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Evaluation of Regionally Calibrated Load and Resistance Factor-Design Method Used for Driven-Steel H-Piles

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Abstract

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Keywords

Driven piles, Highway and road design, Load and resistance factor design, Construction methods, Load factors, Piles, Calibration, Bridge design, Iowa, United States

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Abstract

Since October 2007, the FHWA has required the implementation of LRFD methods in all new bridge designs, including pile design. The resistance factors provided nationally for LRFD of driven piles are relatively conservative. Therefore, the Iowa Department of Transportation and Iowa State University collaborated and established regional resistance factors that are more efficient than those provided in the American Association of State Highway and Transportation Officials (AASHTO) Specifications, which were complemented with improved construction control methods. Iowa's LRFD pile design guidelines have been used in enough completed projects since 2012, allowing an assessment of the accuracy of the regional resistance factors and construction control methods. The piles used in these projects included both end bearing piles in rock and friction piles. The friction piles were installed in cohesive, non-cohesive, and mixed soil sites. The evaluation for the different pile categories and soil types found that the regional LRFD resistance factors developed were successfully applied in Iowa's driven pile design and effectively reduced the piles' contract lengths, resulting in a cost-benefit over AASHTO's recommended resistance factors.

Keywords: Load and Resistance Factor Design (LRFD), pile, driven, design, resistance factors, Iowa

Introduction

Beginning October 2007, the Federal Highway Administration (FHWA) required all new bridges in the United States to be designed using the Load and Resistance Factor Design (LRFD) approach. The LRFD method provides a more reliable approach for structural design than the formerly used Allowable Stress Design (ASD). However, since the AASHTO procedures for foundations were meant to establish design guidelines applicable to the large variety of soil types encountered across the nation, they include unnecessary conservatism at the local level. As a result, several users of the code indicated that the recommended procedures resulted in pile designs that were inconsistent with their previous experiences (Moore, 2007). In order to improve foundation design in the LRFD framework economically, state departments of transportation (DOTs) have been encouraged by AASHTO to establish regional resistance factors that better suit their local soil conditions and design practices.

The Iowa Department of Transportation's (Iowa DOT) approach to improving upon AASHTO's resistance factors was to initially transition to an interim LRFD procedure to design bridge piling using a resistance factor of 0.725, which was calibrated by fitting to the previous ASD method. During this time, the Iowa Highway Research Board (IHRB) funded Iowa State University (ISU) to conduct comprehensive research on piling (http://srg.cce.iastate.edu/lrfd) in order to develop more efficient resistance factors and establish the best approach for the design of piles in Iowa using LRFD. This research utilized historical and new load test data to produce a four-volume report and improved design and construction control methods for steel H-piles, which has been implemented in practice since October 2012. Improving upon AASHTO's national factors and establishing regional resistance factors can benefit state DOTs economically by ensuring that they are using their materials efficiently, and thus examining Iowa's approach can assist other regions in developing their own methods and factors. However, developing new resistance factors has a risk of underestimating the pile lengths as well, and a validation of the research success in establishing more efficient regional resistance factors first needs to be performed. The LRFD pile design procedure created through the efforts of ISU and Iowa DOT is a relatively new method having only been implemented in the state's bridge design projects since 2012. Given that there are now a sufficient number of projects with adequate data on completed pile driving, the primary objective of this paper was to 1) evaluate the effectiveness of the regionally calibrated LRFD method in estimating the piles' contract lengths and 2) determine if the design, specifically the resistance factors, requires some adjustments. To accomplish the study goal, a summary of ISU LRFD research and outcomes are first presented. Then, pile logs from several Iowa DOT projects are collected and analyzed to determine the amount of cutoffs, extensions, retapping, refusal, and pile length that could have been saved if driving had stopped when piles reached target nominal driving resistance.

Improvements to LRFD Methodology for Pile

Resistance Factors Calibration

The resistance factor calibration research started with the development of a system to electronically gather and store data from past and future pile load tests performed in Iowa. The result was a user-friendly database titled PILOT (PIle LOad Test) that included data from 264 past pile load tests performed on steel H-shaped, timber, Monotube, and concrete piles as shown in Fig. 1 (Roling et al. 2010). Of the 164 steel pile load tests, 80 were deemed usable for the resistance factor calibration because they had sufficient information to estimate pile resistance using either static or dynamic analysis methods.

After developing and evaluating the PILOT database, it was found necessary to perform additional load tests to: 1) ensure that all soil profiles encountered in Iowa were adequately represented in the database; and 2) generate the missing data needed to establish the resistance factors for more reliable construction control methods utilizing Pile Driver Analyzer (PDA) data and the CAse Pile Wave Analysis Program (CAPWAP). Consequently, a field load test program that included 10 steel H-piles was conducted to further examine piling behavior in different soils. The locations of these tests (i.e. ISU#1 through ISU10) are shown in Fig. 2 along with those of the previously completed tests. The locations of the new tests were selected such that all geological regions in Iowa were covered. Extensive in-situ and laboratory testing were conducted to characterize the soil profile at the test sites. Data were also collected during the driving and load test phases. The information gathered included lateral earth and pore water pressure measurements, strain and acceleration measurements, and axial static load test data. The investigation led to several findings, the most important of which was that setup could be quantified and integrated into the LRFD of piles in cohesive soils. Ng et al. (2011) determined that setup occurs only in piles embedded in clay and mixed soil profiles and is primarily influenced by soil permeability and compressibility as well as the total thickness of all cohesive soil layers along the pile embedment length. Two improved analytical methods with their corresponding resistance factors were subsequently developed to better quantify pile resistance increase over time in cohesive soils. The new methods were based on soil properties determined from the widely used Standard Penetration Test (SPT) and Cone Penetration Test (CPT) combined with the Wave Equation Analysis Program (WEAP) and CAPWAP dynamic analysis methods (Ng et al. 2013a, 2013b).

In the next phase of the study, AbdelSalam et al. (2011a) analyzed the data collected, calibrated the LRFD resistance factors for static analysis, dynamic analysis, and dynamic formulas, and provided a suggested procedure optimized for Iowa. Also, through this process, a quantitative soil classification method was established to better define pile soil profiles as either cohesive, non-cohesive, or mixed soils. In this classification scheme, a soil profile is categorized as cohesive if 70% or more of the pile length is in contact with cohesive soils or non-cohesive if 70% or more of the pile length is in contact with non-cohesive soils. Anything in between is considered a mixed category. Resistance factors were calibrated for various methods including five static analysis methods, 7 dynamic formulas, and WEAP dynamic analysis using five different soil input methods. The Iowa Blue Book method (Iowa DOT 2011) was found to be the most efficient and was, therefore, recommended for implementation. The recommended resistance factors for a target reliability of 2.30 (i.e., redundant systems) with due consideration of construction control are shown in Table 1 and 2. The factors in Table 1 are used to determine the nominal pile driving resistance and contract length while those in Table 2 are for the target pile driving resistance.

A comparison with the interim resistance factor of 0.725 showed a reduction of 10%, 17%, and 24% for cohesive, mixed, and non-cohesive soils, respectively. A study conducted by Ng et al. (2012) utilizing steel H-shaped production pile data from several Iowa bridge projects showed that the new procedure resulted in an average of 4% reduction of the factored resistance compared to the interim procedure for cohesive soil. As a consequence, plan pile lengths would have increased by 3.3% if the new LRFD procedure was used in those projects. Compared to AASHTO resistance factors (Table 3), the study confirmed that the regional LRFD procedures were economically beneficial due to shortening of the plan length of piles and requiring fewer pile extensions. The addition of setup was also validated, demonstrating it would lower the target driving resistance and reduce the need for retapping. A further investigation (Ng et al. 2014) for mixed and non-cohesive soils resulted in similar observations. The new procedure resulted in 26% and 12% lower factored geotechnical resistance, corresponding to plan pile length increases of 25% and 12% for non-cohesive and mixed soils, respectively. The study also determined that the new procedure would increase the amount of retapping and pile extension required but would still be more economical than AASHTO's recommended factors. The guidelines presented in Table 1 and 2 best fit Iowa's practices and include different factors for a variety of construction control options although WEAP is the common method used in Iowa. The charts are also broken into the three soil classifications defined by AbdelSalam et al. (2011b). The research did not extend to end bearing in rock due to the lack of sufficient data. Therefore, the factor used in the interim LRFD method was kept for rock and rounded down to 0.7. In the last phase of the calibration study, the chosen LRFD pile design process was summarized, and design examples were developed to illustrate the process in steps for various conditions (Green et al. 2012).

LRFD and Construction Process

The LRFD design method developed for Iowa DOT, as summarized in by Green et al. (2012), is broken down into 12 steps, which are shown in Table 4. The first ten steps occur during the design process while the final two take place in the field. First, the preliminary design engineer prepares the situation plan for the bridge; the soils design engineer develops the soil information and recommendations, and the final design engineer determines the pile arrangement and loads (Steps 1-3). Then, the nominal pile resistance (Step 4) is determined from the friction and end bearing resistances for the different soil types given in the Iowa Blue Book (Iowa DOT 2011). The appropriate resistance factor (Step 5) is selected from Table 1, and the nominal pile resistance is calculated in Step 6, using Eq. 1.

$$R_n = \frac{\sum \eta\gamma Q + \gamma_{DD} DD}{\varphi} \tag{1}$$

where,

$\sum \eta\gamma Q$ = factored axial load per pile in tons

$\gamma_{DD}DD$ = factored downdrag in tons

φ = resistance factor

The contract length, including allowances for cutoff and pile cap embedment, is then estimated in Step 7. For piles with end bearing in rock, a recommended depth of penetration dependent on rock classification must also be included. In step 8, the target nominal driving resistance, R_{EOD}, is estimated using Eq. 2, which properly accounts for setup effects in cohesive soils only.

$$R_{EOD} = \frac{\sum \eta\gamma Q + \gamma_{DD} DD}{\varphi_{EOD} + \varphi_{SETUP}(F_{SETUP} - 1)} \tag{2}$$

where,

$\sum \eta\gamma Q$ = factored axial load per pile in tons

$\gamma_{DD}DD$ = factored downdrag in tons

φ_{EOD} = resistance factor for end of driving condition

φ_{SETUP} = resistance factor for setup

F_{SETUP} = setup ratio

φ_{EOD} and φ_{SETUP} are shown in Table 2, where the value of φ_{SETUP} was conservatively chosen to recognize that the uncertainties associated with estimated pile resistance at end of driving (EOD) are different from those associated with the additional resistance from setup effects (4). F_{SETUP} is determined from Fig. 3, where setup is dependent on average blow counts and number of days after EOD until retap, typically a 1 day, 3 day, or 7 day retap.

Once the required values are computed, the hammer and its details are chosen and used to complete a WEAP analysis and to prepare a bearing graph (Step 11). The bearing graph determines the driving resistance in the field and is dependent on the blow count at the EOD and the ram rise. Each pile driving is monitored and recorded in pile logs in the field. The pile is driven to the full contract length unless refusal, 160 blows/0.30 m (1 ft) or greater, is reached. If the average blows per meter result in an inadequate driving resistance, the pile is retapped one day later. According to the Iowa DOT (2012) Standard Specifications, only one of every ten piles or a minimum of two piles per bent are required to be retapped without additional cost. If the piles with the lowest resistance are accepted after retapping, the other piles within the bent, which fell short of reaching resistance are accepted as well. If the pile still does not meet the required resistance, either Pile Dynamic Analyzer (PDA) tests can be performed to check pile resistance, and pile extensions are added if necessary; or pile extensions can be added immediately without the PDA.

Data Collection

In order to determine the effectiveness of the calibrated resistance factors and LRFD procedure, data was gathered from Iowa DOT's LRFD piling projects performed since the new design was implemented in 2012. The field data was first collected, organized, and analyzed using Excel spreadsheets. From there, comparing the predicted pile lengths provided in the plans with the data recorded during the pile driving would determine the accuracy of the resistance factors used. For each project involving steel H-pile foundations designed using the new LRFD, the piling logs were gathered, providing the majority of the information for answering the objective questions, along with plan sets and soil information. Since being implemented, 68 projects in Iowa have used the established LRFD procedures. Piling logs for 47 of those projects were available as summarized in Table 5. Based on the soil type assumed for construction control in the plan sheets, the bents in each project were divided into the soil categories of cohesive, mixed, non-cohesive, and rock. The geographical map presented in Fig. 4 indicates that the completed projects were relatively well scattered across the state such that the piling data used in this study provided a reasonable representation of the region's geology. The figure also shows that 53% of the projects analyzed included piles with end bearing on rock. The analysis was performed looking at both piles individually and at each bent as a whole so that possible trends could be examined in each case; moreover it was more logical to consider piles when analyzing some variables and bents for others.

Presentation of Results

From the 47 projects, 173 bents with a total of 3,470 steel H-piles were examined in this study. The accuracy and need for refinements of the resistance factors for piling in cohesive, mixed, and non-cohesive soils as well as rock were all investigated individually using five parameters including cutoff, extensions, retapping, refusal, and reaching nominal resistance early. Piles in the cohesive soil category consisted of 10 bridge projects, providing 30 bents and 481 piles. As a whole, the LRFD method and resistance factors for the cohesive category are satisfactory. As shown in Fig. 5, the cutoff lengths were reasonable and the number of retaps and pile extensions required were minimal. Nevertheless, a relatively large percentage of piles tended to reach the target resistance at significantly shorter lengths than anticipated meaning the resistance factors are arguably too conservative. The design procedure for cohesive sites includes a setup component, and its resistance factor was estimated conservatively (Table 2). Though the possibility of increasing this resistance factor should also be explored in further investigation, the findings indicated that the regional factors for cohesive soils perform adequately and are more efficient than the national values recommended by AASHTO.

The resistance factors for determining pile contract lengths in mixed soils were also found to be satisfactory. Forty bents including 718 piles from 15 different projects were categorized under mixed soil. As shown in Fig. 6, the cutoffs and occurrence of hitting refusal are minimal. The need for pile extensions is also small, and although retapping occurs more frequently, it is not unreasonable. With a few exceptions, the amount of piling that could have been saved from reaching the target resistance early is also acceptable. The results infer that the contract lengths were generally appropriate, and the state's LRFD method is a satisfactory improvement for the mixed soil classification compared to the national resistance factors though incorporating setup could improve the amount of retapping.

The non-cohesive soil category had the smallest set of data available, having only eight projects with 12 bents and 326 piles, which made interpreting the data difficult. Fig. 7 summarizes the findings for piles and bents in non-cohesive soils. Pile extensions were nonexistent. Retapping was relatively high but with a high success rate. The number of piles hitting refusal was relatively high as well. The number of piles that reached the target resistance early was dominated by those that hit refusal since the percentages are nearly the same. Once again, the small sample of piling makes it difficult to draw definite conclusions, but the resistance factors appear adequate. The factors were reduced from the interim value of 0.725, and this decrease is validated by the findings of this report.

Given the lack of data, the resistance calibration study did not consider piles with end bearing in rock, and therefore, the resistance factor for this category was based on Iowa DOT's LRFD interim method. The rock category had an ample amount of projects, totaling 1,945 piles from 91 bents and 25 projects. Cutoff lengths, pile extensions, the number of times refusal was hit, and the number of times the target resistance was reached early were all larger for rock than for the other soil categories. The data for rock is somewhat more variable compared to the other soil categories. Additional soil borings and better classification of the rock could lead to more consistent results. Nevertheless, the findings for rock were still reasonable as seen in Fig. 7. Therefore, no adjustments for driving to rock are suggested at this time though future investigations examining rock more closely is encouraged.

Discussion of Results

Cutoff

The amount of cutoff would ideally be 0.30 m (1 ft) for every pile since that is the excess considered when calculating the contract length to account for damaged pile tips during driving. However, since assuming 100% accuracy would be impractical, it was agreed upon from the foundations design group within Iowa DOT that satisfactory pile designs should include at least 85% with cutoffs between 0 and 1.52 m (5 ft), 10% or less between 1.52 m (5 ft) and 3.05 m (10 ft), and no more than 5% with cutoffs greater than 3.04 m (10 ft). These criteria suggest that most piles should be driven fully into the ground, requiring only minimal cutoff. Small amounts of cutoff would not indicate, however, that the full contract length was required to reach the target resistance since current Iowa DOT policy requires the full pile be driven into the ground unless refusal is reached first. Projects requiring pile extensions were not considered while reviewing the cutoff at EOD.

For the cohesive soil category, it was found that 81% of the piles required cutoffs of 1.52 m (5 ft) or less, 12% cutoffs between 1.52 m (5 ft) and 3.04 m (10 ft), and 7% cutoffs greater than 3.04 m (10 ft). Though not exactly within the established ranges, these percentages are within proximity and indicate that pile cutoff is not excessive, indicating a satisfactory current LRFD design procedure.

For mixed soils, the amount of cutoff was much more consistent than the cutoff for piles in cohesive soils with 96% of the cutoff lengths smaller than 1.52 m (5 ft), which is well within the 85-100% target range. This only left 2% of the piles having cutoffs between 1.52 m (5 ft) and 3.05 m (10 ft) and 3% having more than 3.05 m (10 ft) of cutoff. Half of the piles had 0.30 m (1 ft) or less of cutoff, which indicated that most of the piles only required minor trimming. As stated before, this does not signify the resistance factors were accurate in predicting the minimal contract length needed, but it does show the piles are not reaching refusal prematurely, which is also desirable from an economic standpoint.

For the non-cohesive soil category, the pile data analysis showed that 77% had cutoffs less than 1.52 m (5 ft), 1% between 1.52 m (5 ft) and 3.05 m (10 ft), and 22% greater than 3.05 m (10 ft). These values do not meet the criteria set for cutoff lengths of 1.52 m (5 ft) or less and greater than 3.05 m (10 ft); they also do not necessarily mean pile driving in sandy soils performed poorly in terms of cutoff. All piles with cutoffs greater than 3.05 m (10 ft) came from only two bents. Both bents reached refusal, which explains why those cutoffs are larger; and since there are only 12 bents to examine, two bents have a significant effect on the statistics. If these two bents are excluded, nearly all piles (except four) had cutoffs in the desired range of less than 1.52 m (5 ft). More projects are needed to establish a trend.

For piles with end bearing in rock, the amount of piling cutoff at EOD was generally higher than that for the other soil categories. Only 38% of the piles had cutoff lengths of 1.52 m (5 ft) or less while 34% were between 1.52 m (5 ft) and 3.05 m (10 ft) and 28% were over 3.05 m (10 ft). The portion of piles with cut off less than 0.30 m (1 ft) was far fewer for piles driven to rock compared to the friction piles. This is understandable since designers are typically more conservative with the contract lengths to account for the higher variability associated with the design of piles bearing on rock. Altering the resistance factors for rock would currently have no effect on determining contract pile length since friction resistance in the rock itself is not relied upon; only end bearing is considered.

Pile Extensions

Pile extensions can be very costly and time consuming. Therefore, it is important that the resistance factors and LRFD pile design method compute the contract length conservatively enough to avoid needing extensions as much as possible. The method and factors used for cohesive soils avoid this scenario well. In the projects analyzed, only one bent consisting of nine piles required extensions. The added lengths ranged from 1.25 m (4.1 ft) to 3.84 m (12.6 ft), averaging 2.35 m (7.7 ft). As summarized in Fig. 4, this represents only 2% of the piles in cohesive soils. This low percentage was expected because the verifications performed on the regional LRFD factors prior to implementing the design procedure predicted only 1% of the piles would require additional piling (Ng et al. 2012). This value represents half the percentage of pile extension that would be needed under the interim method. This low percentage is due to accounting for pile resistance gain over time due to setup, allowing the piles to reach capacity at shorter lengths than the ASD method and using lower resistance during driving. The minor amount of extensions needed is highly assuring.

The percentage of pile extensions required in mixed soils was also acceptable. Similar to the cohesive soil category, only one bent including 14 piles, needed extensions of 4.57 m (15 ft) each. That accounts for 2% of the piles, which is considerably lower than the 11% predicted by the verification process for mixed soils (Ng et al. 2014). The percentage of pile extensions for the mixed soil category is small enough to conclude that the resistance factors for mixed soils is sufficient in reducing pile extensions.

For the non-cohesive soil category, no pile extensions were required. With the limited amount of projects available, this result is easily susceptible to change. However, this observation is consistent with findings from the verification process, which determined that only 0.4% of piles in non-cohesive soils would need extensions (Ng et al. 2014). The lack of extensions seems to make sense since the contracted lengths resulting from the LRFD method are generally longer than those previously determined using the ASD method. However, the relatively high amount of retapping is somewhat counter-intuitive.

Piles ending in rock had the largest number of pile extensions. Of the piles considered 132 required extensions, making up 7% of the total piles and 10% of the bents. The average extension length was 3.05 m (10 ft). Since the regional resistance factor calibration performed by ISU did not did not include piling in rock due to the lack of data, no predictions were made for comparison. However, due to high variability in designing and driving through rock, pile extensions were expected to be larger for this category. Of course, pile extensions are expensive and unwanted; but due to the variablility of driving in rock, striving to eliminate pile extensions would be impractical. Having 7% of the piles needing extensions is an acceptable proportion.

Retapping

Retapping is preferable over pile extensions but still undesirable. Retaps are less expensive than adding pile extensions; and as stated previously, only a portion of the bent piles which do not meet the target resistance require retapping whereas all insufficient piles need extensions. Since retaps can add cost to a project through construction schedule delays, only a small percentage of retaps are desirable. The regional LRFD procedure does well in minimizing the amount of retapping required for piles in cohesive soils. As shown in Fig. 4, only six piles (1%) were retapped out of necessity. The portion of bents that required retapping is larger (i.e., 10%) and in some ways more accurately reflects what goes on in the field since retapping is not required for every insufficient pile but is for every bent that has an insufficient pile or piles. However, 10% is still adequately small and lower than what was expected from the verification study, which predicted that about 15% of the piles would likely need retapping (Ng et al. 2012). The gains achieved due to retapping should also be considered. Bents in cohesive soil requiring retaps needed to gain between 1 and 27%) of the resistance at EOD and typically gained 25 to 37% increase in resistance. Since it cannot be established from the averages that retapping was effective in every case, a separate verification was made, which confirmed that retapping was effective 100% of the time. With a small percentage of bents requiring retaps and a high success rate in effectiveness, the regional resistance factors did well to not underestimate the pile length.

Retapping for mixed soils included 50 piles, which represents 7% of the total number of piles in this soil category. These retapped piles spanned 14 of the 40 bents, meaning 35% of the bents required retapping. This is higher than for cohesive soils and is likely due to not incorporating setup into the LRFD design for mixed soils. However, even though one-third of the bents required retapping, this is less than what was expected in the studies done prior to applying the new factors, which estimated 47% would need retaps (Ng et al. 2014). While bents with insufficient resistance at EOD required resistance gains varying between 0 and 95%, retapping achieved 18 to 139% increase as shown in Fig.9. A total of nine retapped piles had resistance exceeding the bearing graph, and thus the actual resistance gain could not be determined. Further examination demonstrated that retapping for mixed soils was 93% effective for bents because two piles did not reach the planned driving resistance after retapping and required pile extensions. The two unsuccessful retaps were from the same bent with the pile extensions as discussed earlier. With the exception of this particular bent, retapping the piles for the mixed soil category was effective in minimizing pile extensions and occurred less frequently than anticipated.

For non-cohesive soils, a total of 14 piles (4%) were retapped. These piles were spread out amongst five of the 12 bents, raising the percentage for bents to 42%. This value is significantly greater than the 15% estimated from the verification study performed prior to implementation (Ng et al. 2014). The pile resistance at EOD was 0 to 99% smaller than required for bents, but increased by as much as 44% during the retaps (Fig.9). Actual percentage increase could not be determined for 8 piles because they either hit refusal or their resistance exceeded the bearing graph during retap. Retapping was 100% effective, thereby eliminating the need for extensions. The relatively high amount of piles requiring retaps suggests the resistance factor for determining contract pile length may still be too high. Nevertheless, every retap was successful in reaching the nominal resistance, and no extensions were needed. Indeed the setup gains in the non-cohesive soil category were surprising.

For pile bearing in rock, the need for and success of retapping were minimal. Only 16 piles were retapped, which accounts for 1% of the total piles ending in rock and 11% of the bents (10 bents). These values were smaller than those observed for piling in mixed and non-cohesive soils. Retapping in rock had the poorest efficiency and was unsuccessful 50% of the time. Bents needed an additional resistance ranging between 8 and 189%, but retapping achieved 0 to 228% resistance increase. The piles which failed to reach the nominal resistance needed pile extensions, further increasing construction cost. In general retapping in rock is only likely to be effective when a significant amount of the pile's resistance is derived through friction in (cohesive) soil layers above the rock since there is more potential for significant setup to occur.

Refusal

When considering refusal, the piles were subsidivided into three cases at EOD: the pile hit refusal, the pile's resistance did not necessarily hit refusal but was too large to be determined from the bearing graphs, and the pile's resistance did not hit refusal and was obtainable from the graphs. Reaching refusal was examined by bents as well. A bent was determined to have reached refusal if 80% or more of the piles within the bent had hit refusal. For cohesive soils, over one-third of the individual piles hit refusal while an additional 22% had high enough blow counts to exceed the bearing graphs. The numbers of bents considered to have reached refusal was 27%. Further investigation involved a review of the soil layers for patterns in hitting refusal but no clear patterns could be inferred. Piles reaching refusal tended to end in firm glacial clay, some with occasional boulders, but piles which did not hit refusal also encountered similar soil compositions based on the soil boring information.

For the mixed soil category, the percentage of pile refusal was the least of all four soil categories with only 7% of the piles hitting refusal and another 8% exceeding the bearing graphs. The majority of pile resistances could still be measured with the charts at the EOD. The amount of bents which reached refusal was even smaller; only 1 pier had more than 80% of its piles reach refusal, accounting for only 3% of the bents. This correlates well with the small cutoff lengths found earlier for mixed soils. With less instances of reaching refusal, more piles could be driven to their full length.

For non-cohesive soils, 44% of the piles analyzed hit refusal, and another 4% were off the bearing charts. The number of bents reaching refusal was 33%. Since the number of piles and bents reaching refusal was relatively high, further investigation into the soil compositions at each bent was undertaken. However, no patterns between soil layers at the pile tips were distinguishable. It is also important to note that, again, there is very little data to examine. The one-third of bents which hit refusal only consists of 4 bents from 3 projects. More projects should be collected to form a more accurate understanding of what is happening in the non-cohesive soil classification.

Not surprisingly a large percentage of piles in the rock category hit refusal. Over half (57%) of the piles hit refusal at EOD with another 19% surpassing the limits of the WEAP graphs. Of the bents examined, 46% had over 80% of their piles reach refusal. This observation coincides with the higher cutoffs and the larger amount of piles reaching the planned driving resistance early.

Reaching Nominal Resistance Early

The last aspect analyzed was how often the nominal resistance was reached early and how much piling could have been saved. Only the logged piles supplied the appropriate information to inspect this portion of the study, limiting the amount of data available since only one logged pile is typically performed per bent. For piles in cohesive soils, the percentage of how often resistance was reached early was 82%. The lengths of pile that could have been saved ranged from 0.40 m (1.3 ft) to 11.28 m (37 ft) and averaged 5.42 m (17.8 ft). A length of 3.05 m (10 ft) or less was regarded as an acceptable amount of extra length for the purpose of this study with input from the Iowa DOT designers. Half of the projects in cohesive soils exceeded this limit. The logged piles were further examined individually to determine if they accurately represented the bents. All four projects that reached the planned resistance considerably early had logged piles that either reached refusal or went off the bearing graphs, further supporting the earlier results that over half of the piles hit refusal or went off the bearing graph at EOD. Moreover, while inspecting the logged piles, the final resistances and cutoff lengths were compared with the other piles in their corresponding bents and were found to be within proximity of each other. This confirms that the logged piles were sufficiently representing the other piles within the bents. The amount of piling that could have been saved due to reaching the target resistance early is significant; however, numerous variables could account for the larger discrepancies. Possible factors could include inappropriate soil classification, inconsistent soil borings at the site, design error in selecting resistance factors, mistakes in interpreting the piling logs due to their variability in formatting, etc. Despite the potential errors, the results from reviewing when nominal resistance was reached indicated that the regional resistance factors were, if anything, conservative even though they are considerably higher than those recommended in the

AASHTO specifications. Improving the resistance factor corresponding to soil setup may reduce the number of piles reaching the target capacity early.

For the mixed soil category, 70% of the piles reached nominal resistance early as shown in Fig.5. A majority of the piling stayed under the 3.05 m (10 ft) benchmark set for this study. The average extra length for which the resistance was reached early was 5.49 m (18 ft). These relatively high averages are due to three projects, which had bents reaching their target resistances 9.75 (18) or more meters (feet) early. These bents were inspected more closely to identify any outliers, but the logged piles appear to adequately represent each bent as a whole. As stated in the analysis for piling in cohesive soils, there are numerous factors which could contribute to the larger differences between the contract lengths and what was required in the field. Besides these three projects, the majority of piling could have only saved less than 3.05 m (10 ft) of length, which suggests that the contract lengths are reasonably accurate.

In non-cohesive soils, only 50% of the piles reached the desired capacity early. From these piles, only an average length of 2.13 m (7 ft) could have been saved. Further investigation into the data validates that the final pile lengths in the structure and the lengths where nominal resistance was reached early are within a few meters of each other for all but one bent. The lengths are also within close proximity to the contracted lengths in the structure. It should be noted that while nearly half of the piles used the full length, most of them were also not reaching the target resistance at EOD, requiring retaps. But as stated before, all retaps were successful and no extensions were necessary.

Since the number of projects for analysis in the rock category was large, a more substantial amount of logged piles were available as well. Of these piles, 83% reached nominal resistance early. Most of the piles could have saved less than 3.05 m (10 ft), averaging 2.87 m (9.4 ft), which is preferable. Considering that designers add length to account for rock's variability and the refusal rate is rather high, it is even more impressive that most of the piles remained under the 3.05 m (10 ft) mark. The six projects that had significant differences were examined, and again, the logged piles adequately represented the bents.

Conclusion

Since 2012, an LRFD procedure for driven piles, modified to fit Iowa's needs based on local soils conditions, has been applied to bridge design projects all across the state. The procedure, which was established through the combined efforts of Iowa DOT and ISU, resulted in the development of regional resistance factors to replace the conservative values provided by AASHTO along with complementary construction control methods. Given that there had only been theoretical verifications performed before implementation of the factors, this paper aimed to review completed pile design projects utilizing the developed LRFD guidelines and assess the new procedure's ability to determine accurate contract lengths for driven piles. Projects were broken down by bent and examined in four categories: friction piles in cohesive, mixed, and non-cohesive soils, and end bearing piles in rock. This study indicated that though the resistance factors can still be refined to more precisely estimate the contract lengths, developing regional factors has proven to be a less conservative alternative to using AASHTO's resistance factors, improving cost-effectiveness of foundation piles. The key findings can be summarized as follow:

1. The regional LRFD procedures for piling in cohesive soils perform well in terms of limiting pile retaps and pile extensions attributable to the incorporation of setup, but the pile length tends to be overestimated, as illustrated by the large percentage of piles reaching the target resistance early. Therefore, the resistance factors are somewhat conservative though still an improvement upon AASHTO's factors.
2. The current resistance factors and design procedure for piles in mixed soils are satisfactory and more accurate than using the national regional factors. The number of piles cutoffs, extensions, and piles hitting refusal were small, ranging from 2% to 7%. With the exception of three of the projects considered, all other piles could have saved less than 3.05 m (10 ft) with a more accurate resistance prediction. Incorporating setup when designing piles in mixed soils could help with reducing the

number of retapping by lowering the required strength at the end of construction as implemented for cohesive soils.

3. Although the resistance factor for non-cohesive soils was reduced from the interim value of 0.725 to 0.55 to meet the target reliability of 2.30, this reduction appears satisfactory when the percentages of pile extension, retapping, pile hitting refusal and pile reaching target resistance early are compared to those established for cohesive and mixed soils. However, it is noted that the sample of projects available was too small and thus a future evaluation of piles in non-cohesive soils is recommended.
4. The lack of data prevented the development of resistance factors for pile bearing in rock. The plan lengths for these piles are harder to predict as reflected in the findings of this study. In general, more subsurface investigations at each project site would better establish the depth to rock and its quality in order to achieve better estimates of pile contract lengths.

Data Availability Statement

Some or all data, models, or code generated or used during the study are available from the corresponding author by request. The data used include bridge project pile logs and boring logs.

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Table 1. Regional Resistance Factors Used to Determine the Contract Length

Theoretical Analysis (1)	Construction Control (Field Verification) (2)					Axial Compression Resistance Factor (3)				
	Driving Criteria Basis		PDA/ CAPWAP	Planned Retap Test 3-Days After EOD	Static Pile Load Test	Cohesive			Mixed	Non-Cohesive
	Iowa DOT ENR Formula	WEAP				φ	φ_{EOD}	φ_{SETUP}	φ	φ
Iowa Blue Book	Yes					0.60			0.60	0.50
		Yes (4)				0.65			0.65	0.55
		Yes (4)	Yes			0.70 (5)			0.70	0.60
		Yes (4)	Yes	Yes		0.80			0.70	0.60
		Yes (4)			Yes	0.80			0.80	0.80

Source: Data from Iowa DOT (2011)
Notes:
(1) Use the geotechnical resistance charts (i.e. soil charts) to estimate the theoretical nominal pile resistance for friction bearing. If soil or rock at the pile tip is capable of end bearing, estimate the theoretical end resistance. Resistance factors in this table apply for friction and end bearing in soil. The resistance factor for end bearing in rock is 0.70.
(2) Use the construction control that will be specified on the plans. Except in unusual cases, the construction control for state projects will be WEAP.
(3) These resistance factors are for redundant pile groups, which the office defines as five piles minimum except four piles minimum for abutments.
(4) Use the Blue Book soil input procedure to complete WEAP analyses.
(5) Setup effect has been included when WEAP is used to establish driving criteria and CAPWAP is used as a construction control.

Table 2. Regional Resistance Factors for Construction Control

Theoretical Analysis (1)	Construction Control (Field Verification) (2)					Axial Compression Resistance Factor (3)				
	Driving Criteria Basis		PDA/ CAPWAP	Planned Retap Test 3-Days After EOD	Static Pile Load Test	Cohesive			Mixed	Non-Cohesive
	Iowa DOT ENR Formula	WEAP				φ	φ_{EOD}	φ_{SETUP}	φ	φ
Iowa Blue Book	Yes					0.55 (6)			0.55 (6)	0.50 (6)
		Yes (4)					0.65 (7)	0.20 (7)	0.65 (7)	0.55 (7)
		Yes (4)		Yes		0.70			0.65	0.55
		Yes (4)	Yes (5)				0.75	0.40	0.70	0.70
		Yes (4)	Yes (5)	Yes		0.80			0.70	0.70
		Yes (4)			Yes	0.80			0.80	0.80

Source: Data from Iowa DOT (2011)
Notes:
(1) Use the geotechnical resistance charts (i.e. soil charts) to estimate the theoretical nominal pile resistance for friction bearing.
(2) Use the construction control specified on the plans. Except in unusual cases, the construction control for state projects will be WEAP.
(3) These resistance factors are for redundant pile groups, which the office defines as five piles minimum except four piles minimum for abutments.
(4) Use the Blue Book soil input procedure to complete WEAP analyses.

(5) Use signal matching to determine nominal driving resistance.
(6) Based on historic timber pile test data, reduce the resistance factor to 0.35 for redundant groups of timber pile if Iowa DOT ENR formula (modified for LRFD) is used for construction control.
(7) For redundant groups of timber pile, reduce the resistance factor to 0.40 without increase for setup if WEAP is used for construction control.

Table 3. AASHTO LRFD Resistance Factors for Driven Piles

Condition	Geomaterial/Resistance Type	Resistance Determination Method	Resistance Factor
Nominal Bearing Resistance of Single Pile—Dynamic Analysis and Static Load Test Methods, ϕ_{dyn}		Driving criteria established by successful static load test of at least one pile per site condition and dynamic testing* of at least two piles per site condition, but no less than 2% of the production piles	0.85
		Driving criteria established by successful static load test of at least one pile per site condition without dynamic testing	0.75
		Driving criteria established by dynamic testing* conducted on 100% of production piles	0.75
		Driving criteria established by dynamic testing,* quality control by dynamic testing* of at least two piles per site condition, but no less than 2% of the production piles	0.65
		Wave equation analysis, without pile dynamic measurements or load test but with field confirmation of hammer performance	0.50
		FHWA-modified Gates dynamic pile formula (End of Drive condition only)	0.40
		Engineering News (as defined in Article 10.7.3.8.5) dynamic pile formula (End of Drive condition only)	0.10
Nominal Bearing Resistance of Single Pile—Static Analysis Methods, ϕ_{stat}	Side Resistance and End Bearing: Clay and Mixed Soils	α-method	0.35
		β-method	0.25
		λ-method	0.40
	Side Resistance and End Bearing: Sand	Nordlund/Thurman Method	0.45
		SPT-method (Meyerhof)	0.30
		CPT-method (Schmertmann)	0.50
	End bearing in rock	Canadian Geotech. Society, 1985	0.45
Block Failure, ϕ_{b1}	Clay		0.60
Uplift Resistance of Single Piles, ϕ_{up}		Nordlund Method	0.35
		α-method	0.25
		β-method	0.20
		λ-method	0.30
		SPT-method	0.25
		CPT-method	0.40
		Static load test	0.60
		Dynamic test with signal matching	0.50

Group Uplift Resistance, ϕ_{ug}	All soils		0.50
Lateral Geotechnical Resistance of Single Pile or Pile Group		All soils and rock	1.0
Structural Limit State		Steel piles See the provisions of Article 6.5.4.2 Concrete piles See the provisions of Article 5.5.4.2.1 Timber piles See the provisions of Article 8.5.2.2 and 8.5.2.3	
Pile Drivability Analysis, ϕ_{da}		Steel piles See the provisions of Article 6.5.4.2 Concrete piles See the provisions of Article 5.5.4.2.1 Timber piles See the provisions of Article 8.5.2.2 In all three Articles identified above, use ϕ identified as "resistance during pile driving"	

Source: Data from AASHTO (2012); AASHTO (2013)

* Dynamic testing requires signal matching, and best estimates of nominal resistance are made from a restrike. Dynamic tests are calibrated to the static load test, when available.

Table 4. Design Chart

Stage	Steps	Description
Design	Step 1	Develop bridge situation plan (or, TS&L, Type, Size, and Location)
	Step 2	Develop soil package, including soil borings and foundation recommendations
	Step 3	Determine pile arrangement, pile loads, and other design requirements
	Step 4	Estimate the nominal geotechnical resistance per foot of pile embedment
	Step 5	Select resistance factor(s) to estimate pile length based on the soil profile and construction control
	Step 6	Calculate the required nominal resistance, R_n
	Step 7	Estimate contract pile length, L
	Step 8	Estimate target nominal pile driving resistance, $R_{ndr\text{-}T}$
	Step 9	Prepare CADD note for bridge plans
	Step 10	Check the design
Construction	Step 11	Prepare bearing graph
	Step 12	Observe construction, record driven resistance, and resolve any construction issues

Source: Data from Iowa DOT (2011)

Table 5. Summary of Projects

Project Summary	Cohesive	Mixed	Non-Cohesive	Rock	Total
Number of Projects*	10	15	8	25	47
Number of Bents	30	40	12	91	173
Number of Piles	481	718	326	1945	3470

*Eleven projects had bents divided amongst multiple soil categories and were included twice.

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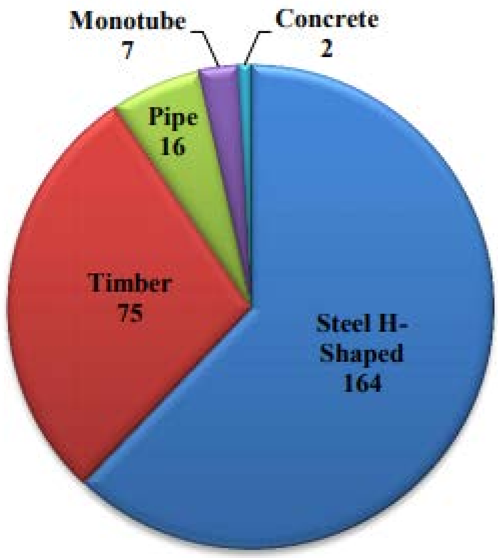
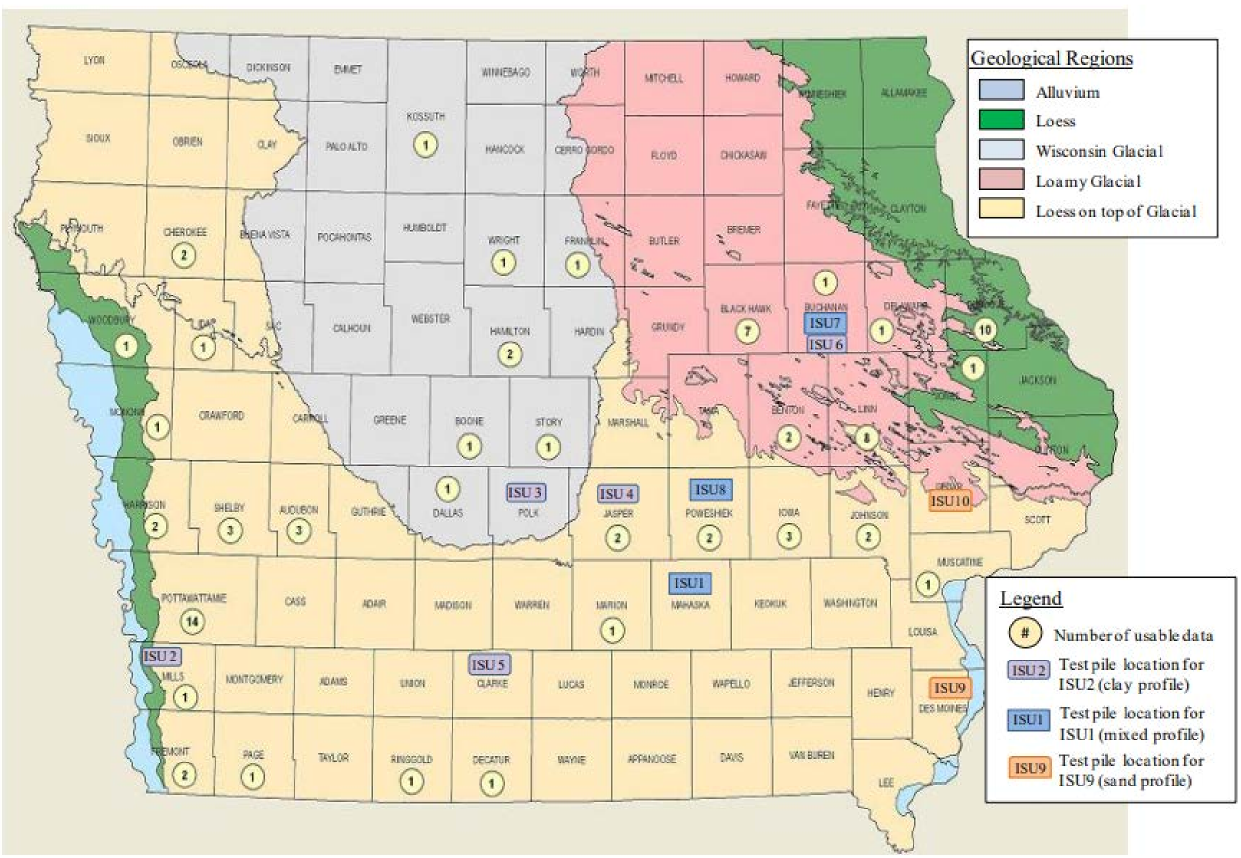


Fig. 1. Distribution of Iowa Past Pile Static Load Tests by Pile Type (Data from Roling et al. 2010)



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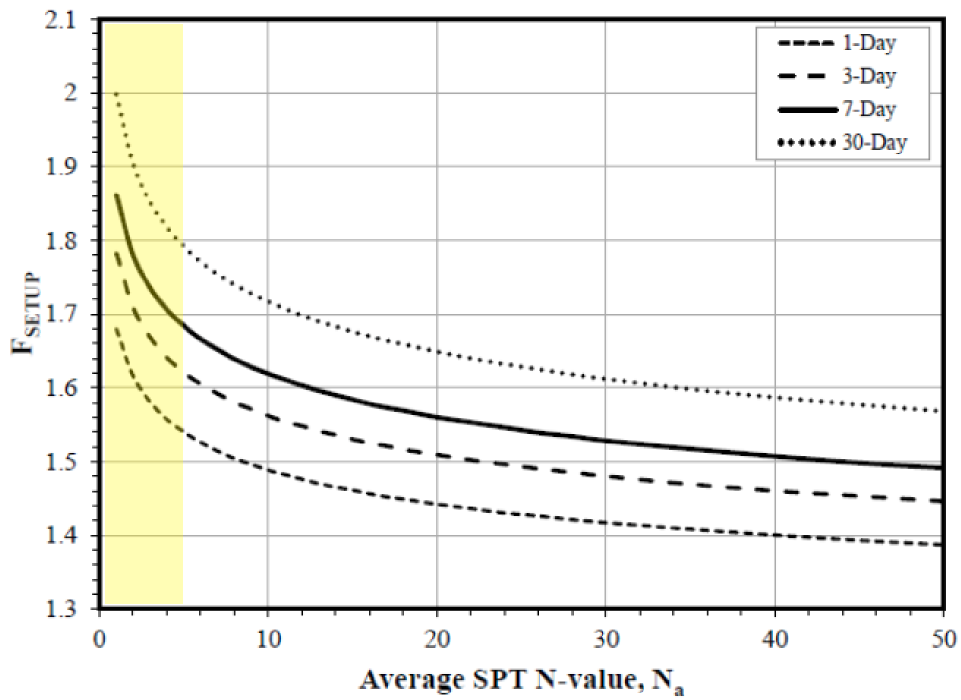

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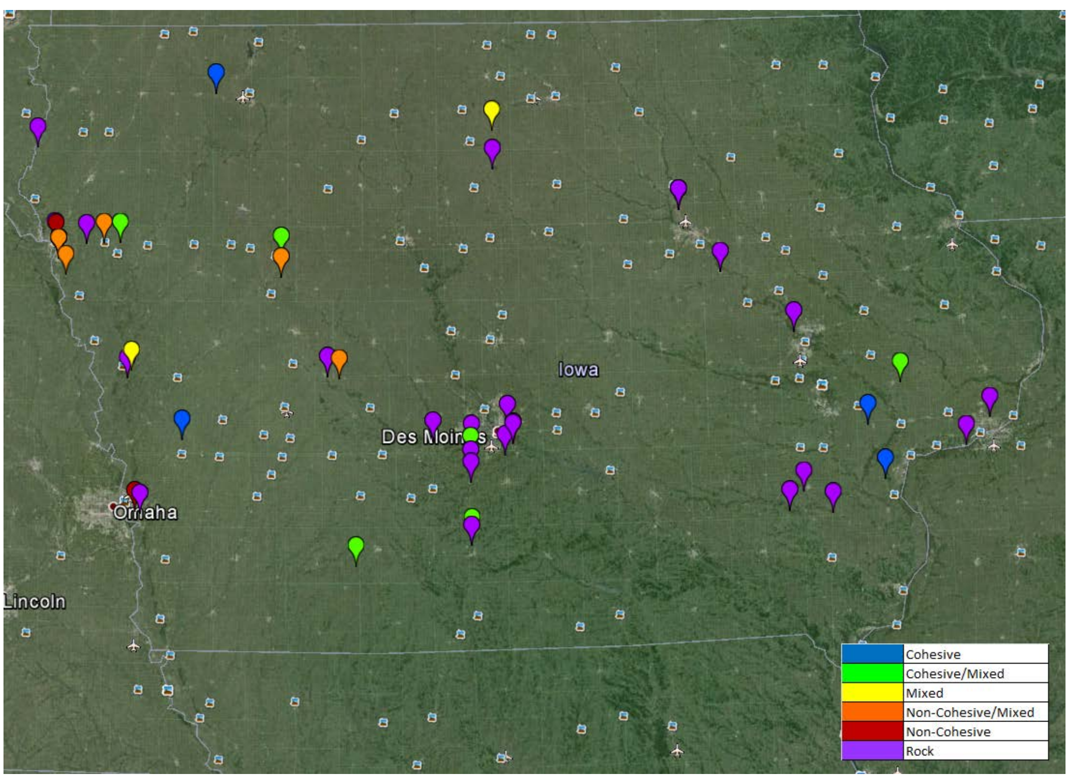

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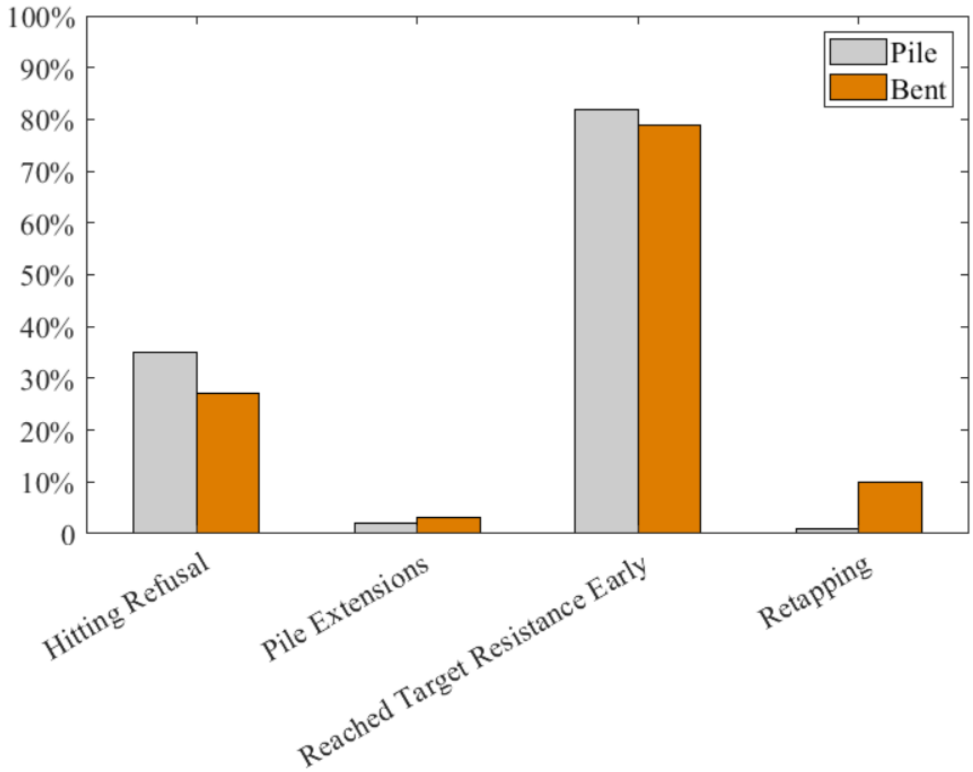
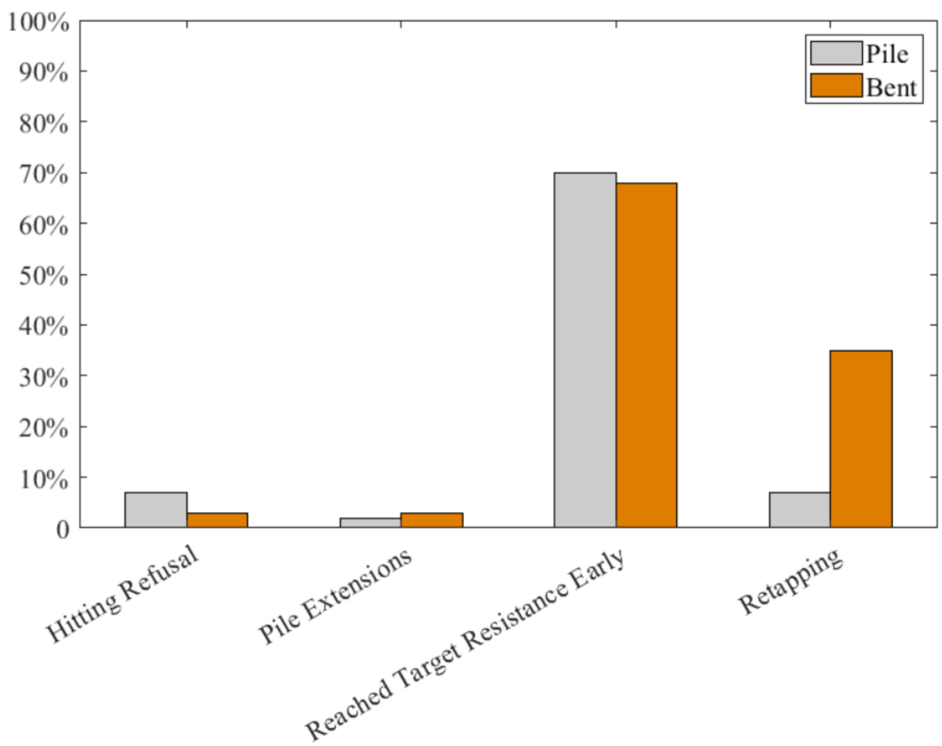


Fig. 5. Percentages of Variables Examined For Piling in Cohesive Soils



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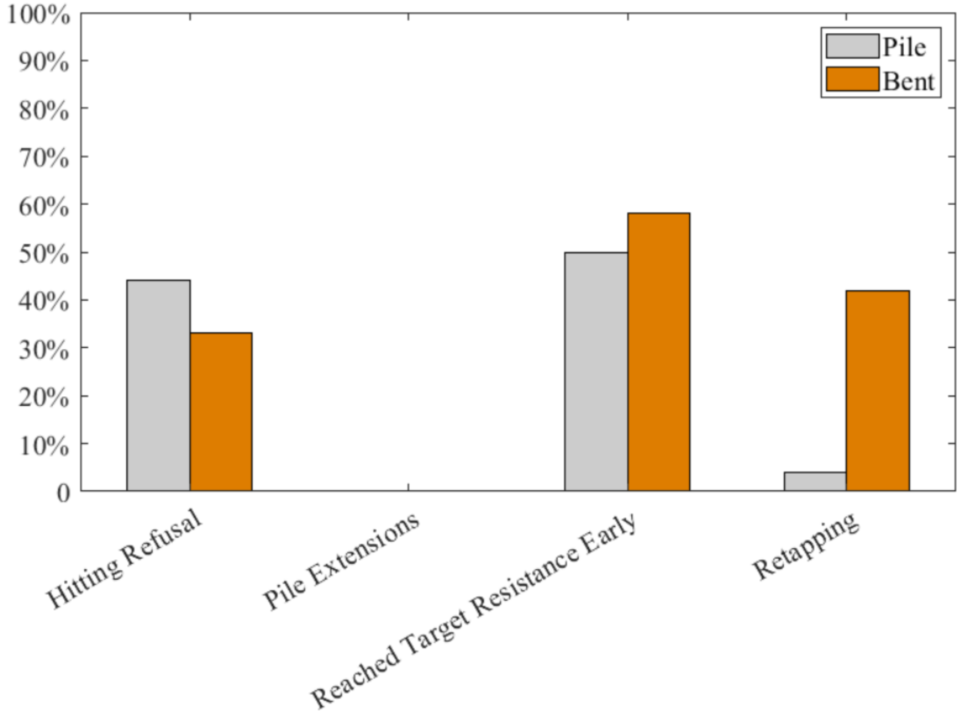

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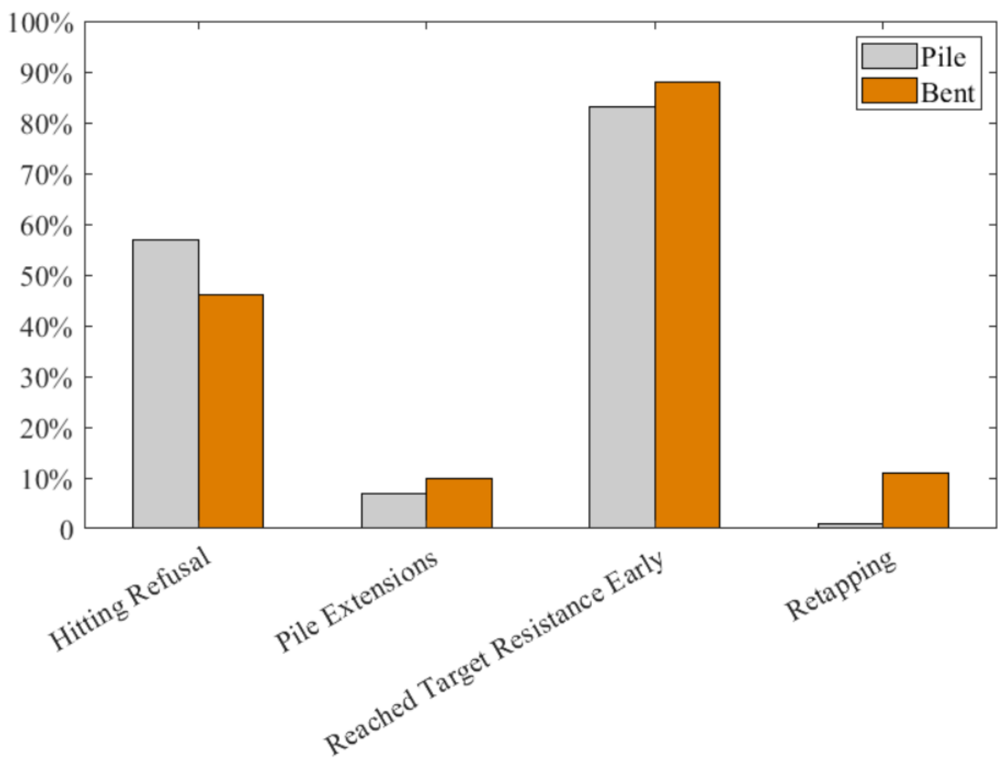

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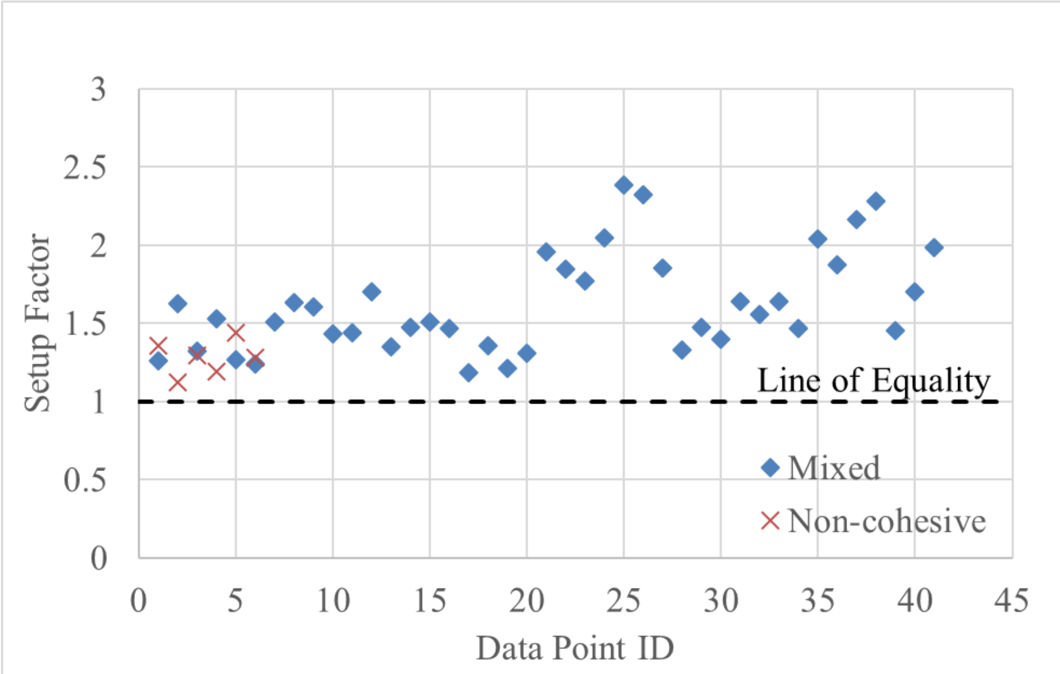

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