219.1	257.2	473.8	-	-	-	-
A8681	22	218.4	265.3	581.1	-	-	-	-
A8693	4	168	1.4	165.5	4.7	157.2	95.4	258.6
A8693	6	222.7	1	277.3	3.2	275.3	91.8	452.8
A8693	12	233.1	1.2	341.2	3.2	353.9	74.5	444.5
A8693	21a	168.6	1.6	147.8	3.1	133.9	75.7	162.0
A8693	21b	169.9	67.4	359.3	-	-	-	-
A7381	143	94.8	94.3	164.8	-	-	-	-
A7381	144	110.5	163.1	182.6	-	-	-	-
A7381	145	98.0	164.5	189.2	-	-	-	-
A8038	5	132.3	188.1	254	-	-	-	-
A8038	6	245.4	188	360.4	-	-	-	-

3.6.2 ISU Iowa Sites

The soil profile designations for the Iowa test sites are presented in Table 8. The designations are based on the criteria shown in Table 5 and soil profile information provided in Ng et al., 2011. Load test data from the Iowa sites are presented in Table 9. The Iowa data were not used in model development but are later compared to the Northern Missouri data.

Table 8 Soil profile types for ISU test piles - all piles are 10-in. H piles

Test Pile	Soil Profile Type
ISU2	Clay
ISU3	Clay
ISU4	Clay
ISU5	Clay
ISU6	Clay
ISU8	Mixed
ISU9	Sand
ISU10	Sand

Table 9 Load test results from EOD and BOR from ISU test piles (from Ng et al., 2011)

Test Pile	EOD	BOR1	BOR2	BOR3	BOR4	BOR5	BOR6	BOR7	BOR8
ISU2 Cap. (kips)	80.71	116.23	129.94	129.94	-	-	-	-	-
ISU2 time (hr.)	0	4.08	22.08	71.28	-	-	-	-	-
ISU3 Cap (kips)	98.7	103.2	105.0	129.7	143.2	147.7	-	-	-
ISU3 time (hr.)	0	0.07	0.18	0.28	26.6	47.0	-	-	-
ISU4 Cap (kips)	101.8	105.4	108.8	121.0	135.1	144.3	154.0	-	-
ISU4 time (hr.)	0	0.09	0.38	0.96	17.8	41.76	114	-	-
ISU5 Cap (kips)	177.6	189.3	215.1	220.1	232.7	234.7	244.6	-	-
ISU5 time (hr.)	0	0.13	0.3	1.15	22.1	69.6	190.1	-	-
ISU6 Cap (kips)	144.8	144.8	148.8	147.9	176.7	186.8	196.7	210.9	210.7
ISU6 time (hr.)	0	0.04	0.1	0.28	1.61	19.9	67.7	163	235.4
ISU8 Cap (kips)	140.0	143.0	146.0	153.0	155.0	159.0	160.0	-	-
ISU8 time (hr.)	0	0.17	0.26	0.94	23.3	95.3	118.8	-	-
ISU9 Cap (kips)	169.0	168.0	166.0	161.0	159.0	157.0	155.0	-	-
ISU9 time (hr.)	0	0.09	0.26	0.91	16.5	68.9	234.5	-	-
ISU10 Cap (kips)	121.0	105.0	106.0	114.0	121.0	118.0	-	-	-
ISU10 time (hr.)	0	0.09	0.26	0.94	15.4	111.4	-	-	-

3.6.3 Southeast Missouri Sites

Due to limited soil boring information at the Southeast Missouri pile test sites no soil parameter data such as N_{60} values were compiled. Based on site descriptions provided in the reports and soil boring information, four Southeast Missouri sites were characterized as Sand profiles and four were characterized as Mixed, as shown in Table 10. Load test data at these sites only included one restrike in all cases. A summary of the load test results from Southeast Missouri sites is presented in Table 11.

Table 10 Soil profile types for Southeast Missouri piles - all piles are 14-in. closed-end pipe piles

Bridge	Pile	Soil Profile Type
A8648	6	Sand
A8798	4	Mixed
A8798	8	Sand
A8771	1	Mixed
A5643	7	Mixed
A5643	17	Sand
A5643	23	Sand
A5643	44	Mixed

Table 11 Load test results from EOD and BOR from Southeast Missouri piles (only a single restrike was performed in each case)

Bridge	Pile	EOD Total Capacity (kips)	BOR1 Time (hrs.)	BOR1 Total Capacity (kips)
A8648	6	239.2	1.5	261
A8798	4	242.6	162.4	270.3
A8798	8	241.4	158.3	241
A8771	1	187.8	1.5	194.5
A5643	7	150.7	46.6	173
A5643	17	154.4	45.7	242.2
A5643	23	173.3	312.2	223
A5643	44	234.9	49.3	198.7

3.7 Pile Setup Model Development

After cleaning the data, removing piles with insufficient time between EOD and BOR, and classifying as Clay or Mixed, 18 piles across seven sites remained in Northern Missouri. The 18 piles are divided evenly among Clay and Mixed, with nine piles in Clay profiles from four sites and nine piles in Mixed profiles from three sites. Nine piles and three or four sites is sufficient to reliably characterize the average value of pile setup, but likely insufficient to develop more complicated models, e.g., a pile setup versus time model. A pile setup versus time model is further limited by the time between EOD and BOR, which was one day or less for most of the Clay piles. Other potential predictor variables, for example, soil strength, are similarly limited in range. However, the limitation in range of such variables is, in fact, an advantage that improves the precision of the average model. Moreover, the average model is an appropriate format that satisfies the research objective of providing a means for relying on pile setup without restrikes.

After cleaning the data from Southern Missouri, eight piles are available for model development. The piles are predominately in coarse-grained deposits, but with the percent embedment in clay layers varying considerably, from two piles wholly in sand to one pile with 65% embedment in clay and the rest scattered between. The pile setup values are similarly variable and generally low. Because of this, no reliable model for pile setup can be developed for Southern Missouri with the available data. Results from Southern Missouri piles are presented in greater detail in Chapter 4.

3.8 Reliability Analysis

The primary objective of the reliability analysis is to probabilistically calibrate resistance factors for the design scenario of relying on pile setup without demonstrating pile setup through restrikes. For the case where pile setup is demonstrated through restrikes, current EPG provisions (751.36.5.3) are appropriate. The current provisions are consistent with AASHTO LRFD Specifications (2020). The provisions assign a resistance factor of 0.65 for resistance determined through HSDT-SM, whether the resistance is at EOD or BOR.

This section outlines the procedure used for the reliability analysis. It starts with an overview of the design equation for relying on pile setup without restrikes, then describes the Monte Carlo simulation procedure inputs used in the analysis. Special attention is given to the distribution of resistance based on HSDT-SM, and to how the dataset results described in Section 3.6 inform the distribution of pile setup resistance.

3.8.1 Design Equation

The design inequality for the case of relying on pile setup without restrikes is presented in Eq. 10:

$$\boldsymbol{\varphi_{dyn}} \cdot \boldsymbol{R_{ndr}} + \boldsymbol{\varphi_{setup}} \cdot \boldsymbol{R_{n-setup}} \geq \boldsymbol{\gamma_{DL} DL_n} + \boldsymbol{\gamma_{LL} LL_n} \tag{10}$$

where $\boldsymbol{\varphi_{dyn}}$ is the resistance factor for design based on HSDT-SM, $\boldsymbol{R_{ndr}}$ is the nominal resistance at EOD, $\boldsymbol{\varphi_{setup}}$ is the resistance factor for the setup resistance (without restrikes), $\boldsymbol{R_{n-setup}}$ is the nominal setup resistance (that occurs in addition to the EOD resistance), $\boldsymbol{\gamma_{DL}}$ is the dead load factor, $\boldsymbol{DL_n}$ is the nominal dead load, $\boldsymbol{\gamma_{LL}}$ is the live load factor, and $\boldsymbol{LL_n}$ is the nominal live load.

3.8.2 Setup Resistance

The second term of Eq. 10, $\boldsymbol{\varphi_{setup}} \cdot \boldsymbol{R_{n-setup}}$, represents the factored setup resistance that occurs after EOD. If the second term of Eq. 10 is omitted, the design inequality is reduced to the familiar case with pile resistance from HSDT-SM.

The resistance factor for pile setup, $\boldsymbol{\varphi_{setup}}$, is the value to be used when setup is relied upon without restrikes. Probabilistic calibration of $\boldsymbol{\varphi_{setup}}$ is the objective of this reliability analysis.

The nominal setup resistance, $\boldsymbol{R_{n-setup}}$, is defined based on the results of the setup model. The setup model is a simple average of the observed setup factors from the cleaned datasets. The setup factor values used in the cleaned dataset are based on restrikes after at least 60 hours. Accordingly, the nominal setup factor is termed $\left(\frac{\boldsymbol{R_{BOR}}}{\boldsymbol{R_{ndr}}}\right)_{\boldsymbol{n}}$, where $\boldsymbol{R_{BOR}}$ is the resistance at the beginning of the restrike. This is consistent with the definition of setup factor presented in Section 3.3; the ratio of the total resistance after setup to the total resistance at EOD.

Employing some algebra and factoring terms, we can isolate the resistance due to setup, $\boldsymbol{R_{n-setup}}$, with the definition in Eq. 11:

$$\boldsymbol{R_{n-setup}} = \boldsymbol{R_{ndr}}\left(\left(\frac{\boldsymbol{R_{BOR}}}{\boldsymbol{R_{ndr}}}\right)_{\boldsymbol{n}} - \boldsymbol{1}\right) \quad (11)$$

where $\boldsymbol{R_{ndr}}$ is the nominal resistance at EOD (as defined previously). Again, this definition of setup resistance treats it as additive to the EOD resistance; it is not the total resistance after setup has occurred. As explained in Chapter 5, to rely on pile setup without restrike information, the value of $\boldsymbol{R_{ndr}}$ must be based on HSDT-SM (i.e., not on pile driving formula or empirical predictions from static methods).

3.8.3 Monte Carlo Procedure and Inputs

The computational method for the reliability analysis is the Monte Carlo procedure, wherein each of the probabilistic terms of the design equation (Eq. 10) is randomly sampled for a large number, *n*, of trials. For each trial, the combination of randomly sampled values is evaluated to determine if the outcome is a success (resistance exceeds loads) or failure (loads exceed resistance). The probability of failure for the Monte Carlo procedure is the proportion of trials that result in failure, i.e., the number of failures divided by *n*.

The target probability of failure for the reliability analysis is 1 in 10,000. This is at the small (i.e., conservative) end of values typically employed for reliability analysis in foundation engineering, but is consistent with the value used for major bridges (>$100 million) in EPG 751.37 (Loehr et al., 2011). A conservative target probability of failure was also deemed appropriate given the relatively novel approach of relying on pile setup without requiring restrikes.

A summary of Monte Carlo inputs and their definitions are presented in Table 12. Both dead load and live load are treated probabilistically (i.e., they are randomly sampled), with lognormal distributions of each defined based on the findings from Kulicki et al. (2007). The report by Kulicki et al. noted a COV of 0.1 for dead loading and 0.12 for live loading. The report also noted that nominal load definitions for both dead and live load are slightly unconservative, with bias values of 1.05 and 1.1, respectively. For the Monte Carlo simulations, a ratio of dead-to-live load of 2.0 was assumed. Load factors are based on AASHTO values for the Strength I limit state.

The EOD component of resistance, R_{ndr}, was sampled based on an unbiased lognormal distribution, with "unbiased" indicating the mean of the distribution is equal to the nominal resistance (i.e., $\mu_{R_{ndr}} = R_{ndr}$). The nominal EOD resistance was computed by rearranging the design inequality (Eq. 10) to just satisfy stability, rearranging to isolate R_{ndr}, and substituting Eq. 11 for $R_{n-setup}$. The COV of R_{ndr} is 0.17, as described in the next section.

For each Monte Carlo trial, the setup component of resistance, R_{setup}, is computed from (1) the randomly sampled value of the EOD component of resistance (R_{ndr}) (as described in the previous paragraph) and (2) a randomly sampled value of the setup factor, $\frac{R_{BOR}}{R_{ndr}}$. The setup factors were randomly sampled from distributions of the setup factor based on the model described in Chapter 4.

Table 12 Summary of Monte Carlo analysis inputs

Input	Treatment	Probability Distribution	Mean Parameter	Coefficient of Variation	Comment
DL	Probabilistic	Lognormal	DL_n = 1,000 kips $\mu_{DL} = 1.05 * DL_n$	0.10	Bias and COV per Kulicki et al. (2007)
γ_{DL}	Deterministic		γ_{DL} = 1.25		AASHTO Strength I
LL	Probabilistic	Lognormal	LL_n = 500 kips $\mu_{LL} = 1.1 * LL_n$	0.12	Bias and COV per Kulicki et al. (2007)
γ_{LL}	Deterministic		γ_{LL} = 1.75		AASHTO Strength I
φ_{dyn}	Deterministic		φ_{dyn} = 0.65		Per EPG 751.36.5.3
R_{ndr}	Probabilistic	Lognormal	$R_{ndr} = \frac{\gamma_{DL} DL_n + \gamma_{LL} LL_n}{\varphi_{dyn} + \varphi_{setup}\left(\left(\frac{R_{BOR}}{R_{ndr}}\right)_n - 1\right)}$ $\mu_{R_{ndr}} = 1 * R_{ndr}$	0.17	R_{ndr} is from rearranging the design equation and substituting for $R_{n-setup}$. For COV, See Chapter 4.
φ_{setup}	Deterministic		Calibrated to achieve target probability of failure of 1/10,000		
R_{setup}	Probabilistic, via dependence on R_{ndr} and $\frac{R_{BOR}}{R_{ndr}}$		For each Monte Carlo trial *i*, $R_{setup-i} = R_{ndr-i} \cdot \left(\left(\frac{R_{BOR}}{R_{ndr}}\right)_i - 1\right)$		
$\frac{R_{BOR}}{R_{ndr}}$	Probabilistic	Lognormal	$\mu_{\frac{R_{BOR}}{R_{ndr}}} = \begin{cases} 1.67 & \text{Clay} \\ 1.86 & \text{Mixed} \end{cases}$	0.13 Clay 0.25 Mixed	See Chapter 4.

3.8.4 Distribution of Resistance from HSDT-SM

As is evident from the description of the previous section and evaluation of Table 12, the distribution of EOD resistance is a critical input for the reliability analysis. The design procedure for relying on pile setup without restrikes requires determination of EOD resistance using HSDT-SM. The distribution of EOD resistance should therefore be based on the mean bias and precision of HSDT-SM predictions compared to the true value (i.e., the value from static load tests). Ng (2011) compiled the results of 38 published comparisons of piles with both HSDT-SM and static load test results. The literature survey found an average observed ratio of resistance estimated from HSDT-SM to SLT of 0.98, indicating HSDT-SM produces, on average, nearly unbiased results. The coefficient of variability for the average ratio of the 38 studies was 0.17.

To evaluate the findings from Ng (2011), a separate reliability analysis was performed to compute the COV of HSDT-SM predictions that would be associated with the dynamic resistance factor of 0.65. The analysis assumed unbiased predictions from HSDT-SM (consistent with the findings of Ng) and used a target probability of failure of 1 in 10,000. The resulting COV is 0.17, consistent with Ng. The finding indicates the conclusions of Ng (2011) provide rational basis for the AASHTO resistance factor, which was established based on fitting to historical practices. Stated differently, the AASHTO resistance factor for HSDT-SM is calibrated to an appropriate, albeit somewhat conservative, level of reliability based on the findings of Ng (2011) and this reliability analysis. The reliability analysis for pile setup therefore assumes unbiased predictions of resistance from HSDT-SM with a COV of 0.17.

4. Results and Discussion

Results from the data collection and analyses procedures described in Chapter 3 are presented in this chapter. First, the recommended setup models for Clay and Mixed soil are presented, along with corresponding resistance factors. After the design model is presented, results of more detailed data analysis are presented, including evaluation of pile setup versus time and pocket penetrometer strength for the Northern Missouri piles. Results from the Northern Missouri piles are also presented to the Iowa data. Data from Southern Missouri piles are also presented. The chapter closes with an evaluation of the effect of pile hammer warmup.

4.1 Design Model

As explained in Chapter 3, the design pile setup model that was developed for consideration of pile setup without restrikes includes two values, one average value for piles in Clay soil profiles in Northern Missouri and one average value for piles in Mixed soil profiles in Northern Missouri. The design model is represented by the LRFD design inequality of Eq. 10 and the setup resistance definition of Eq. 11, both of which are presented in Chapter 3. This section presents statistics and resistance factors for each model.

Table 13 presents the nominal pile setup, coefficient of variation of pile setup, and resistance factor for piles in Clay profiles and in Mixed profiles. The nominal values are equal to the average value for the nine piles included in each dataset (nine for Clay, nine for Mixed). Use of the average for nominal means the model is unbiased, in contrast with other design models that introduce a conservative bias by using a nominal value less than the average. (Conservatism in the approach here is achieved by calibrating resistance factors to a probability of failure of 1 in 10,000.) The COV values in the table are total values, meaning they represent variation of both the mean value as well as variation of the pile setup data. Use of total COV is appropriate for new predictions of pile setup and therefore reliability analysis.

The resistance factor for pile setup in Clay profiles, 0.38, is more than four times greater than the resistance factor in Mixed soil profiles, 0.09. The disparity results from the significant difference between COV values for the two soil profiles. The data from piles in Clay profiles are relatively uniform compared to the data from piles in Mixed profiles, which were significantly more variable.

The difference in average values between Clay and Mixed soil profiles is also noteworthy. Both are similar and relatively modest compared to reported values in literature (Chapter 2). However, it is somewhat surprising that the piles in Clay had less setup, on average, than the piles in Mixed soil profiles. One possible explanation is that the difference is a result of using results from relatively early restrikes. With limited time between EOD and BOR, significant pile setup could have remained to occur after the restrike. Not only does this add a source of conservatism to the model, but it could explain why the piles in Clay had less setup, with clay layers generally draining excess pore pressures more slowly than Mixed profiles.

Table 13 Design model for pile setup in Northern Missouri without restrikes

Model	Nominal Pile Setup, $\left(\frac{R_{BOR}}{R_{ndr}}\right)_n$	Basis for Nominal Pile Setup	Coefficient of Variation (Total)	Resistance Factor, φ_{setup}
Clay	1.64	Average of nine piles (i.e., nominal is unbiased)	0.138	0.38
Mixed	1.91	Average of nine piles (i.e., nominal is unbiased)	0.266	0.09

Detailed statistical results regarding the effect of the Clay-versus-Mixed soil profile definition are shown in Figure 12, Figure 13, and Figure 14. Comparison of the results among the figures also shows the effect of the time cutoff: Figure 12 includes results from final restrikes for all piles after data cleaning, Figure 13 includes results from only piles with at least 20 hours between EOD and BOR, and Figure 14 includes results from only piles with at least 60 hours between EOD and BOR. For each figure, two sets of statistics are plotted versus the cutoff definition (between Clay and Mixed) on the horizontal axis. First, on the left vertical axis and in orange is the average pile setup value. Second, on the right vertical axis and in blue is the COV of the pile setup. Statistics for piles in Clay profiles are shown with solid lines and solid square symbols. Statistics for piles in Mixed soil profiles are shown with dashed lines and empty triangle symbols.

For each of the time cutoffs (i.e., in all three figures), the average value of pile setup for Clay and Mixed profiles is relatively insensitive to the value of the cutoff definition. As discussed above, the average in Mixed profiles is modestly but consistently greater than the average in Clay profiles. With similar consistency, the COV of pile setup in Clay profiles is less than the COV in Mixed profiles. For all three-time cutoffs, the variability of both datasets (i.e., the COV of setup in Clay and in Mixed) decreases from a cutoff value of 30% to a cutoff value of 70%, beyond which the variability is relatively constant. For setup in Mixed profiles, the decrease up to 70% is especially significant. The trend of decreasing variability up to 70% is the basis for the cutoff definition used in the pile setup model for Northern Missouri.

All three plots show similar trends in average and variability statistics. Two main differences are evident among the plots. First, the average increases somewhat with the time cutoff value, reflecting the increase in pile setup with time, as expected. Second, the number of piles included in the datasets decreases for greater time cutoff values (because piles with limited time are removed from consideration). These two trends reflect the tradeoff discussed in Section 3.5. The value of 20 hrs. was used for piles in Clay to avoid having only five piles for Clay.

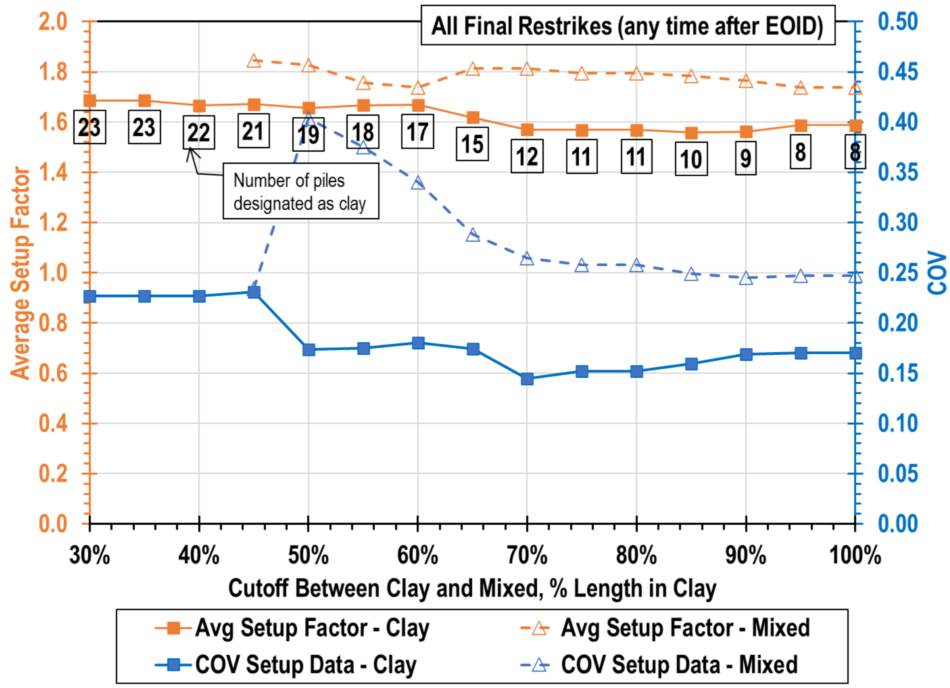


Figure 12 Average and COV of pile setup for different % pile length in Clay for final restrikes, regardless of the time between EOD and BOR

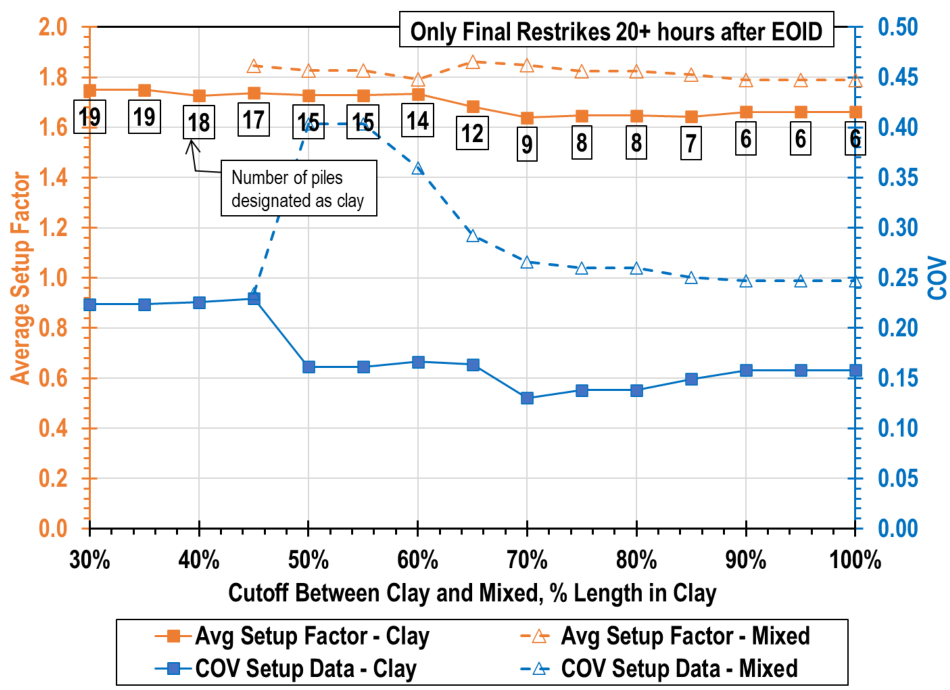


Figure 13 Average and COV of pile setup for different % pile length in Clay for final restrikes with at least 20 hrs. between EOD and BOR

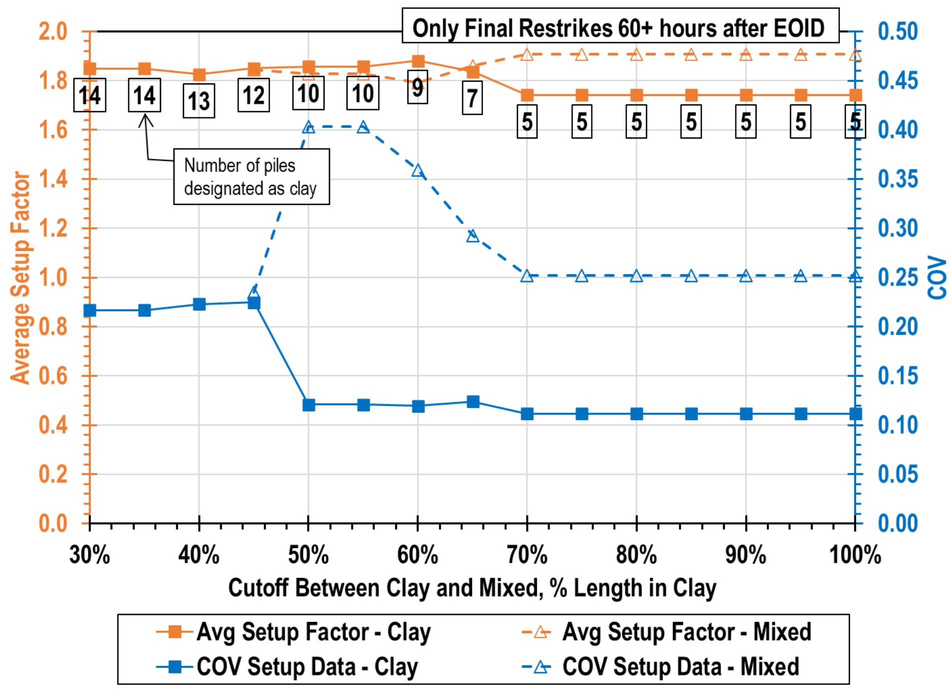


Figure 14 Average and COV of pile setup for different % pile length in Clay for final restrikes with at least 60 hrs. between EOD and BOR

4.2 Analysis of Restrike Performed within 24 Hrs. of End of Driving

An alternative analysis of the restrike data was performed to evaluate the likelihood of success of a restrike performed within 24 hours of the EOD. The analysis is based on the same dataset used in the reliability analysis, filtered using the same criteria defined in Section 3.3.3, except the time of restrike was limited to less than 24 hrs. Because the volume of data at 24 hrs. or less is limited, results from piles in Clay profiles and Mixed profiles were combined. For a given pile, only the final restrike within 24 hrs. is included (e.g., if a pile had one restrike at three hrs. and another at 21 hrs., only the results from the 21-hr. restrike are included). Statistics for the dataset are presented in Table 14. Compared to the data for three day restrikes presented previously, the 24-hr. dataset results in a smaller, more variable setup factor, which is not surprising considering the expected magnitude and variability of same-day restrikes.

Table 14 Setup factor statistics for 24-hr. restrikes

	All Restrikes before 24 Hrs.
Number of Sites	5
Number of Piles	14
Average Setup Factor	1.35
COV of Setup Factor	0.19

The dataset was used in a probability analysis to evaluate the probability of a successful restrike after only 24 hours. “Successful restrike” was defined as one in which sufficient pile setup is demonstrated to compensate for the difference between the observed EOD resistance (R_{EOD}) and the required nominal driving resistance at EOD (R_{ndr}). This difference is defined using the term X, which is normalized by the required resistance:

$$\boldsymbol{X} = \frac{\boldsymbol{R_{ndr}} - \boldsymbol{R_{EOD}}}{\boldsymbol{R_{ndr}}} \tag{12}$$

Results of the analysis are presented in Figure 15, which shows the probability of restrike success as a function of X. The trend in the results is consistent with intuition. For small differences between required and demonstrated EOD resistance, the probability of a successful 24-hour restrike is relatively high, but the probability of success diminishes quickly as the difference increases. For differences between required and observed EOD resistance of 40% or greater, the likelihood of success is less than 10%. It is interesting that the probability is less than one, even for zero difference, which reflects the observance of small values of relaxation among same day restrikes in two piles in Mixed soils. (Subsequent restrikes of the same piles showed increased resistance.) Results from Figure 15 are summarized qualitatively in Table 15.

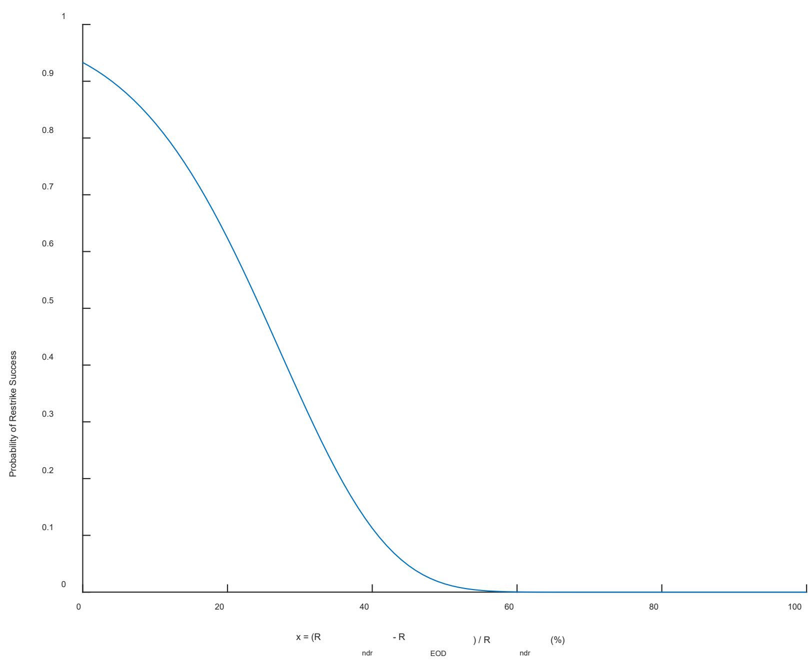


Figure 15 Probabilistic analysis of restrike success as a function of the difference between required and demonstrated resistance at EOD

Table 15 Likelihood of 24-hr. restrike success

***X*, Normalized Difference between Required and Observed EOD Resistance**	**Relative Likelihood of Successful Restrike**
0-15	Strong
15-25	Questionable
25-40	Unlikely
>40	Highly Unlikely

As for the analysis supporting the proposed guidance, the analysis presented in Figure 15 is based only on 14-inch closed-end pipe piles in Northern Missouri. There is insufficient data to determine whether the same likelihood of restrike success could be observed for other piles or in other locations.

Importantly, this analysis represents an approach to driven pile design and construction that is incompatible with the proposed and recommended procedure for relying on pile setup without restrikes. The analysis performed with 24-hour restrikes is compatible with current practice, using the same definition of required nominal driving resistance at EOD as current EPG provisions. The crux of the proposed procedure is a reduced value of required nominal driving resistance at EOD that accounts for the value of pile setup that can be expected reliably. The two approaches are based on different definitions of required nominal driving resistance at EOD, so the results from Figure 15 are not applicable to the proposed approach of relying on pile setup without restrikes.

While the analysis with 24-hr. restrikes is useful information for current practice and avoids any departure from current EPG provisions, it will not produce the same agency-wide pile length savings that could be achieved by implementation of the proposed guidelines.

4.3 Trends in Pile Setup from Northern Missouri Sites

4.3.1 Time Dependent Pile Setup for Different Soil Profiles

Pile setup factors plotted as a function of time for the 23 piles remaining after data cleaning are presented in Figure 16. For cases where multiple restrike tests were performed, the data are connected with a solid line. When only a single restrike was performed, a single point is plotted. Except for one pile (A8693 – pile 21a) all piles showed significant capacity increase with time. Most piles showed capacity increases one hour after EOD, and nearly all showed increases of almost 50% one day after EOD. The Northern Missouri piles showed long-term (> 60 hrs.) setup values in the range of about 1.4 to 2.7.

The Northern Missouri data set were divided into soil profile categories using the procedures described in Section 3.4. Figure 17 shows the pile setup data from sites that were designated as Clay profile sites (i.e., >70% of the profile the pile penetrated through was clay). For these sites, all piles experienced setup after the EOD. Long-term setup values were in the range of about 1.4 to 1.9. Interestingly, some of the highest values of setup were not observed for the Clay profile sites. Pile setup factors from sites that were designated as Mixed are shown in Figure 18. The setup values for the Mixed profile condition were much more variable with long-term setup values ranging from 0.96 to 2.7. The high values of setup measured at some of the Mixed profile sites was one of the unexpected results from this study. It was expected that a trend of higher setup factors with increasing percentage of pile penetration in clay would be observed. Instead, as shown in Figure 19, the opposite trend of increasing pile setup with decreasing percentage of clay was observed. One possible explanation of this trend is that the Mixed profiles allow pore pressures to dissipate faster, as compared to the Clay profiles, so at a given time the Mixed profiles have experienced more setup. This suggests that greater setup could be expected at longer time intervals for the Clay profiles.

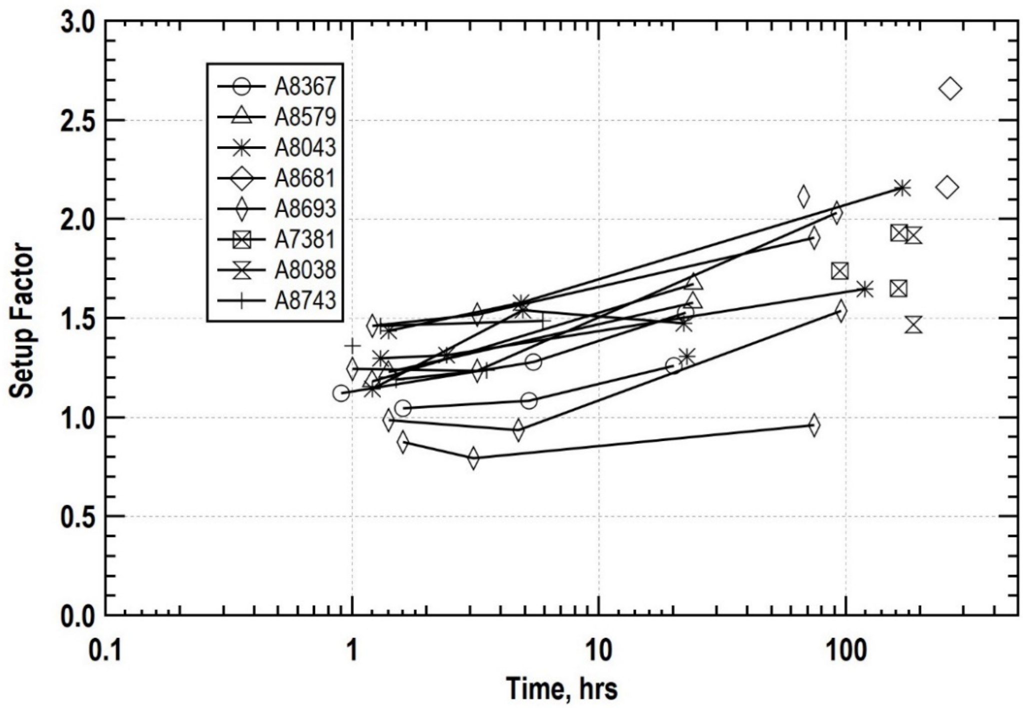


Figure 16 Pile setup factors versus time from Northern Missouri sites – all profiles

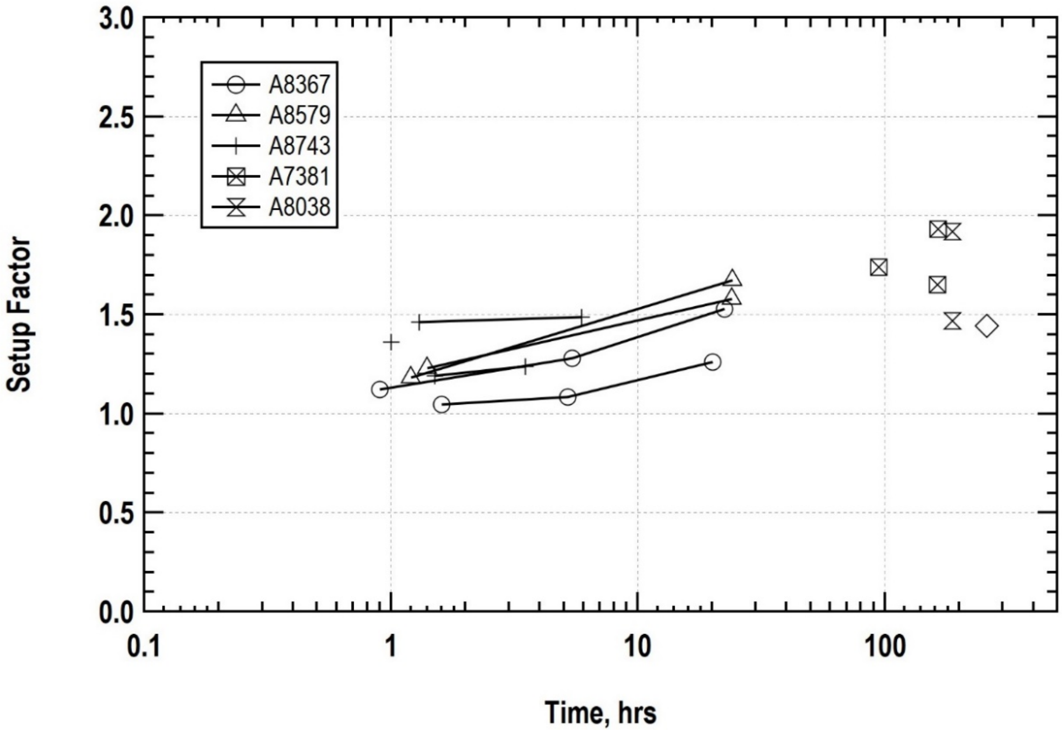


Figure 17 Pile setup factors versus time from Northern Missouri sites – Clay profiles

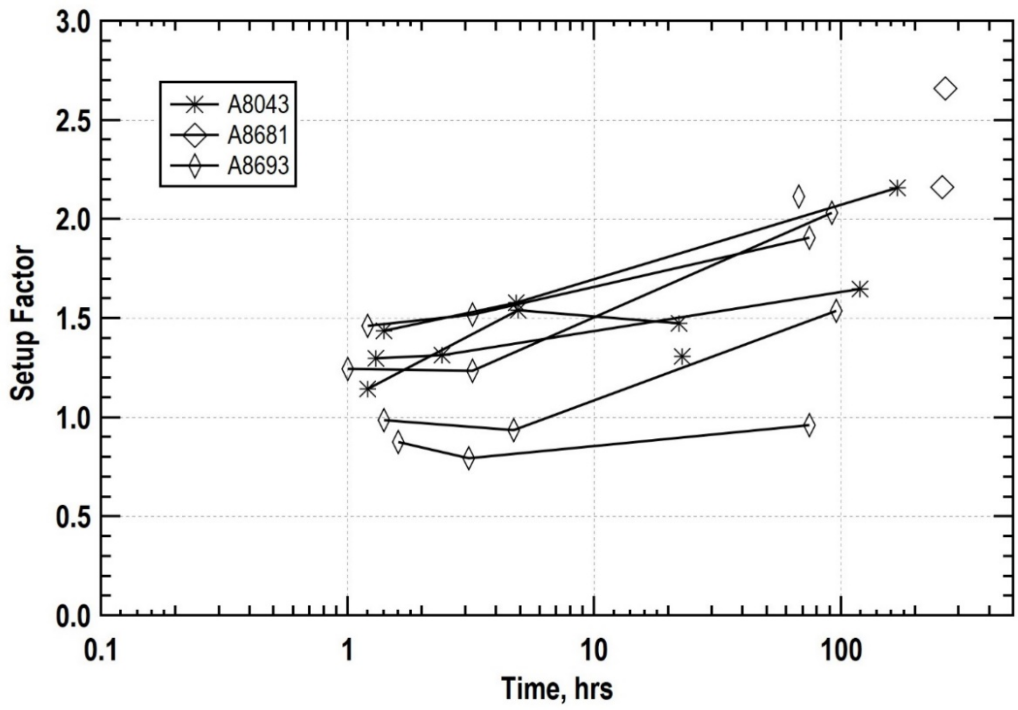


Figure 18 Pile setup factors versus time from Northern Missouri sites – Mixed profiles

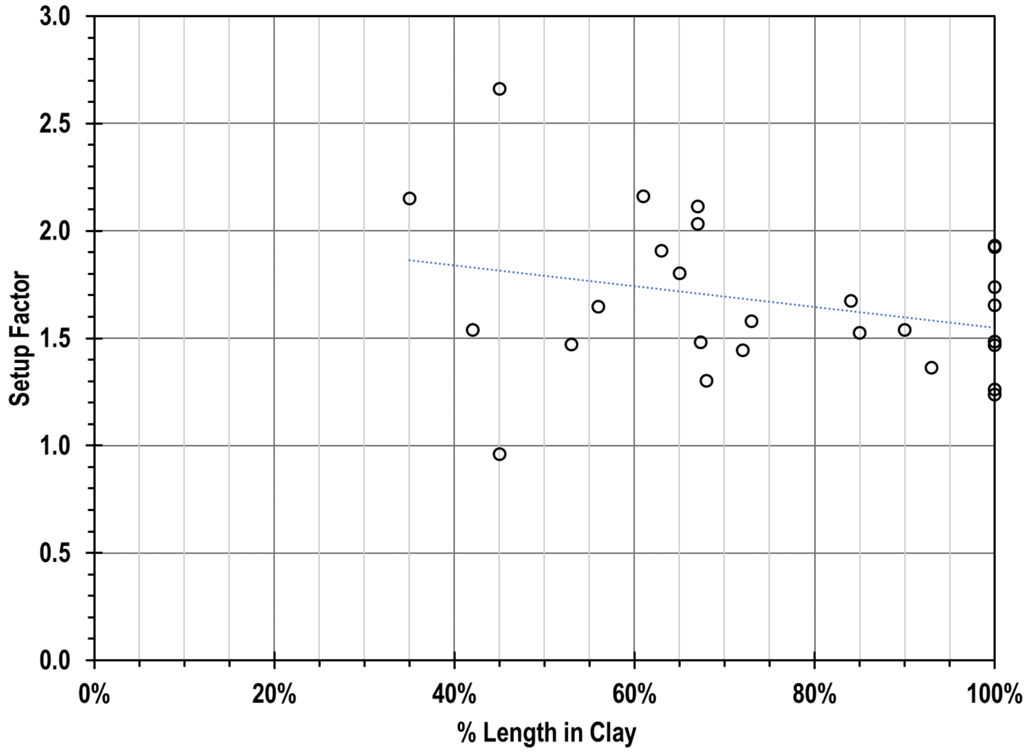


Figure 19 Long-term pile setup factor versus length of pile in Clay for Northern Missouri sites

4.3.2 Pile Setup Correlations with Soil Parameters

Relationships between pile setup and soil parameter values were examined in this study. For this portion of the study, long-term setup was defined as restrike times of 60 hrs. or more for both Clay and Mixed conditions so that the setup factors were compared over similar time intervals. In addition, the pile test that was excluded from the model development due to a low pocket penetrometer (PP) value was included here to examine a larger range of parameter values. Average values of PI, N_{60} and pocket penetrometer were calculated as defined in Section 3.3.2 and plotted versus setup factor in Figure 20, Figure 21, and Figure 22. A linear fit to the Clay data in each case is also shown. For Mixed soil profiles, none of the three soil parameters produced a meaningful correlation. For Clay profiles, a trend of decreasing setup with increasing PI was observed, but the linear fit was poor (r^2=0.26). A trend of decreasing setup with increasing N_{60} values was observed, but also produced a poor linear relationship (r^2=0.28).

The average shear strength as measured with the pocket penetrometer (PP), however, showed a strong correlation between increasing pile setup with decreasing average PP (i.e., undrained strength) for Clay profiles (r^2=0.91). This trend is consistent with expectations that soft, weaker clay (lower PP values) will tend to generate higher pore pressure when the pile is installed and hence experience greater setup as the pore pressures dissipate. It was originally considered that PP values could be included as part of the pile setup model developed in this study. However, although there is a clear trend, there were not enough data to incorporate PP values in the pile setup model. As seen in Figure 22, all but the one outlier point had average PP values in the range of 2 to 3 tsf. Therefore, due to the generally narrow range of PP values observed in this study, PP was not included as a parameter in the pile setup model.

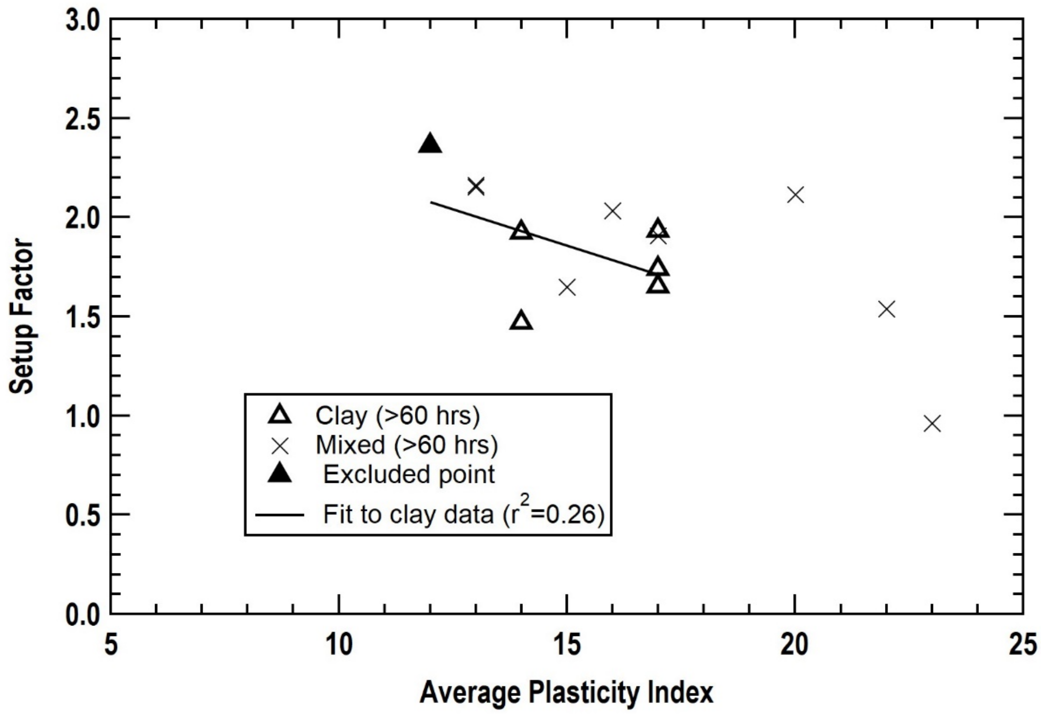


Figure 20 Relationship between pile setup and PI values for Clay and Mixed profiles at Northern Missouri sites

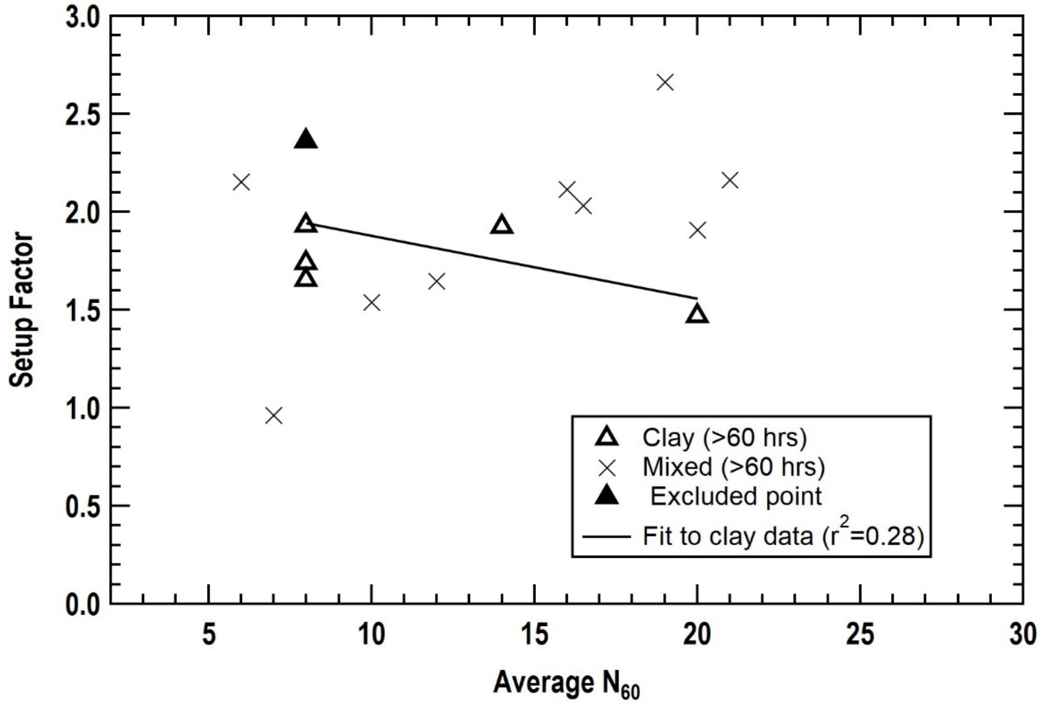


Figure 21 Relationship between pile setup and N_{60} values for Clay and Mixed profiles at Northern Missouri sites

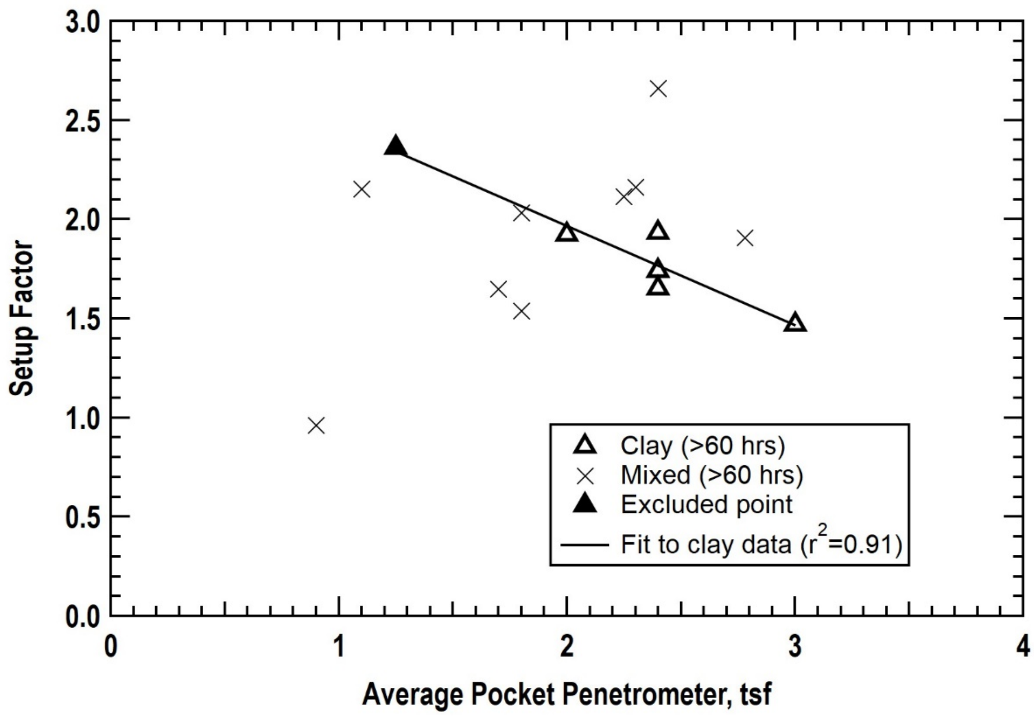


Figure 22 Relationship between pile setup and average pocket penetrometer values for Clay and Mixed profiles at Northern Missouri sites

4.4 Comparison of Iowa and Northern Missouri Data

Pile setup factors obtained by Ng et al. (2011) at eight sites in Iowa are shown in Figure 23. The setup factors from the Iowa sites are significantly lower than the values obtained at Northern Missouri sites. The highest value obtained at any of the Iowa sites was 1.6. When the data are plotted with the Northern Missouri data the differences in long-term setup are especially apparent, as shown in Figure 24. The setup factors from the Iowa sites are all less than 1.6 while the values from Northern Missouri range from 1.4 to 2.7. The data are divided into plots of Clay profiles in Figure 25 and Mixed profiles in Figure 26. Two of the ISU sites are in Sand profiles. Since none of the Northern Missouri sites were in Sand, no comparisons between Sand conditions could be made.

This large difference in setup factors from Iowa and Northern Missouri sites was another unanticipated result in this study. The general geologic conditions in these regions are similar, consisting of glacial deposits. The only clear difference between these data is the pile type. All piles in the ISU study were HP10x42 piles, while the Northern Missouri piles were all 14 in. to 16 in. pipe piles. It was expected that the lower displacement H-piles may have lower setup factors, however, it was not expected that the difference would be so large, with essentially no overlap in long term setup factors. Originally, it was thought that the Iowa pile test data could be included with the Northern Missouri data in the model to develop pile setup resistance factors. However, due to this clear difference in setup factors, likely due to pile type, it was decided that only data from closed-ended pipe piles with diameters of 14 to 16 in. would be used in the pile setup model.

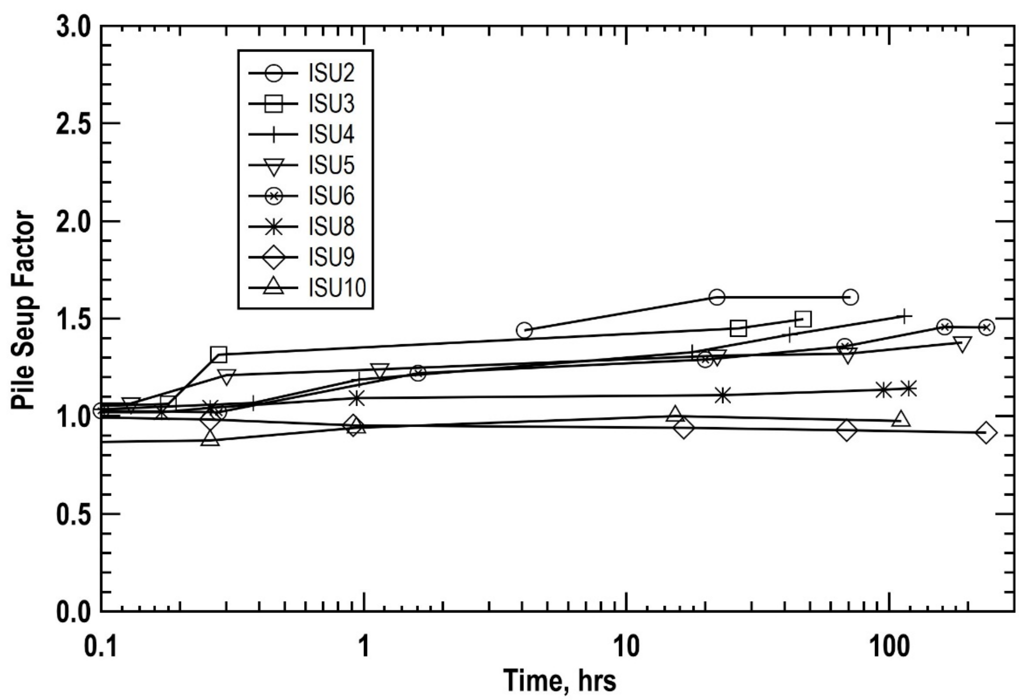


Figure 23 Pile load test results from eight sites in Iowa (after Ng et al., 2011)

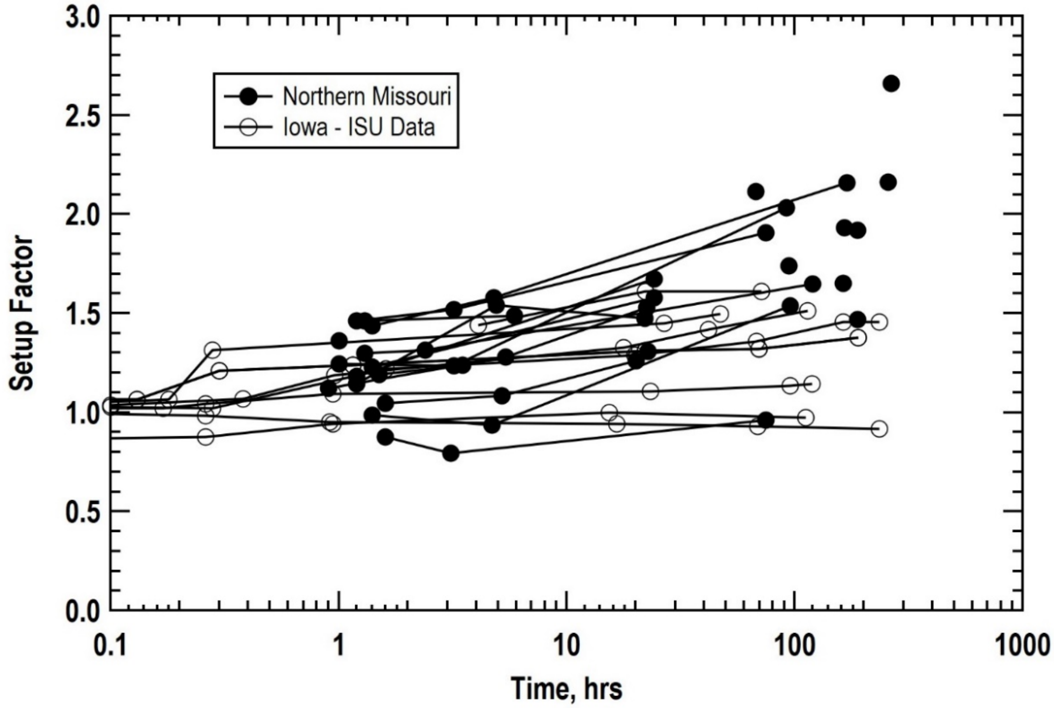


Figure 24 Comparison of setup factors from Northern Missouri sites to Iowa sites

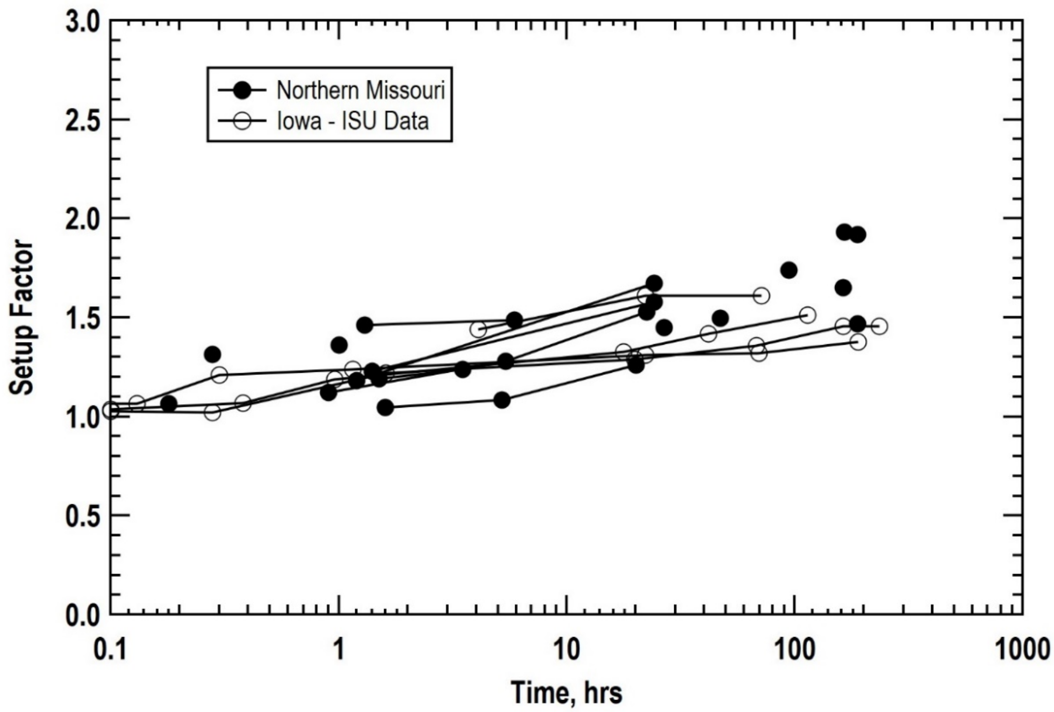


Figure 25 Comparison of setup factors from Northern Missouri sites to Iowa sites – Clay profiles

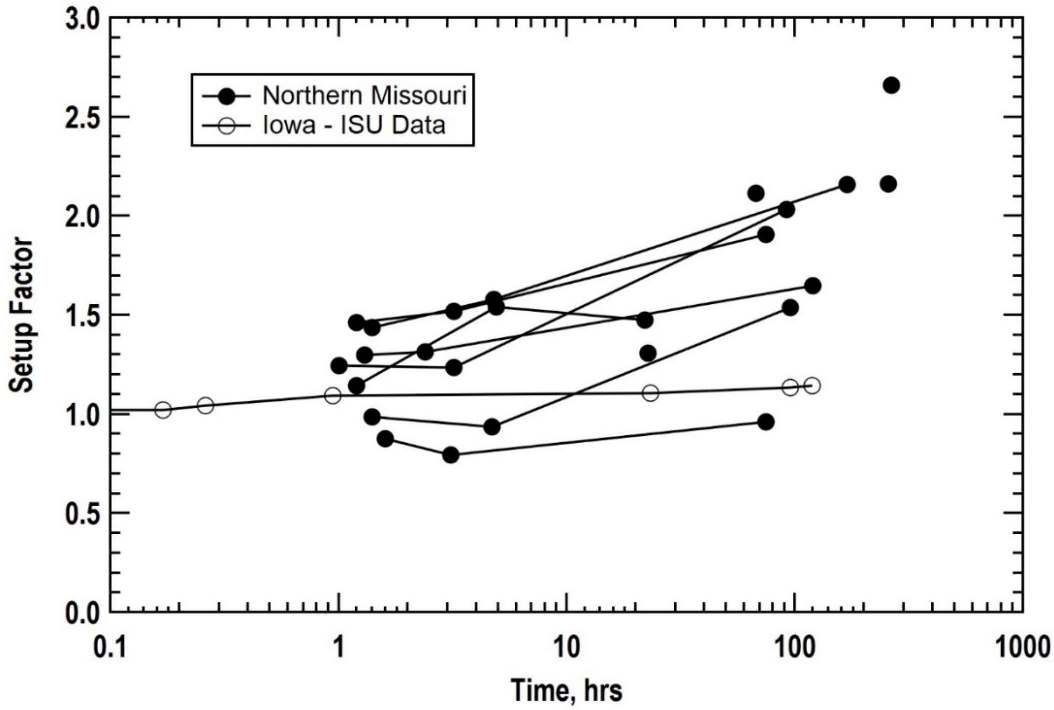


Figure 26 Comparison of setup factors from Northern Missouri sites to Iowa sites – Mixed profiles

4.5 Pile Setup from Southeast Missouri Sites

Pile setup data from the four sites and eight piles in Southeast Missouri are plotted in Figure 27. The setup factors ranged from a low of 0.85 to a high of 1.6. The average long-term setup was 1.1 (calculated from the three data points with restrikes past 60 hrs.). Interestingly, when plotted versus embedment length in clay, the setup factor shows a slight trend of decreasing setup with increasing clay in the profile, as shown in Figure 28, with the highest setup observed for the profiles with no clay.

Unfortunately, pile test data with associated soil borings from the Southeast Missouri sites were limited so it was not possible to examine relationships between soil parameters (PI, N_{60}, PP) and pile setup as was done with the Northern Missouri sites. There was one pile where the capacity at 50 hrs. was lower than the EOD value. However, without soil boring data to compare at these sites or multiple restrike data to observe trends in pile capacity with time, it is not possible to determine if relaxation truly occurred.

Most importantly, due to the limited pile data in the Southeast Missouri region (only three points past 60 hrs.) it was not possible to calibrate resistance factors as was done for the Northern Missouri sites.

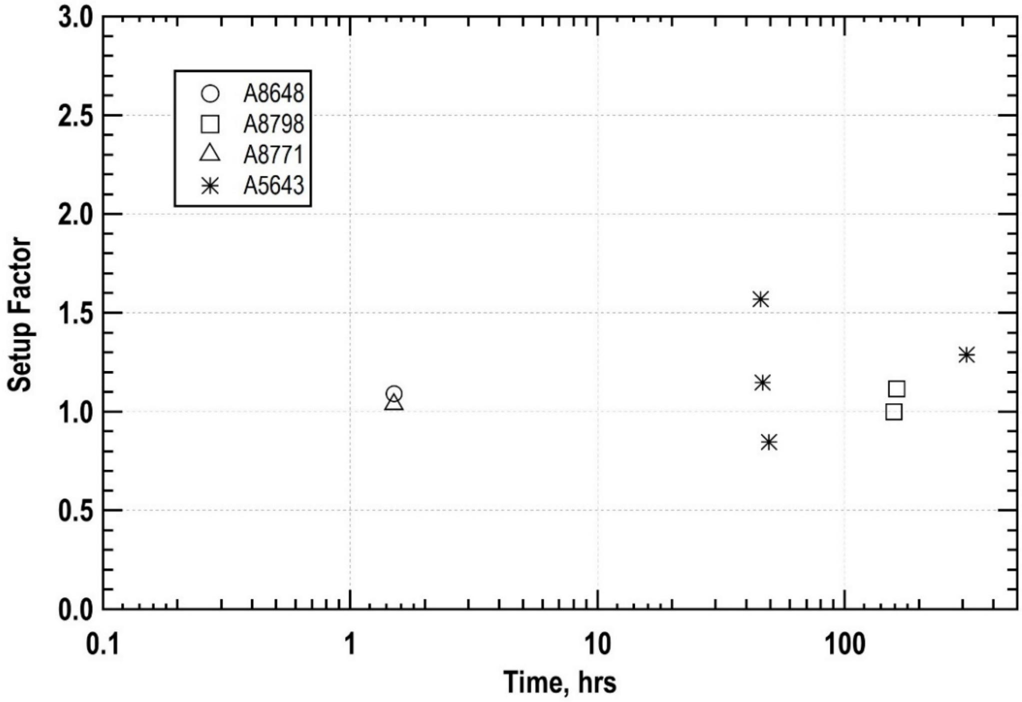


Figure 27 Pile setup factors versus time from Southeast Missouri sites

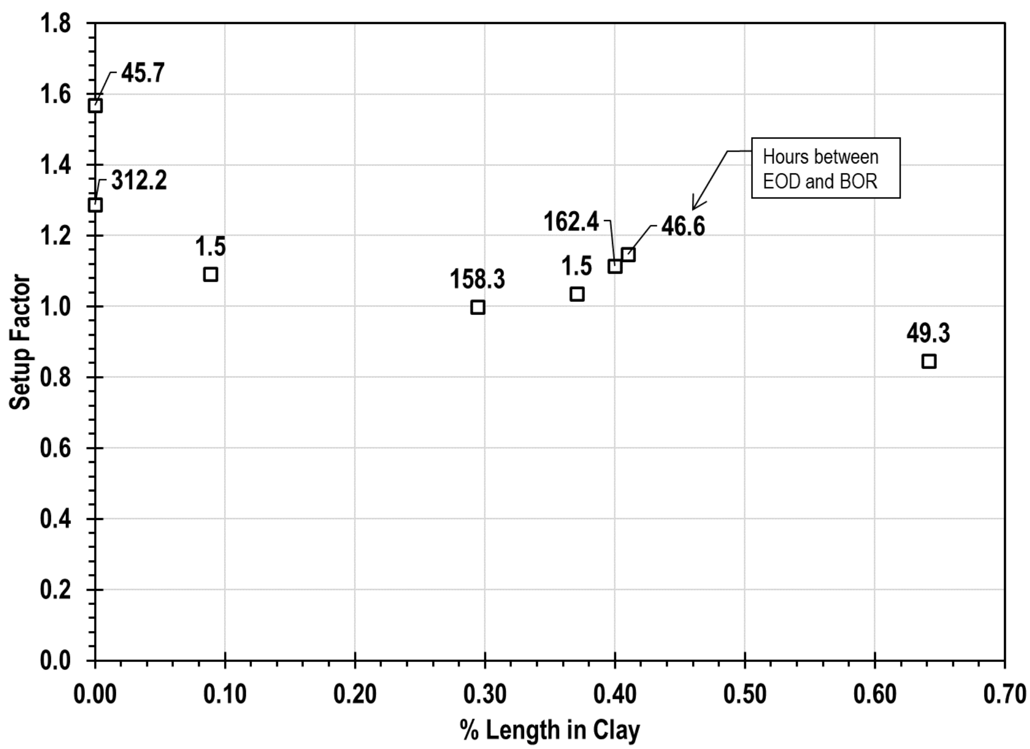


Figure 28 Pile Setup in Southeast Missouri versus % length in Clay

4.6 Pile Hammer Warmup

The effect of pile hammer warmup was also examined as part of this study. At several of the bridge sites restrikes were performed on multiple piles on the same day. The time of day each restrike was performed was recorded in the HSDT-SM reports. Restrike values performed on multiple piles on the same day at the same site are presented in Figure 29, with setup factor plotted against the time of restrike. In seven of nine cases, when a restrike was performed on a second pile within about 40 minutes of the restrike on the first pile, the setup factor increased significantly. At one of the two sites where a decrease in setup was observed in the second pile, Bridge A8371, the two piles were only 20 ft. apart, and it is possible the first restrike generated pore pressures that effectively “reset the clock” on pile setup for the second pile. Neglecting that pile, the likelihood that the same trend of increasing pile setup with time of day would be observed at seven of eight sites by coincidence is about 3.5%.

Such a small likelihood is reason to suspect there is a physical explanation for pile setup increasing for the second pile. The most likely explanation is that the pile driving hammer was not warmed up prior to the first restrike. Driving with a cold hammer delivers less energy for the first several blows, and by the time the hammer has warmed up to deliver an appropriate amount of energy, excess pore pressures have been generated, reducing pile resistance. Accepting this explanation for the data in Figure 29, increases in the setup factor by warming up the hammer were substantial in most cases, ranging from an increased setup factor of 0.1 to 1.0.

These observations indicate that the setup values used in the model development and resistance factor calibration are likely lower than the true values in some cases. Therefore, the resulting nominal setup resistance values are likely conservative. In addition, the observations emphasize the importance of warming up the pile hammer before performing restrikes. Reducing the setup factor by about 0.5 results in significant loss of potential resistance, which is a considerable penalty considering the relatively insignificant burden associated with warming up a pile driving hammer. A requirement for warming up the hammer has therefore been incorporated in the proposed EPG revisions in Chapter 5. (Note the proposed revision to the *Restrike* section of the EPG is independent of the model and resistance factor development, which pertain to pile setup design in the absence of restrike data.)

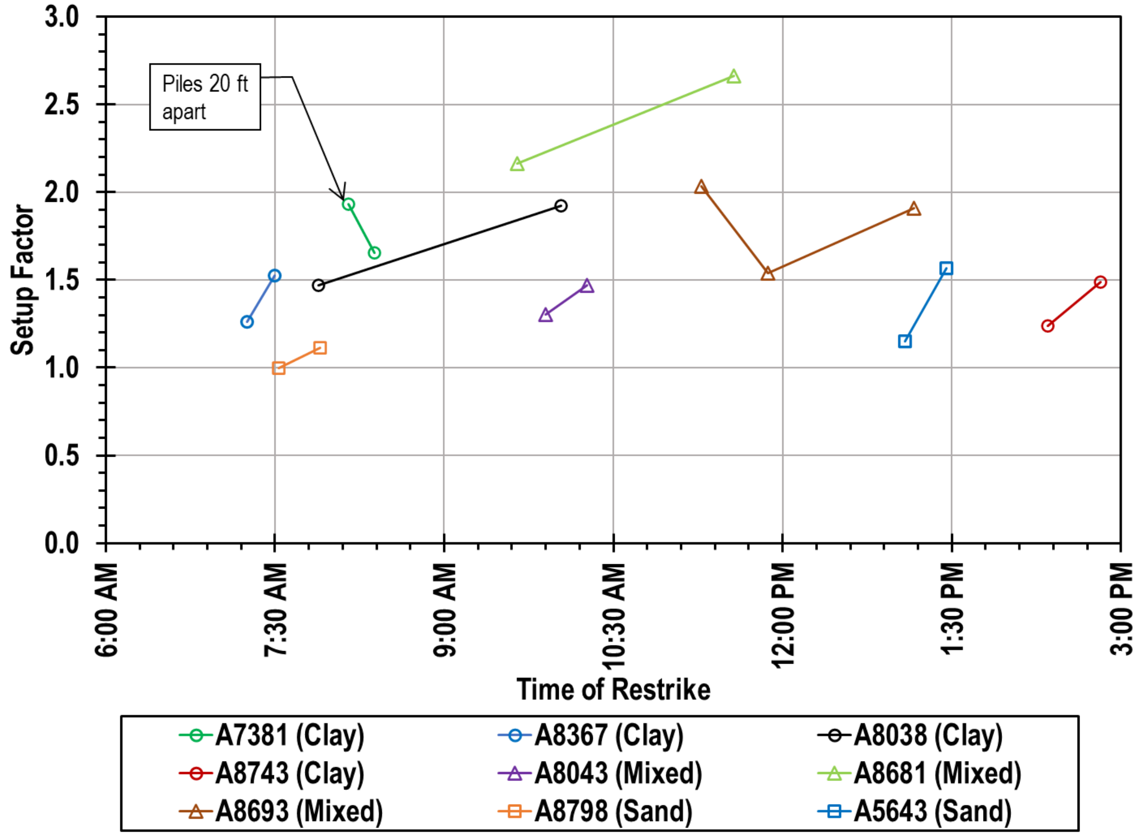


Figure 29 Setup factors from restrikes performed on different piles at the same sites on a single day

5. Recommendations and Example Cases

This chapter presents a series of recommendations that follow from the research presented in previous chapters. First, proposed EPG provisions regarding pile setup and pile restrikes are presented. Next, recommendations regarding application of the EPG provisions are presented, including discussion of situations in which performing restrikes is likely advantageous. A discussion of considering pile setup in Southeast Missouri is also presented. The chapter closes with quantitative examples illustrating the provisions and recommendations.

5.1 Recommended EPG and Standard Specification Provisions for Pile Setup and Pile Restrikes

This section presents proposed provisions for incorporating the results of the pile setup research into MoDOT practice. Primarily, the results include a new LRFD procedure for incorporating pile setup without restrikes. Provisions for the LRFD procedure are included in the EPG provisions in this section. Prior to the EPG provisions, two important notes regarding the implementation are presented. After the EPG provisions, additional provisions to be incorporated in the *Standard Specifications for Highway Construction* are presented.

5.1.1 Definition of Setup Factor

As explained in Chapter 3, the data and reliability analyses were performed using the total setup factor, defined as the ratio of BOR resistance to EOD resistance:

$$\boldsymbol{Setup\ Factor} = \frac{\boldsymbol{R_{BOR}}}{\boldsymbol{R_{EOD}}} \qquad (13)$$

An alternative definition of setup factor is similar, but using the side resistance rather than total resistance, i.e.

$$\boldsymbol{Side\ Setup\ Factor} = \frac{\boldsymbol{R_{BOR} - R_P}}{\boldsymbol{R_{EOD} - R_P}} \qquad (14)$$

where R_P is the tip resistance. The premise of using the side setup factor is that setup only increases side resistance, with tip resistance unchanged after EOD.

Although some increase in tip resistance may occur, it is likely more realistic to apply setup to only the side resistance component of total resistance. Applying setup to only side and not tip resistance is also conservative. Therefore, the proposed procedure uses a definition of setup factor based on side resistance. Thus, while Chapters 3 and 4 refer to setup factor using $\left(\frac{R_{BOR}}{R_{ndr}}\right)_n$, the procedure below uses nominal setup factor, SF_n, where SF_n is defined consistent with Eq. 13.

The data and reliability analyses were performed based on the total setup factor because the total setup factor data were considerably less variable than the side setup factor. The most likely explanation for this observation is the use of HSDT-SM results for the pile setup database. The variability of side setup factor data reflects the imprecision of side-versus-tip distinctions in HSDT-SM analysis.

5.1.2 Avoiding Pile Refusal & Drivability

The LRFD procedure in the proposed EPG provisions starts with a list of requirements for implementation of the procedure. The requirements are intended to ensure that the procedure is not applied in situations that are dissimilar to those in the dataset used to develop the procedure. For example, the procedure can only be applied to 14 and 16 in. CIP piles.

A more difficult to implement requirement is that the piles not be driven to refusal. As explained in Chapter 3, it is inappropriate to rely on significant increases in pile resistance when piles are driven to refusal with an appropriately sized hammer. Moreover, most of the piles in the database were driven to EOD penetrations considerably softer than refusal (typically on the order of two to five blows per inch). Therefore, the proposed EPG procedure includes a requirement that piles be driven to EOD penetration less than or equal to 10 blows per in.

During the design phase, it will be challenging to ensure this requirement is satisfied. To provide designers flexibility, the proposed provisions call for the Engineer of Record to analyze the pile driving record in the event of driving to greater than 10 blows per inch. The Engineer of Record should use the available information, including known ram weight and observations of hammer stroke, to perform an as-built drivability analysis. Results of the analysis should be evaluated, especially with consideration of the proportion of resistance from side versus tip resistance, to determine if the assumed pile setup can be relied upon. If the resistance is predominately in tip resistance, it is inappropriate to rely on the assumed setup. However, in the event the pile was driven to refusal with an appropriately sized hammer, it is likely that the EOD pile resistance will be sufficient even without pile setup.

5.1.3 Proposed EPG Provisions

The list of revisions presented in this section is recommended for incorporation into EPG 751.36 *Driven Piles*. The first three revisions and additions included below are intended for subsection 751.36.5.9.1 *Estimated Pile Length*, but it is feasible the provisions could be incorporated elsewhere in 751.36. The last revision addresses 751.36.1.7 *Restrike.*

1. Add a new introductory paragraph to 751.36.5.9.1:

   Three procedures are included for estimating pile length. The first is for friction piles outside Northern Missouri, the second is for friction piles in Northern Missouri, and the third is for end bearing piles. "Northern Missouri" is defined as any location along the US-36 corridor or north of US-36 in Missouri.

2. Revise the heading "*Friction Piles*" to "*Friction Piles outside Northern Missouri*".

3. Add a new section after *Friction Piles outside Northern Missouri*. The heading should be "*Friction Piles in Northern Missouri*". Proposed language for the new section:

   For sites in Northern Missouri, pile setup can reliably be counted on without restrikes. Each of the following conditions must be satisfied to use the procedure outlined in this section:

   - *The driven piles must be closed-end CIP piles with nominal diameter of 14 or 16 in.*
   - *At least 35% of the proposed pile embedment length must be in layers classified as clay. The average pocket penetrometer resistance (in terms of unconfined compressive strength) in the clay must be less than or equal to 3 tsf.*
   - *The pile tip must be in clay.*
   - *High-strain dynamic testing (HSDT, also known as PDA) with signal matching (SM, also known as CAPWAP) must be performed on the first pile at each bent where pile setup is to be relied upon without restrikes. Results from the first pile shall be used to establish driving criteria for the remaining piles at the bent. The HSDT-SM analysis must produce a fit to measured data of reasonably good quality.*
   - *At the end of initial drive (EOD), the terminal penetration must be less than or equal to 10 blows per inch, measured over the final five blows considered in the HSDT-SM analysis. If the terminal penetration exceeds 10 blows per inch, the Engineer of Record shall analyze the pile driving record and make a determination as to whether the pile setup contribution to resistance can be relied upon. Consistent with the procedure described above.*

   If criteria 1 through 3 cannot be satisfied, then use existing EPG definition of Rndr. If results of driving indicate criteria 4 or 5 are not verified, then a restrike is necessary. Estimating pile length when relying on pile setup without restrikes follows the same procedure outlined in the previous section for Friction Piles outside Northern Missouri, with length determined from the depth that achieves $\varphi_{stat} R_{nstat} \geq Factored\ Load.$

   Although the procedure for estimating length is the same, the required nominal resistance at EOD, R_{ndr}*, is less based on the procedure outlined in this section. Because the length estimate follows the same procedure but* R_{ndr} *is less, relying on pile setup in Northern Missouri should reduce the incidence of piles failing to achieve* R_{ndr} *at the estimated length.*

   Relying on pile setup without restrikes is governed by the LRFD design inequality:

$$\varphi_{dyn} \cdot R_{ndr} + \varphi_{setup} \cdot R_{n-setup} \geq Factored\ Load$$

Where

$\varphi_{dyn} = 0.65$ *based on the requirement for HSDT-SM to determine* R_{ndr}
R_{ndr} = *required nominal resistance at EOD*
φ_{setup} = *pile setup resistance factor*
$R_{n-setup}$ = *nominal pile setup resistance*

The nominal pile setup resistance, $R_{n-setup}$*, is defined as a function of the nominal resistance at EOD and the nominal setup factor,* SF_n*:*

$$R_{n-setup} = \left(R_{ndr} - R_p\right)(SF_n - 1)$$

Where the quantity $\left(R_{ndr} - R_p\right)$ *represents the nominal side resistance at EOD and* R_p *is the nominal tip resistance, which is computed from the soil undrained shear strength,* s_u*, and the cross-sectional area of the pile,* A_p*:*

$$R_p = 9 \cdot s_u \cdot A_p$$

Values of the pile setup resistance factor, φ_{setup}*, and nominal pile setup factor,* SF_n*, are defined from research (Rosenblad and Boeckmann, 2023) as listed in the table below.*

Soil Profile	Nominal Pile Setup Factor, $\boldsymbol{SF_n}$	Resistance Factor, $\boldsymbol{\varphi_{setup}}$
Clay	1.64	0.38
Mixed	1.91	0.09

The table lists two sets of values, one for piles in Clay profiles and one for piles in Mixed soil profiles. The distinction between the two is based on the clay embedment ratio, r_{clay}*:*

$$r_{clay} = \frac{\sum z_{clay}}{z_{total}}$$

Where

$\sum z_{clay}$ = *sum of embedment length in clay layers*
z_{total} = *total length of pile below ground surface*

Mixed soil profiles have r_{clay} *between 35 and 70% and Clay profiles have* r_{clay} *greater than 70%.*

The resulting required EOD resistance after accounting for pile setup is

$$R_{ndr} \geq \begin{cases} \dfrac{Factored\ Load + 0.24 \cdot R_p}{0.89} & \text{piles in Clay profiles} \\ \dfrac{Factored\ Load + 0.08 \cdot R_p}{0.73} & \text{piles in Mixed soil profiles} \end{cases}$$

The value of $\boldsymbol{R_{ndr}}$ *computed in accordance with this procedure shall be listed in the Foundation Data Table (EPG 751.50 E2) as the minimum nominal axial compressive resistance.*

If the value of R_{ndr} *is not satisfied at EOD and restrikes are performed, the required restrike value of nominal resistance,* $R_{ndr-BOR}$*, shall be*

$$R_{ndr-BOR} = \frac{Factored\ Load}{\varphi_{dyn}}$$

4. Replace the text of 751.36.1.7 *Restrike* with the italicized language below. Note that the proposed language is intended to improve practices in the event pile restrikes are performed. The procedure above (Revision 3) applies to designs relying on pile setup without restrikes.

   Restrikes result in construction delays but may be worthwhile in circumstances where pile setup is likely to be significant, or for projects with large numbers of piles where restrikes can be scheduled efficiently.

   Perform restrikes after a waiting period that starts upon completion of pile driving at the test pile bent. The recommended waiting period shall be one day for piles in Sand profiles, three days for piles in Mixed profiles, and five days for piles in Clay profiles. Note that greater pile setup will occur for greater waiting periods.

   When pile restrikes are performed, the hammer must be warmed up prior to restriking the test pile. The hammer shall be warmed up by operating the hammer on a pile at a different pile bent or using a dummy block at least 50 ft. away from the test pile. Care must be taken not to damage the pile on which the hammer is warmed up. The warmup shall be performed no more than 30 min. prior to the restrike.

   Resistance from pile restrikes shall be interpreted using HSDT-SM. The interpretation should typically be based on data from one of the first five blows of the restrike.

5.1.4 Proposed Revisions to the Standard Specifications for Highway Construction

The language from *Restrike* in the previous section should also be incorporated in the *Standard Specifications for Highway Construction*. The language should be included as a new section 702.4.X *Pile Restrikes*.

5.2 Relying on Pile Setup without Restrikes: Effect on Required EOD Resistance

As noted in the EPG provisions above, the primary effect of applying the proposed provisions is to reduce the required nominal EOD resistance (R_{ndr}) compared to current practice of neglecting pile setup unless restrikes are performed. The value of the reduction in R_{ndr} can be quantified by noting that current practice uses $R_{ndr} = \frac{Factored\ Load}{0.65}$ when dynamic testing is used.

If tip resistance is negligible, the reduction in R_{ndr} is $1 - \frac{0.65}{0.89} = 27\%$ for piles in Clay profiles and $1 - \frac{0.65}{0.73} = 11\%$ for piles in Mixed soil profiles. When tip resistance is included, the reduction is somewhat less than the values of 27% and 11%. The example for Clay presented in Section 5.5 demonstrates the potential reduction.

5.3 Situations in which Restrikes are Likely Advantageous

Reductions in the required nominal resistance at EOD of 27% (Clay profiles) and 11% (Mixed soil profiles) is a considerable advantage compared to neglecting pile setup. However, there are several situations where performing pile restrikes is likely advantageous, providing greater benefits compared to using the procedure of Section 5.1. Each situation is described below.

5.3.1 Projects with a Large Number of Piles

The reductions in R_{ndr} of 27% (Clay) and 11% (Mixed) result primarily from the fact that the model setup factors are considerably greater than unity (1.64 and 1.91, respectively). The resistance factors associated with the setup resistance, φ_{setup}, are relatively low: 0.38 and 0.09, respectively. Both of these resistance factors are significantly less than the resistance factor associated with HSDT-SM, $\varphi_{dyn} = 0.65$. For an “average” Clay site (i.e., one with pile setup equal to the model value), performing restrikes with HSDT-SM will increase factored resistance by about 20%; likewise, for an “average” Mixed soil site, the benefits are even greater, with a 70% increase in factored resistance. For projects with a large number of piles, the time-cost associated with waiting for pile setup and performing restrikes with HSDT-SM may often be worthwhile in light of the anticipated increase in factored resistance. In addition, restrikes may be more easily accommodated in the schedule when the necessary duration of the pile driving operation is longer than for projects with a small number of piles.

5.3.2 Design-Build Projects

The primary impediment to pile restrikes is the wait time required between EOD and BOR and the associated costs and potential remobilization. Contractors are likely to consider these impediments to be more burdensome in a design-bid-build arrangement compared to a design-build arrangement. With design-build, the designers can present the potential benefits of restrikes to the team relatively early, allowing the contractor more time to plan for restrikes. Contractors are also more likely to find logistical flexibility in the ideal collaborative environment of design-build. Most important, the cost savings associated with shorter piles are more tangible in design-build, where the savings are more apparent to the contractor and advantageous to both contractor and owner. In design-bid-build, the state may realize savings, but for the contractor, the restrike appears as just an additional contract requirement.

5.3.3 Soft Clay

Piles in soft clay are likely to experience greater pile setup than the model predicts. For example, a setup factor of 2.4 was observed in the one pile in the database that was installed through soft clay. (This pile was not included in model development because the site has significantly softer ground than typical in Northern Missouri.) This compares with the average value of 1.6 in clay. It is also noteworthy that the pile in soft clay was only partially embedded in soft clay, with the other half in stiff clay, so the setup potential in soft clay is likely significantly greater than the project model predicts.

Because piles in soft clay are likely to experience greater pile setup than predicted by the model, it is conservative to apply the model at sites with soft clay. Use of pile restrikes for soft clay sites is therefore encouraged to take advantage of the greater pile setup potential. In addition to taking advantage of greater setup than the model predicts, performing restrikes is associated with a greater resistance factor, as explained in the previous section.

5.3.4 Southeast Missouri

As discussed in Section 5.4, pile setup cannot be relied upon in Southeast Missouri without restrikes. The pile setup data from Southeast Missouri is variable, but generally indicates modest pile setup (i.e., setup factors between 1.1. and 1.2) is likely at most sites, with even greater pile setup possible. In some circumstances, for instance projects with large numbers of piles, it may be advantageous to perform pile restrikes in Southeast Missouri.

5.3.5 Static Load Testing

To take even greater advantage of pile setup compared to restrikes, static load testing should be performed. Static load tests performed to the geotechnical strength limit state measure the true resistance of a pile (compared to HSDT-SM, which is an interpreted resistance from analysis of dynamic data). Designs based on static load tests are therefore accorded a greater resistance factor, 0.75 or 0.8 (depending on whether the tests are accompanied by HSDT-SM), than HSDT-SM alone (0.65). Thus, the benefits noted in Section 5.3.1 are even greater when static load tests are performed. To capture pile setup, static load tests should be performed at least one week, but preferably one month, after pile installation. Such a waiting period is most practically implemented for large projects where design-phase pile installation and testing are cost beneficial.

5.4 Recommendations for Incorporating Pile Setup in Southeast Missouri

As explained in Chapters 3 and 4, the available data regarding pile setup in Southeast Missouri do not support relying on pile setup without pile restrikes. However, the data also do not suggest that pile setup does not occur in Southeast Missouri. In fact, half of the piles had setup factors between 1.0 and 1.2, one had a setup factor of 1.3, and the pile with the greatest setup had a setup factor of nearly 1.6. Although these data do not support probabilistic calibration of reliable setup resistance, they do indicate that modest pile setup is likely to occur at least most of the time for friction piles in Southeast Missouri.

To rely on the pile setup in Southeast Missouri, restrikes with HSDT-SM must be performed. The resulting factored resistance simply equal to $\varphi_{dyn} \cdot R_{nBOR}$, where R_{nBOR} is the nominal resistance at the beginning of restrike (BOR) from interpretation of HSDT-SM.

The data from Southeast Missouri do not provide a clear indication of the types of sites where pile setup is more likely. In fact, the two sites with the greatest observed pile setup both had clay embedment ratios of 0 (i.e., there is no clay along the pile; in the case of these piles, the soil profile was strictly Sand). In contrast, the sites with greater embedment in clay generally had setup factors between 1 and 1.2. Although the lack of a clear trend with clay embedment ratio is perhaps unsatisfying, an important conclusion is that the potential for pile setup should not be dismissed simply because a site has a predominately coarse-grained soil profile.

5.5 Example of Incorporating Pile Setup in Northern Missouri

In this section, driven pile design is performed for a hypothetical Northern Missouri project site to demonstrate the proposed design methodology for considering pile setup and to present a comparison among available driven pile design approaches with and without consideration of setup. Four alternatives are presented before summarizing with a comparison of the results:

- Case 1: No consideration of pile setup; field verification with Modified Gates formula
- Case 2: No consideration of pile setup; field verification with HSDT-SM
- Case 3: Consideration of pile setup without restrikes
- Case 4: Restrike performed to verify pile setup

Cases 1, 2, and 4 are available under the existing EPG provisions. Case 3 is an application of the provisions presented in Section 5.1. If the provisions of Section 5.1 are incorporated, Case 2 would essentially be moot for Northern Missouri project sites that satisfy the criteria presented at the beginning of Section 5.1. Piles at such qualified sites would presumably be designed according to either Case 3 or 4, unless the designer opted to forgo consideration of pile setup.

As shown in Figure 30, the project site consists of a deep deposit of overconsolidated clay with an average pocket penetrometer value of 3 tsf. For the sake of example, the profile is simplified to a uniform layer with undrained shear strength (s_u) of 3 ksf. The design team is planning to use 14-in. CIP piles. Analysis of the piles for lateral loading results in a minimum pile length of 20 ft. There is no uplift load on the piles. The factored load for the controlling load combination in axial compression is 200 kips.

For all cases, pile length estimates are made based on the alpha method. For s_u of 3 ksf, a value of α equal to 0.5 is assigned, corresponding to nominal unit side resistance, f_{sn}, of 1.5 ksf. The alpha method, like other static methods for evaluating axial pile resistance, predicts unit side resistance ***after*** pile setup has occurred. (Static methods were generally developed based on static load tests performed after EOD.) Therefore, the value of f_{sn} of 1.5 ksf is appropriate for long-term, post-setup evaluation of pile resistance. For evaluation of EOD side resistance, the long-term value should be divided by the setup factor. Based on the results of this work, the average setup factor among piles in Clay profiles in Northern Missouri is 1.64. The estimated EOD value of nominal unit side resistance, f_{sndr}, is therefore 0.9 ksf $(1.5\ \text{ksf}/1.64)$.

Also common to all cases is tip resistance. A bearing capacity factor of 9 is assumed, corresponding to 27 ksf unit tip resistance. For the pile area cross-sectional area of 1.07 ft^2, the resulting nominal tip resistance (R_p) is 28.8 kips. Note that pile setup is assumed to occur only on the side resistance component of total resistance, consistent with the explanation of Section 5.1.1.

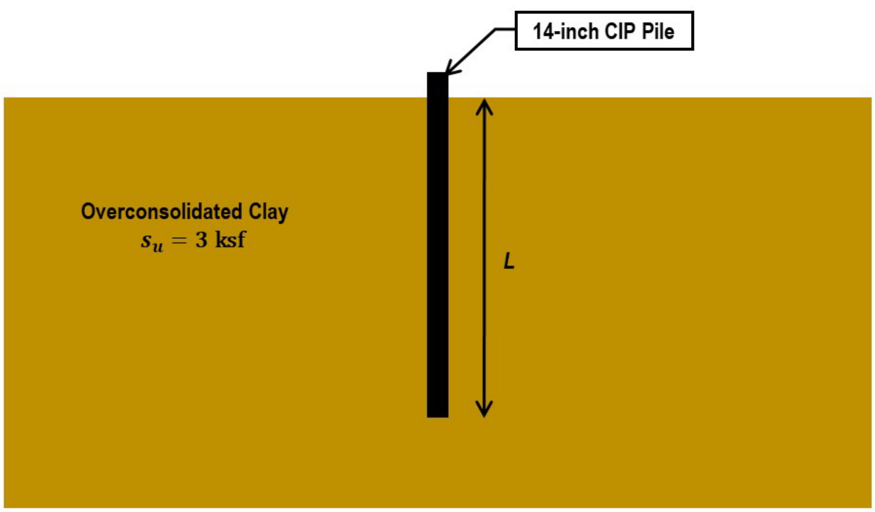


Figure 30 Soil profile for example project site

5.5.1 Case 1: No Consideration of Pile Setup; Verification with Modified Gates Formula

For pile verification with the Modified Gates Formula, the appropriate resistance factor is 0.4. Therefore, the required nominal driving resistance, R_{ndr}, is:

$$R_{ndr} \geq \frac{Factored\ Load}{\varphi_{dyn}} = \frac{200\ kips}{0.4}$$

$$R_{ndr} \geq 500\ kips$$

The estimated pile length for a nominal driving resistance of 500 kips is calculated using the resistance parameters above and introducing the terms R_{sdr} for nominal side resistance at EOD, D for diameter, and L for pile length:

$$R_{ndr} = R_p + R_{sdr}$$

$$R_{ndr} = R_p + f_{sndr} \cdot \pi \cdot D \cdot L$$

Rearranging and solving for L:

$$L = \frac{R_{ndr} - R_p}{f_{sndr} \cdot \pi \cdot D} = \frac{500 \text{ kips} - 28.8 \text{ kips}}{0.9 \text{ ksf} \cdot \pi \cdot \frac{14}{12} \text{ ft.}} = 143 \text{ ft.}$$

Without consideration of pile setup, and verifying pile resistance with the Modified Gates formula, the estimated pile length is 143 ft.

5.5.2 Case 2: No Consideration of Pile Setup; Verification with HSDT-SM

For pile verification with high-strain dynamic testing with signal matching (HSDT-SM), the appropriate resistance factor is 0.65. Therefore, the required nominal driving resistance, R_{ndr}, is:

$$R_{ndr} \geq \frac{Factored\ Load}{\varphi_{dyn}} = \frac{200 \text{ kips}}{0.65}$$

$$R_{ndr} \geq 308 \text{ kips}$$

The estimated pile length for a nominal driving resistance of 308 kips is calculated using the same equation for L determined for Case 1:

$$L = \frac{R_{ndr} - R_p}{f_{sndr} \cdot \pi \cdot D} = \frac{308 \text{ kips} - 28.8 \text{ kips}}{0.9 \text{ ksf} \cdot \pi \cdot \frac{14}{12} \text{ ft.}} = 85 \text{ ft.}$$

Without consideration of pile setup, and verifying pile resistance with HSDT-SM, the estimated pile length is 85 ft. Considerable pile length savings, 40%, are achieved by using a more reliable method of field verification (HSDT-SM).

5.5.3 Case 3: Consideration of Pile Setup Using the Proposed Methodology (Section 5.1)

To rely on pile setup without restrikes, the pile must satisfy the conditions outlined in Section 5.1. The example project does satisfy the criteria:

- ✓ *The driven piles are closed-end CIP piles with nominal diameter of 14 in.*
- ✓ *100% (>35%) of the proposed pile embedment length must be in layers classified as clay.*
- ✓ *The average pocket penetrometer resistance in the clay is less than or equal to 3 tsf.*

- ✓ *High-strain dynamic testing (HSDT, also known as PDA) with signal matching (SM, also known as CAPWAP) will be performed on the first pile at each bent. Results from the first pile will be used to establish driving criteria for the remaining piles at the bent. The Engineer of Record will evaluate the HSDT-SM results to ensure the analysis produces a fit to measured data of reasonably good quality.*

- ✓ *The Engineer of Record will also evaluate results of driving to ensure that at EOD, the terminal penetration is less than or equal to 10 blows per inch, measured over the final five blows considered in the HSDT-SM analysis. If the penetration exceeds 10 blows per inch, the Engineer will analyze the pile driving record (considering, among other things, the size and observed stroke of the hammer) to evaluate if pile setup can reasonably be expected.*

The equation for clay from Section 5.1 is used to determine the required nominal driving resistance at EOD, R_{ndr}:

$$R_{ndr} \geq \frac{200 \text{ kips} + 0.24 \cdot 28.8 \text{ kips}}{0.89} = 232 \text{ kips}$$

To check this result, and to demonstrate that the equation for R_{ndr} with pile setup is consistent with the LRFD framework for pile setup, the longer formulation is presented below:

$$\varphi_{dyn} \cdot R_{ndr} + \varphi_{setup} \cdot R_{n-setup} \geq Factored\ Load$$

Substituting the definition of $R_{n-setup}$,

$$\varphi_{dyn} \cdot R_{ndr} + \varphi_{setup} \cdot \left(R_{ndr} - R_p\right)(SF_n - 1) \geq Factored\ Load$$

$$0.65 \cdot 232 \text{ kips} + 0.38 \cdot (232 \text{ kips} - 28.8 \text{ kips}) \cdot (1.64 - 1) \geq 200 \text{ kips}$$

$$200 \text{ kips} = 200 \text{ kips}$$

The reduction in R_{ndr} by considering pile setup (without restrikes) is 76 kips, or 25% of the value neglecting pile setup (308 kips for Case 2). This value is consistent with the value reported in Section 5.2.

The estimated pile length for a nominal driving resistance of 232 kips is calculated using the same equation for L determined for Case 1:

$$L = \frac{R_{ndr} - R_p}{f_{sndr} \cdot \pi \cdot D} = \frac{232 \text{ kips} - 28.8 \text{ kips}}{0.9 \text{ ksf} \cdot \pi \cdot \frac{14}{12} \text{ ft.}} = 62 \text{ ft.}$$

By considering pile setup, the estimated pile length is reduced from 85 ft. to 62 ft. Both values are based on pile verification by HSDT-SM, so the 27% savings in pile length are attributable solely to consideration of the benefit of pile setup.

5.5.4 Case 4: Consideration of Pile Setup with Pile Restrikes

The design team is interested in the potential for even greater pile length savings by waiting to perform restrikes and capturing the setup resistance with the HSDT-SM resistance factor. In this case, the required nominal resistance at BOR, $R_{ndr-BOR}$, is

$$R_{ndr-BOR} \geq \frac{Factored\ Load}{\varphi_{dyn}} = \frac{200\ \text{kips}}{0.65}$$

$$R_{ndr-BOR} \geq 308\ \text{kips}$$

Note this is the same as the value from Case 2, as both cases are verified with HSDT-SM. The difference is that for this case, the resistance of 308 kips is to be verified after a significant portion of pile setup has occurred. Therefore, use of the long-term nominal unit side resistance, f_{sn}, is appropriate for estimating the pile length:

$$L = \frac{R_{ndr} - R_p}{f_{sn} \cdot \pi \cdot D} = \frac{308\ \text{kips} - 28.8\ \text{kips}}{1.5\ \text{ksf} \cdot \pi \cdot \frac{14}{12}\ \text{ft.}} = 51\ \text{ft.}$$

The corresponding required nominal resistance at EOD, R_{ndr}, is calculated using the nominal unit side resistance at EOD and the required long-term pile length:

$$R_{ndr} = L \cdot f_{sndr} \cdot \pi \cdot D + R_p$$

$$R_{ndr} = 51\ \text{ft} \cdot 0.9\ \text{ksf} \cdot \pi \cdot \frac{14}{12}\ \text{ft} + 28.8\ \text{kips} = 197\ \text{kips}$$

5.5.5 Comparison of Results for Four Design Approaches

A summary of results for the four design approaches is presented in Table 16. The table includes the required nominal resistance at EOD, R_{ndr}, and estimated pile length for each case. Also included in the table are the relevant comparisons. Each consecutive design approach offers savings versus the previous. Although not exclusive to the case of pile setup, use of HSDT-SM in Case 2 versus the Modified Gates pile driving formula (Case 1) produces significant savings, reducing pile length by about 40%. These savings are attributed to the increased resistance factor associated with HSDT-SM, a more reliable method for verifying resistance than pile driving formula.

Relying on pile setup without restrikes (Case 3) provides further benefits, reducing pile length by 27% compared to the case of neglecting pile setup with HSDT-SM (Case 2). Since both cases use the same field verification method, these savings are attributed directly to the pile setup contribution. Finally, by demonstrating the setup resistance with restrikes (Case 4), an additional 18% reduction in pile length is achieved versus Case 3. The reduction is attributed to the increased resistance factor associated with HSDT-SM versus simply relying on setup without restrikes. As discussed in Section 5.3, the Case 4 savings would likely be even greater for a Mixed soil profile site because the setup resistance factor for Mixed profiles is considerably less than that for Clay profiles.

Table 16 Summary of results for four approaches to example pile setup design

Case	Pile Setup Considered?	Verification Method	Estimated Pile Length, ft.	Required Nominal Resistance at EOD, R_{ndr}, kips	Relevant Comparison Case	Reduction in Pile Length, %	Reduction in R_{ndr}, %
1	No	Modified Gates	143	500	N/A		
2	No	HSDT-SM	85	308	1	41	38
3	Yes	HSDT-SM, EOD Only	62	232	2	27	25
4	Yes	HSDT-SM, Restrike	51	197	2	40	36
					3	18	15

The pile length reduction between Case 1 and Case 4, 64%, is considerable, likely resulting in cost savings of at least $10,000 per pile. It is also worthwhile to consider that reductions in pile length not only result in savings in material costs, but also in elimination of required pile splices. Case 1 would likely require multiple splices; Case 2 would most likely require one splice. Case 3 may be feasible without a splice (depending on stickup requirements and the extra length added to reduce the risk of piles being too short). Case 4 would likely not require any splicing.

5.6 Recommendations for Additional Data

Additional data is always beneficial for reliability-based design methods. The case for additional pile setup data is especially strong. The benefits associated with types of recommended data are explained below.

- In Northern Missouri, additional data from Clay sites with at least three days and preferably seven days of setup time would almost certainly increase the model setup factor. Half of the data used in the model for this research was from approximately one day, at which point considerable pile setup was likely remaining. Additional data from sites with average pocket penetrometer values greater than 3 tsf would also be beneficial, as such data would likely support increasing the limit for applying the model from its current value (3 tsf). Data from Mixed sites may reduce uncertainty and improve the resistance factor, although this is of lesser priority than the Clay data.

- In Southeast Missouri, additional data from coarse-grained sites may provide justification for relying on pile setup without restrikes, like the procedure for Northern Missouri (Section 5.1). The data collected included just two piles from relatively clean Sand sites, with setup factors of approximately 1.3 and 1.6. A dataset of two piles is insufficient basis for developing a new design procedure, but the setup factor values suggest such a procedure could be justified with additional data. An advantage of setup for piles in Sand is that restrikes after 24 hrs. are likely sufficient to capture most pile setup.

- Pile setup data from static load tests would be beneficial. The existing datasets are based entirely on comparisons of HSDT-SM at EOD and BOR. Additional comparisons based on static load tests would be beneficial to evaluate the major fundamental assumption in this research that HSDT-SM provides an unbiased estimate of pile resistance.

If additional data are collected, updating the models presented in this report and re-calibrating the associated resistance factors could be performed relatively efficiently. A new model for piles in Sand profiles in Southeast Missouri could be developed with similar efficiency.

6. Summary and Conclusions

Load test reports from high-strain dynamic testing (HSDT) and associated soil boring data were compiled from sites in Northern Missouri and Southeast Missouri, where the use of friction piles is common. The load test reports were carefully reviewed and many of the pile test results were removed due to issues including, poor quality signal matching, testing problems, inconsistent pile size or diameter with the rest of the database, outlier soil properties, or piles that reached refusal (i.e., large end bearing capacity). Soil boring information was used to characterize the profile conditions as Sand, Clay, or Mixed based on the percentage of the pile that penetrated through clay layers. In addition, average values of soil properties (pocket penetrometer values, standard penetration test (SPT) blow counts, and plasticity index) in the clay layers were computed when these parameters were available. Pile setup factors (ratio of total capacity at restrike time to total capacity at end of driving (EOD)) were calculated and plotted versus time.

Sufficient data were compiled from sites in Northern Missouri to create a model for long-term pile setup and develop resistance factors that can be used to account for pile setup without the need for restrikes. Resistance factors were developed for Clay and Mixed profile conditions in Northern Missouri considering a 1 in 10,000 probability of failure. The results showed that a significant reduction in required nominal resistance at the EOD (up to 27% in some cases) can be achieved using these resistance factors. Cost savings of thousands of dollars per pile can be achieved from the use of shorter piles. This approach also avoids the remobilization cost and construction delays associated with pile restrikes. Situations where the use of restrikes and the larger associated resistance factor may be advantageous are described and examples of various approaches to incorporating pile setup are presented in Chapter 5. Proposed additions and revisions to the Engineering Policy Guidelines (EPG) are presented in Chapter 5.

Pile setup data from Northern Missouri also showed larger setup factors than those determined from a prior study of piles in similar geological conditions in Iowa performed by other researchers. The differences are likely due to different pile types used in these two studies. Therefore, the model and resistance factors developed in this study are limited to 14 in. to 16 in.-diameter, closed-ended pipe piles. Also, the setup factors determined in this study were shown to correlate with pocket penetrometer (PP) strength values for profiles in Clay. However, due to the limited range of values and limited data it was not possible to incorporate this information into the setup model.

In Southeast Missouri, there was insufficient data to develop a meaningful model of pile setup or calibrate resistance factors. However, the limited data did show that moderate pile setup can be expected in these soils. If pile setup is to be included in pile design in Southeast Missouri, restrikes must be performed. It is recommended that future data collection of restrikes should be performed in Southeast Missouri so that similar calibration factors and procedures can be developed for this region.

Finally, pile load test data from this project showed convincingly that pile capacity is often underestimated due to the use of a pile driving hammer that has not been properly warmed up. Therefore, proposed revisions to the EPG regarding pile hammer warm-up are presented in Chapter 5.

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