Pile Setup in Missouri Soils

Summary Document

1. Introduction

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 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).

Given the important influence pile setup can have on economical pile design, it is important that MoDOT's pile designers have a solid understanding of the potential for pile setup in the soils of Missouri. The objective of this document is to provide MoDOT's designers with a broad understanding of pile setup and its importance for pile design in Missouri. A brief overview of the literature on pile setup is presented first, including mechanisms responsible for setup, the effect of soil type on pile setup, effect of pile type on pile setup, soil parameters that have been correlated with pile setup, and general models that have been developed for pile setup. Next, a general overview of soil conditions encountered in Missouri is provided along with regions in the state where use of friction piles are common and pile setup should be considered. Lastly, the findings from a compilation of pile load tests performed in Missouri are presented and a model for pile setup is presented.

2. Review of Literature on Pile Setup

Mechanisms of Pile Setup

Pile setup refers to the increase in pile capacity that often occurs after initial driving of piles in many 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). In some soil conditions, the opposite effect called *pile relaxation* may occur, where soil capacity decreases with time.

Pile Setup/Relaxation in Different Soil Types

The magnitude of pile setup is affected by the soil type and profile that the pile is driven into. Pile setup can be quantified using a setup factor, which is the ratio of the total capacity at some time after driving to the total capacity measured at a reference time (often end of driving). Soil profile conditions can be broadly separated into categories of Clay, Sand and Mixed. General expectations for setup in these profile conditions are discussed below.

Clay: Greater pile setup is usually observed in piles driven into clays, particularly soft, weaker clays (e.g. Peck, 1958) as compared to sands. As described above, setup is primarily associated with positive excess pore pressure generation due to the shearing and remolding of the soil. Soft, weaker clays 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 show pile setup measured in clays 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 some days after driving to the capacity measured at some early reference time (often the end of driving). The setup factor from this database varies considerably with setup factors from 1 to as high as 6. This illustrates the difficulty in applying a generic factor for setup in clay.

Sand: Piles driven in sand may also experience setup, as shown in Figure 1b. The magnitude of setup is typically lower than what is observed in clays. 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 sands is likewise related to pore pressure generation during pile driving in most cases. Piles installed in loose sands 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 sands due to dilation of the sands. 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 sands (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.

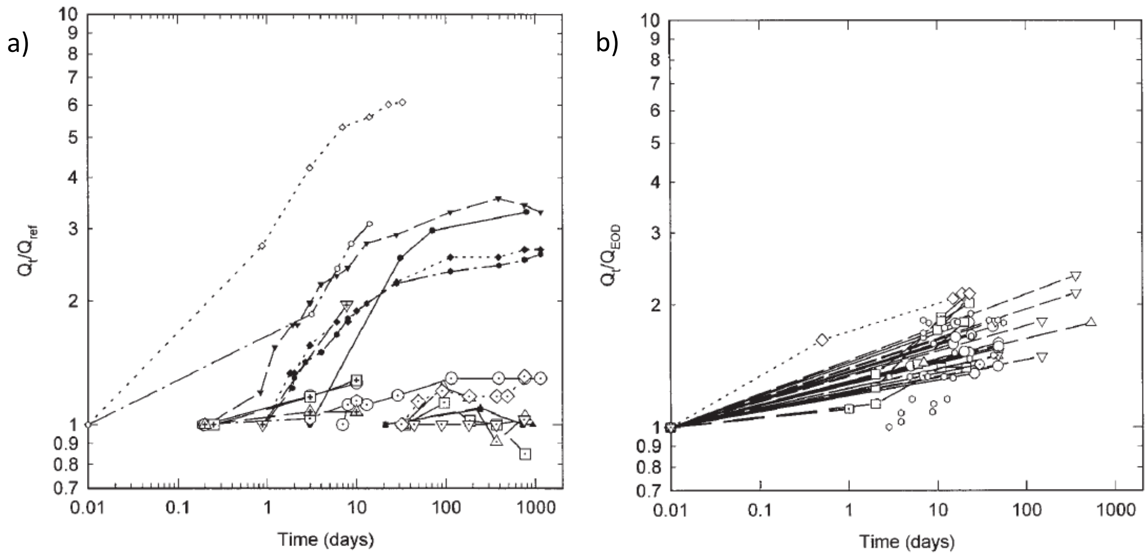

Figure 1: Pile setup in (a) clay versus (b) sand (Long et al., 1999)

Mixed: Mixed soil conditions refers 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 2 shows the setup observed from the database presented by Long et al. (1999). Surprisingly, these data showed little difference in the range of setup factors observed for mixed soil conditions versus clay soil. This indicates that other factors may dominate the observed pile setup response.

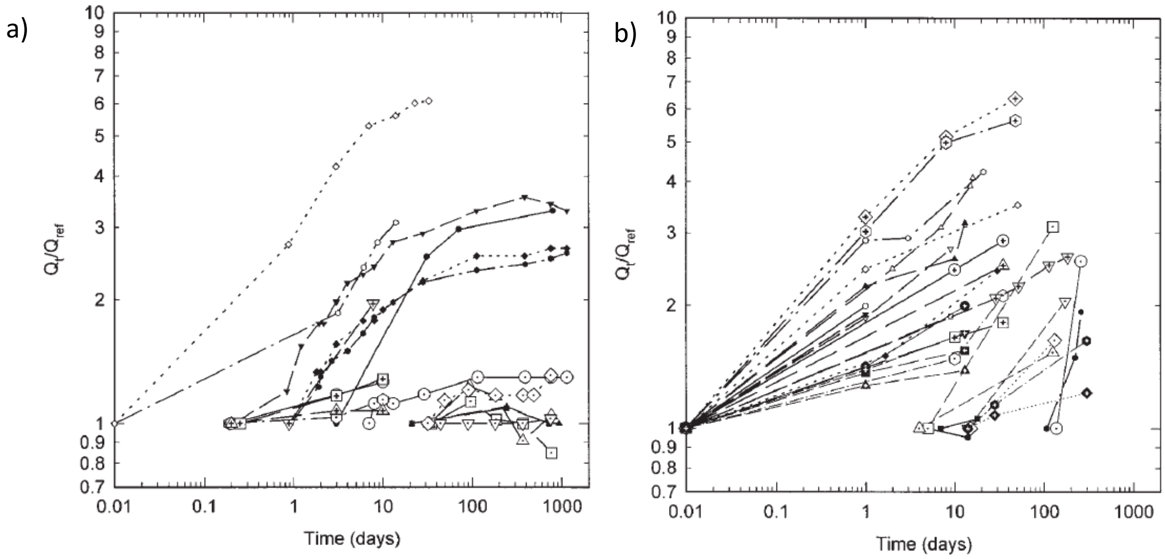

Figure 2: Pile setup in (a) clay versus (b) mixed soil (Long et al., 1999)

Effect of Pile Type and Size on Soil Setup

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 at 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 actually be lower.

Soil Parameters and Pile Setup

In clays, greater pile setup is generally associated with softer weaker soils. Therefore, soil parameters that indicate the strength of the soil may correlate with pile setup factors. Ng et. al. (2013a), for example, showed strong correlations between strength parameters (undrained strength and N-values) and pile setup, as shown in Figure 3. As shown later, data from testing in Missouri showed strong correlations between pocket penetrometer values and pile setup.

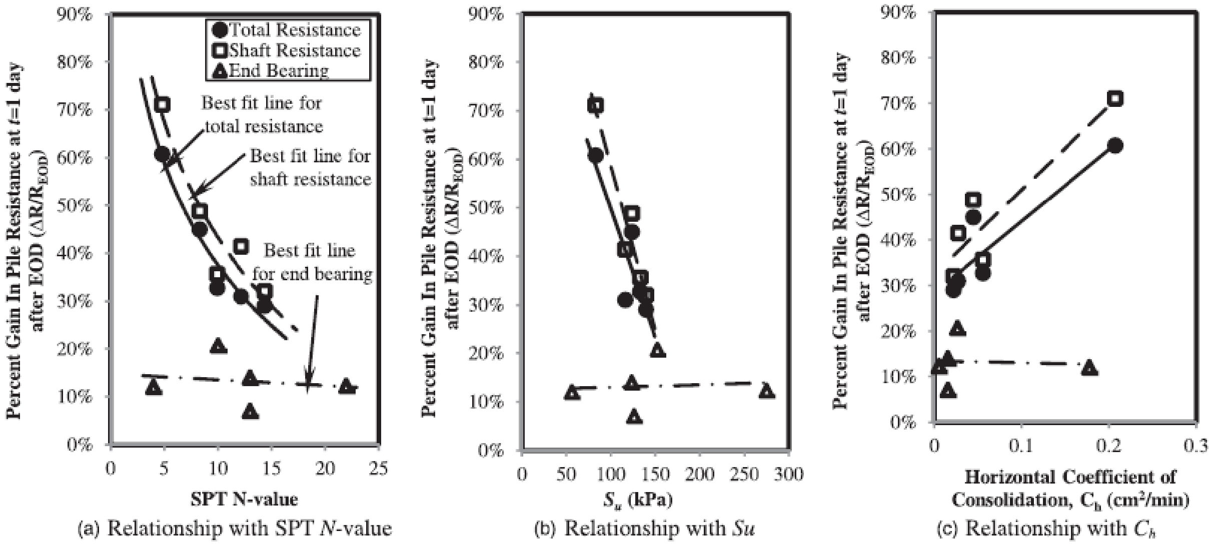

Figure 3: Relationships between percent gain in pile resistance after one day and various soil parameters (Ng et al., 2013)

<u>*Pile Setup Models*</u>

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

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:

$$\boldsymbol{Q_t/Q_0 - 1 = A \log\left(t/t_0\right)} \quad (1)$$

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.

Svinkin (1996)

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

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

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.

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:

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

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

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

$$\frac{Q_t}{Q_R} = [\frac{t}{t_0}]^{\frac{C_D C_\alpha}{C_c}} \tag{4}$$

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.

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

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

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 $(\frac{f_c c_{ha}}{N_a r_p^2} + f_r)$ is grouped into a single fitting parameter.

3. Missouri Geology and Typical Bridge Foundations in Missouri

<u>*Overview of Geology in Missouri*</u>

Missouri Soil and Bedrock Depth
As shown in Figure 4, Missouri is composed of four distinct physiographic regions, the northern plains, western plains, Ozark highlands and southeast lowlands. The regions of primary interest for pile setup are the northern plains and southeast lowlands. General soil conditions in these regions are described in the sections that follow.

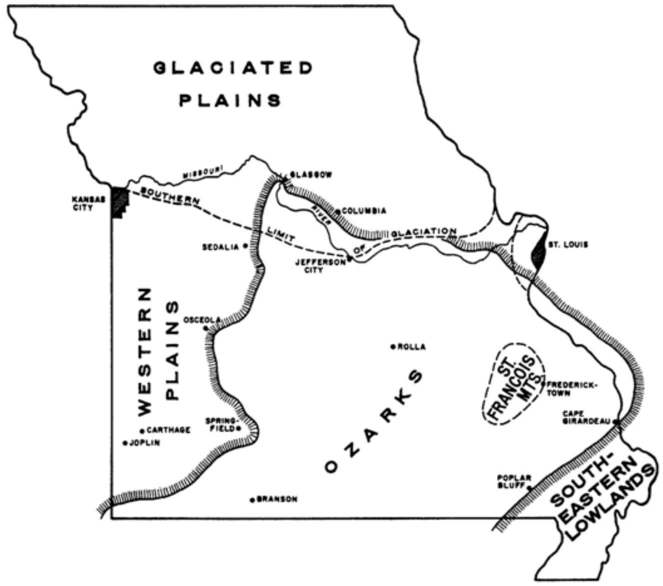

Figure 4: Surficial materials map of Missouri (Saville et al., 1962)

Northern Glaciated Plains

Soil conditions in the northern plains generally consists 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 clays, 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 similar to 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 the upland areas, with the thickest deposits near the Missouri and Mississippi rivers.

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 ranges from 5 to 30 feet 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, silt, and sand that can reach a thickness of up to 150 feet in some places.

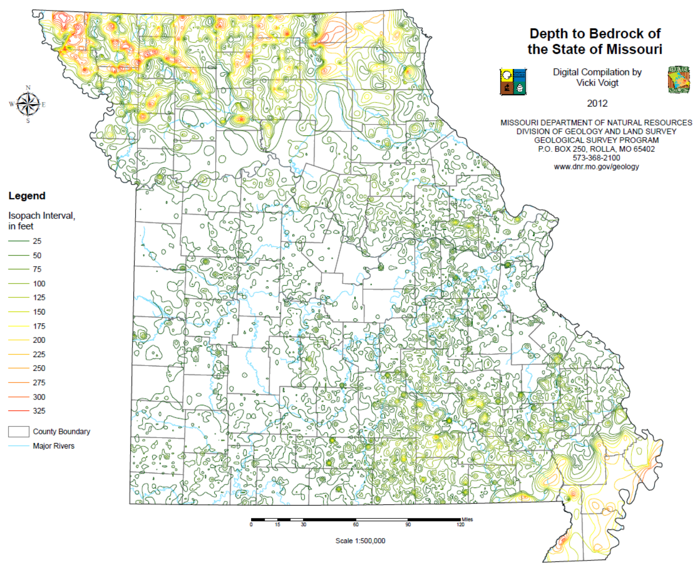

Figure 5: Depth to bedrock in Missouri (Missouri DNR)

Bridge Foundations in Missouri

The depth of bedrock is quite variable through the state of Missouri, as shown in Figure 5. The deepest bedrock is found in southeast and northern portions of the state. Throughout much of the rest of Missouri bedrock is relatively shallow. The bridge foundation of choice for shallow bedrock 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. Therefore, the portions of the state where pile setup is of greatest importance is in the glaciated plains to the north and the southern lowlands. In these regions, closed-ended pipe piles are the most common foundation type, although other types, such as H-piles and open-ended pipe piles may also be used.

4. Pile Setup in Missouri Soils

Northern Missouri

Procedures

Data from high strain dynamic load tests with signal matching (HSDT-SM) were compiled from 14 bridge projects and 46 piles in Northern Missouri. Data "cleaning" was performed to remove unreliable data due to issues such as problems during HSDT and poor-quality signal matching fits to the data. Also, to eliminate the effect of pile type and size on the results, open-ended pipe piles, H-piles, and large diameter piles were removed from the dataset. After data cleaning and pile removal, 23 pile loads tests from eight bridge sites were retained. All remaining piles were closed-ended pipe piles with diameters of 14 or 16 in. Pile lengths ranged from 37 ft to 104 ft with an average of 53 ft. Project site locations are shown in Figure 6.

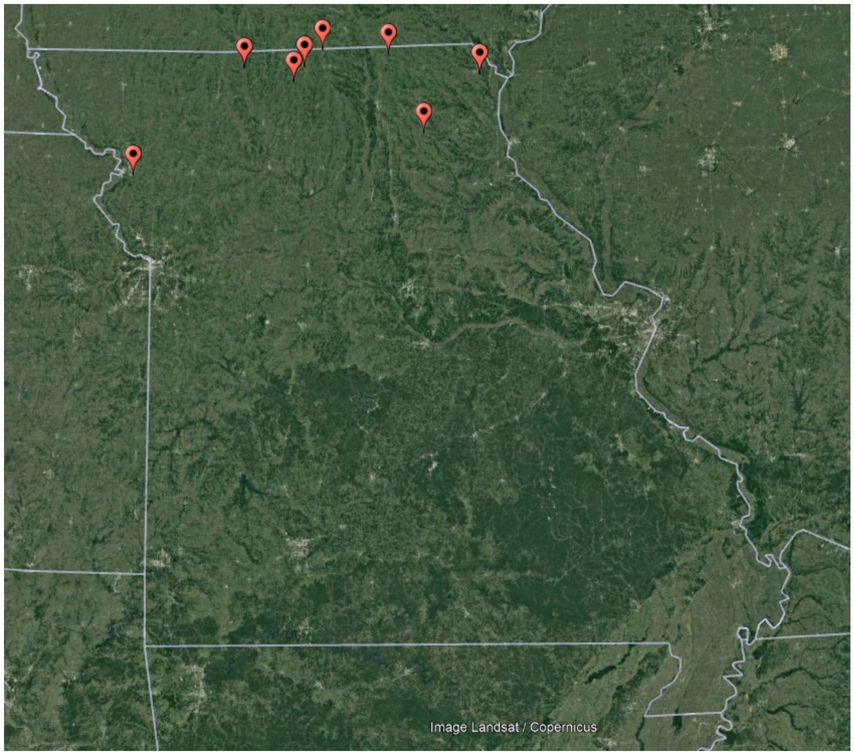

Figure 6: Google Earth image showing the location of the eight bridge sites where 23 piles were tested using HSDT-SM.

Soil borings located nearest to each pile were identified and used to characterize the soil profile and properties. The length of each driven pile $\left(L_{pile}\right)$ was obtained from the HSDT report and the length driven through clay (L_{clay}) was determined by examining the soil stratigraphy at the closest boring location. A clay embedment percentage (CEP) was calculated, defined as:

$$CEP = \frac{L_{clay}}{L_{pile}} \times 100 \tag{6}$$

The CEP was used to categorize the profile as Clay, Mixed, or Sand, using the criteria shown in Table 1. The 70% cutoff between Clay and Mixed was determined by examining changes in the coefficient of variation (COV) of the setup factor for different cutoff criteria (Rosenblad and Boeckmann, 2023). The 70% value was found to be where a large change in COV occurred. This value for the cutoff between Mixed and Clay is consistent with values used by Ng et al. (2013a).

Table 1. Soil profile designation based on clay embedment percentage (CEP)

Soil Profile Designation	CER
Clay	70% to 100%
Mixed	35% to 70%
Sand	<35%

Pile Setup Factors

Pile setup factors are plotted as a function of time for all 23 piles in Figure 7. Piles with multiple restrikes are shown with connected markers, while piles with only one restrike are indicated with a single marker. All but one of the piles exhibited significant setup, but there was large variability in setup factors. Apart from the single pile with no setup, setup factors ranged from 1.4 to 2.7 after 60 hrs.

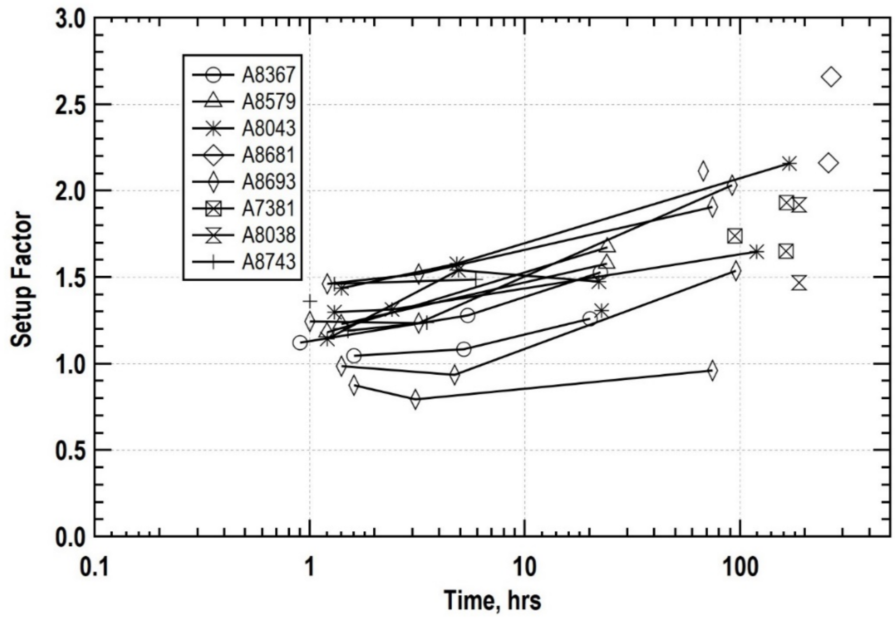

Figure 7: Pile setup factor versus time determined from dynamic tests on 23 piles at eight bridge locations in northern Missouri.

To investigate the variation in setup factor values, the data in Figure 7 were separated into Clay profiles and Mixed profiles using the criteria shown in Table 1 (no profiles were Sand). Surprisingly, Mixed profile sites had a similar range of setup factors as the Clay profiles. In fact, the highest setup of 2.7 was measured at one of the Mixed profile sites.

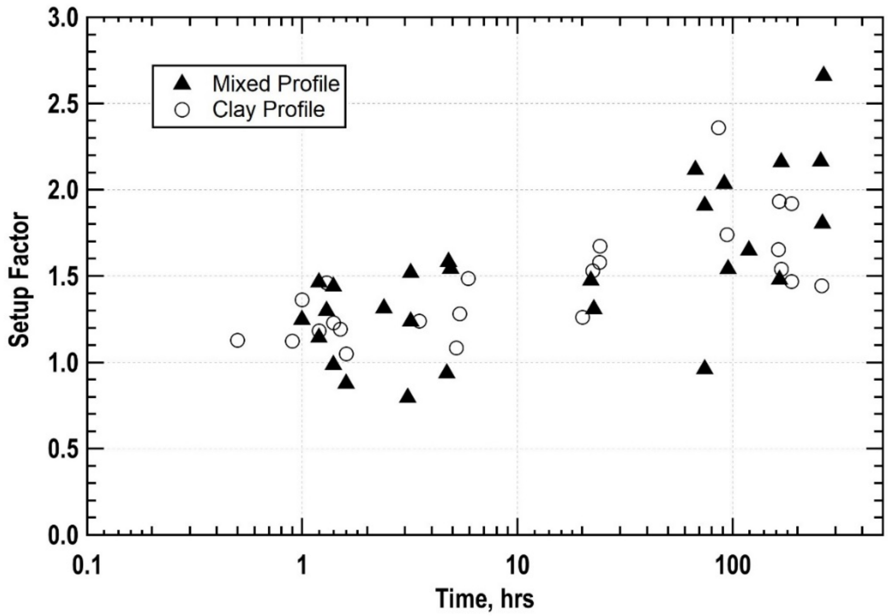

Figure 5. Pile setup factor versus time determined from dynamic tests performed on piles installed in Mixed profiles versus piles installed in Clay profiles

Correlations with Soil Parameters

Changes in pile setup factors were also examined as a function of three soil parameters, average blow counts ($N_{60,ave}$), average plasticity index (PI_{ave}) and average pocket penetrometer values (PP_{ave}). As shown in Figure 6, no trend was observed between setup factors and $N_{60,ave}$ for the Mixed profiles. However, the Clay profiles showed a general trend of decreasing setup factor values with increasing $N_{60,ave}$. A linear fit through the Clay data produced an r^2 value of 0.51. This trend is consistent with the expectation of higher setup for weaker soils. The correlation with PI_{ave} was very poor for both the Mixed profile condition and the Clay profile condition, as shown in Figure 7. No correlation with PP_{ave} was found for the Mixed condition, but a strong correlation between PP_{ave} and setup factor was observed for the Clay profile condition with an r^2 value of 0.93, as shown in Figure 8.

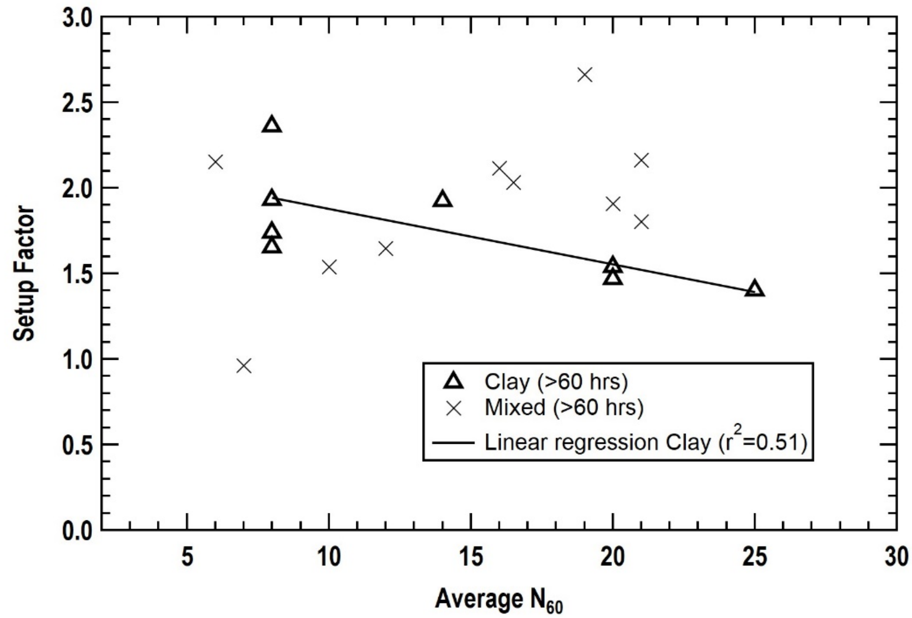

Figure 6. Relationship between pile setup and N_{60} values for Clay and Mixed profiles at Northern Missouri sites

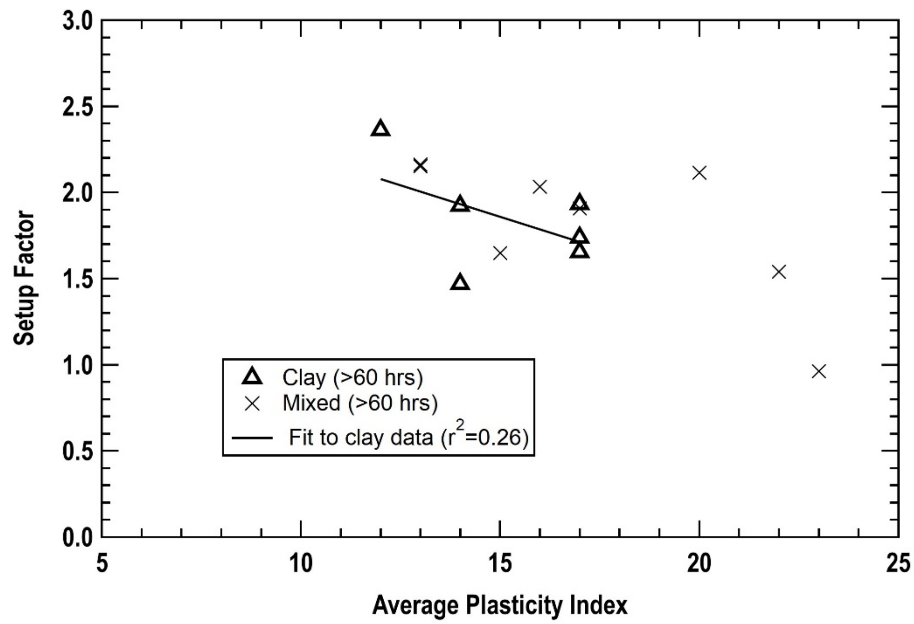

Figure 7. Relationship between pile setup and PI values for Clay and Mixed profiles at Northern Missouri sites

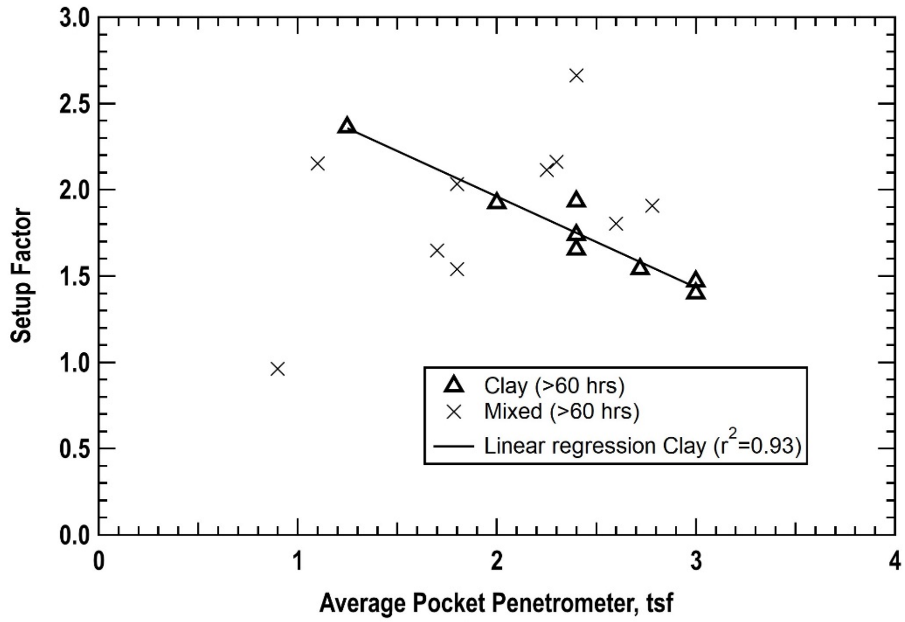

Figure 8: Relationship between pile setup and pocket penetrometer values for Clay and Mixed profiles at Northern Missouri sites

Comparison with Pile Setup in Iowa Soils

A research project investigating pile setup in Iowa soils was performed in 2011 by Iowa State University (ISU). Data from this project were obtained from a published report that documented in detail the load test program (Ng et al., 2011). A comparison of the setup factors from the Iowa testing and the Northern Missouri sites is shown in Figure 9. Although the piles are in similar glacial soils, setup factors from the Iowa tests were much lower than the setup factors measured in Missouri. This difference is likely because of differences in pile size and type, as discussed earlier. The Iowa tests utilized 10 in. H-piles while the northern Missouri tests were performed on closed-ended pipe piles with diameters of 14 to 16 in.

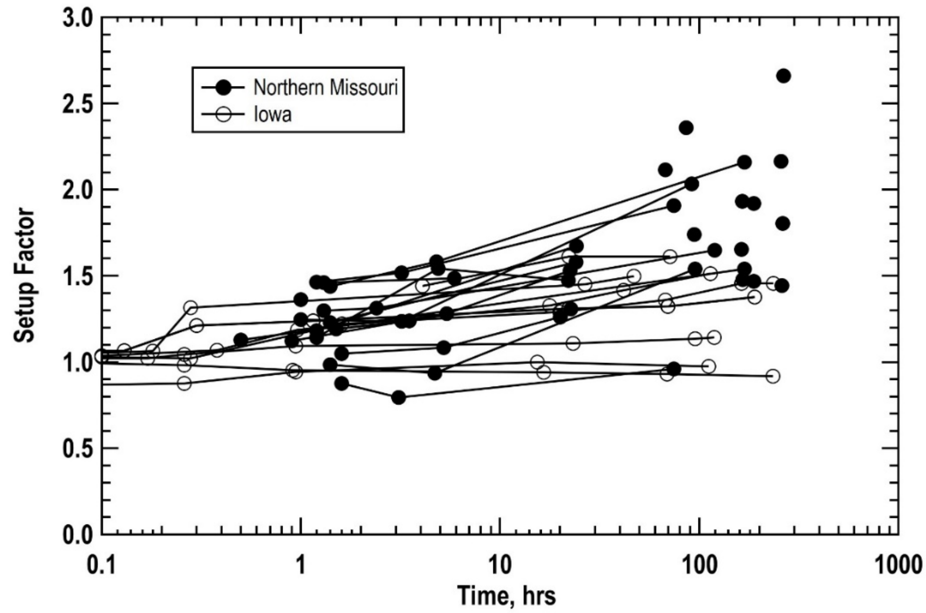

Figure 9: Comparison of setup factors from Northern Missouri sites and Iowa sites

<u>*Pile Setup in Southeast Missouri*</u>

Procedures:

Data were obtained from 8 projects in Southeast Missouri with load test data available from tests performed on 24 piles. Soil information was only available for 4 of the 8 project sites and 8 of the 24 piles, which greatly limited the number of piles that could be used in this study. The locations of the four load test sites in Southeast Missouri are shown in Figure 10.

Due to a lack of soil boring information at the Southeast Missouri pile test sites, no soil parameter data (N_{60}, PI, PP) were collected. Based on site descriptions provided in the reports and limited soil boring information four of the sites were characterized as Sand profiles and four were characterized as Mixed.

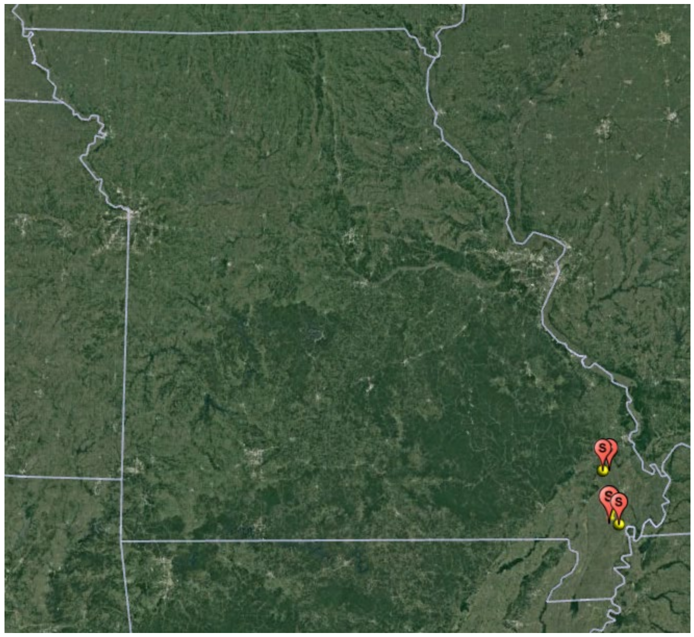

Figure 10: Missouri project sites in Southeast Missouri where pile load test data and soil information were available

Pile Setup Factors

Pile setup data from the four sites and eight piles in SM are plotted in Figure 11. Although the data is very limited, it suggests that modest pile setup does 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.

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), as shown in Figure 12. 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. It should also be noted that there was one pile where the capacity at 50 hrs was lower than the EOD value. 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 pile relaxation is truly occurring at this site

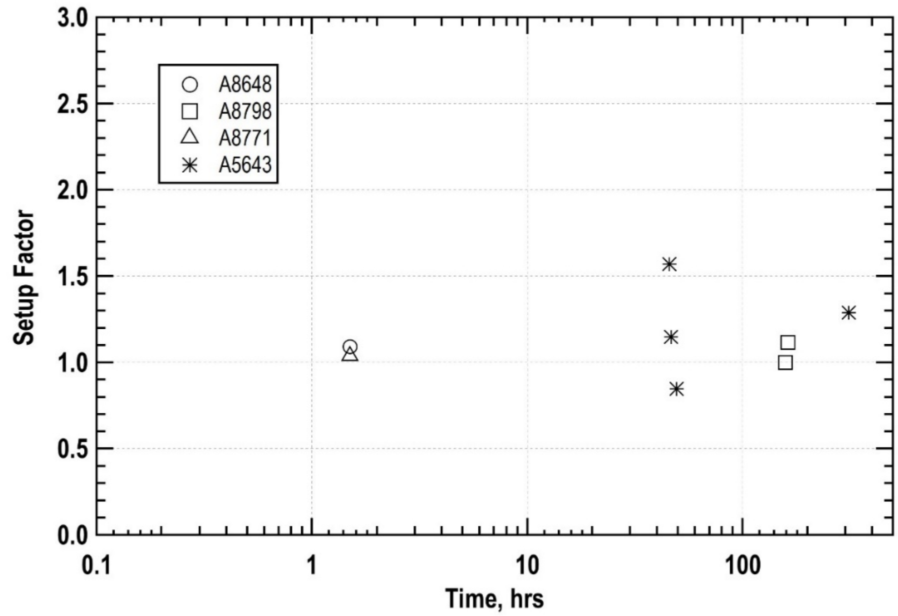

Figure 11: Setup Factors from sites in Southeast Missouri

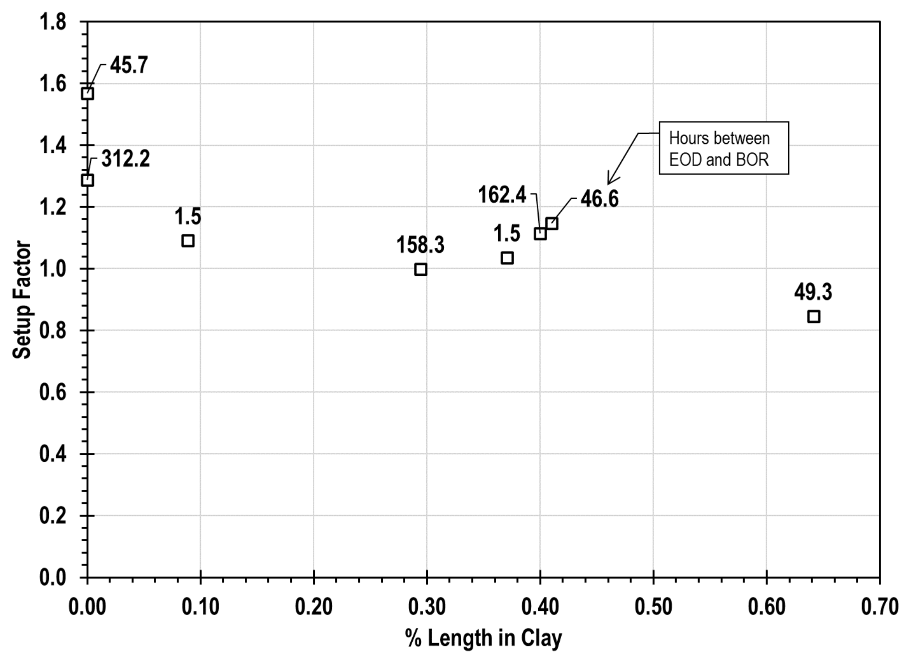

Figure 12: Pile Setup in Southeast Missouri versus % length in Clay

5. 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 13, 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 7 of 8 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 13, 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 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 presented in Rosenblad and Boeckmann (2023).

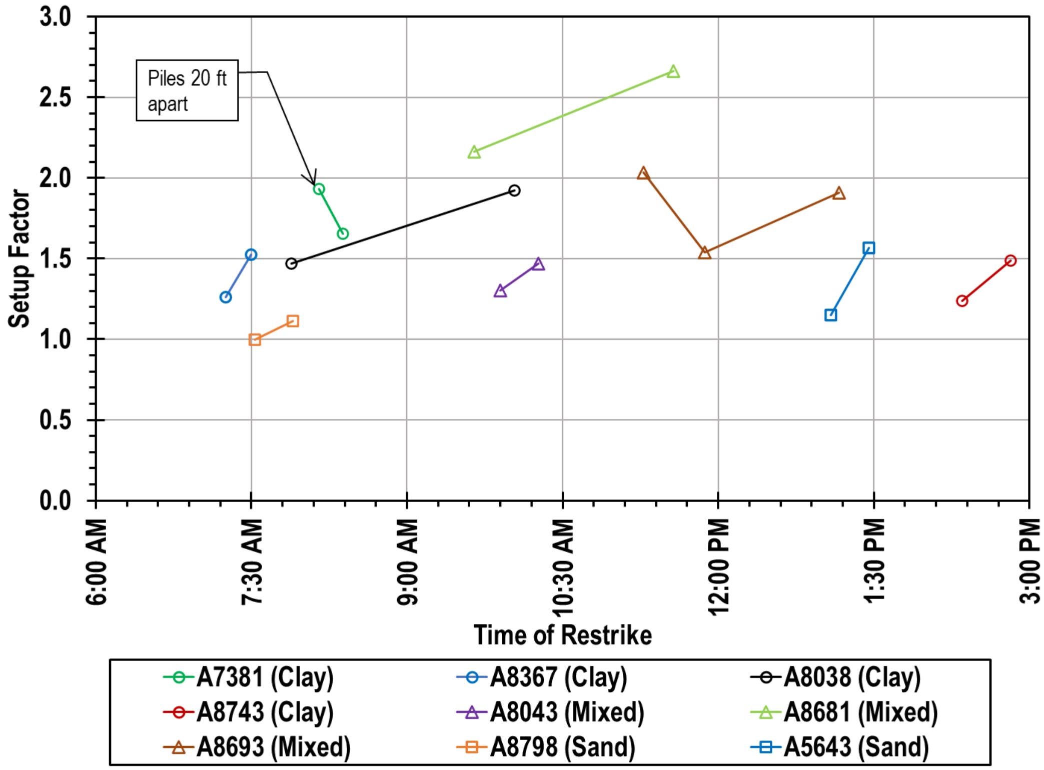

Figure 13: Setup factors from restrikes performed on different piles at the same sites on a single day.

6. Summary

This document provided an overview of pile setup and the various factors that affect the magnitude and rate of setup. General trends of pile setup that were observed from HSDT performed on piles in Northern Missouri and Southeast Missouri were presented. The pile setup results from Northern Missouri were compared to results from a prior study of setup in glacial soils of Iowa. Setup factors in Northern Missouri were shown to be significantly larger than those measured in Iowa, likely due to differences in pile type.

The pile setup models developed from this research were used to develop reliability-based procedures to incorporate pile setup in MoDOT's design procedures without the need for restrikes. The details of these procedures along with examples of incorporating pile setup in LRFD pile design can be found in Rosenblad and Boeckmann (2023). Proposed revisions to MoDOT's Engineering Policy Guide (EPG) are also presented in Rosenblad and Boeckmann (2023).

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