Insights into Plugging of Pipe Piles Based on Pile Dimensions

Antonio Kodsy and Magued Iskander

Civil and Urban Engineering Department, Tandon School of Engineering, New York University, New York, NY 11201, USA; kodsy@nyu.edu
* Correspondence: iskander@nyu.edu

Abstract: Preliminary identification of plugging of open-ended pipe piles based on their dimensions, ahead of driving, is explored in this study using data analytics. Piles can be unplugged, plugged, or internally plugged, depending on their dimensions, and geotechnical conditions. Plugging of pipe piles influences both pile capacity and driving behavior; however, the classification assumed at the design time does not always manifest during driving, sometimes resulting in driving difficulties. The relationship between pile plugging and pile dimensions was investigated using a dataset of 74 load tests on pipe piles, where geotechnical profiles were also available. An analytics approach borrowed from data science was adopted. First, capacity was computed using four recognized designed methods considering the unplugged, plugged, and internally plugged conditions. Next, the calculated capacities were compared to capacities measured (interpreted) from static load tests. Finally, voting was employed to identify plugging based on the closeness of the computed capacity assumptions to the interpreted capacity. Most piles were found to be unplugged. A diameter criterion is proposed as a tool to give early insight into the plugging condition of a pile ahead of driving which resulted in a 70 ± 10% accuracy. The proposed criterion was validated once using a dataset of 23 piles with CPT data and a second time using 24 published driving records where plugging records were available and achieved similar accuracy, in both cases. It was concluded that piles larger than ~0.9 m (36 inches) in diameter have a higher likelihood of being unplugged, while piles smaller than 0.5 m (20 inches) have a higher likelihood of being plugged.

Keywords: deep foundation; resistance; L/D ratio; length; diameter; data-driven decisions; data science; data analytics

1. Introduction

Pipe piles are routinely used to support a variety of structures ranging from residential and commercial structures to infrastructure projects. As a result, and due to the vast differences in soil conditions, these piles are used with a wide range of diameters and lengths. During installation of open-ended pipe piles, initially, the pile penetrates the soil in a coring mode where the soil enters the pile at an equal or higher rate to the rate of pile penetration. As penetration advances, the pile may become plugged if the soil core inside the pile develops ample frictional resistance along the inner pile wall, impeding further soil incursion inside the pile. Technically, the soil core is typically referred to as a “plug” only when it is wedged against the pile, thus preventing any additional soil entry into the pile. Unfortunately, the term plug has often been used to refer to the core regardless of its state during installation [1].

The driving response of piles is affected by the plugging condition [2], which makes their dynamic analyses more intricate [3]; however, plugging is perhaps more crucial since it directly contributes to the end bearing capacity of the pile. In addition, plugged piles displace more soil than unplugged piles, which consequently increases the effective stresses around the pile [4], thus indirectly contributing to the shaft capacity.

Generally, the majority of piles that experience plugging during static loading do not plug during driving [5]. This could be attributed to a combination of an increase in
the bearing capacity factor, \( N_q \), over its static value due to inertial effects [6]; moreover, Smith et al. [7] claimed that the internal and external friction of a driven pile is mobilized intermittently during penetration, and therefore, the soil core advances up the pile. Contrarily, Paikowsky et al. [8] argued that during driving, “the pile plugging phenomenon is of frequent occurrence and is of greater significance than that presently accorded it by the profession”. Nevertheless, the plugging degree relies on the soil properties, pile dimensions, the pile’s frictional resistance, the driving hammer characteristics, and the plug drainage conditions [9,10]. The ability of the plug to resist the applied loads depends on whether these loads are static, cyclic, or seismic [11].

On some occasions, a situation may arise where the available pile driving hammer cannot drive the pile to the design depth, which could stem from the pile being plugged and impeding the driving. The problem is more critical for piles used to resist lateral loading, or more generally, piles with thickened walls near the surface [12]. The installation technique used can also impact the plugging of the piles [13]. Henke and Grabe [14] suggested that piles installed using dynamic methods, such as vibratory driving or impact driving, exhibit less plugging compared to jacked piles. They later showed that piles installed using impact driving also exhibit plugging [15], in contradiction with the earlier findings of Randolph [16] who concluded that no soil plug is formed inside impact-driven open-ended piles and attributed that to the inertia of the soil column inside the pile. If a plug forms during pile installation, the plug may be removed by drilling or jetting; however, this negatively affects the axial capacity and is therefore undesirable.

The effects of the soil plug removal on the final pile capacity are controversial. Brucy et al. [17] claimed that static loading results remain unchanged by partially removing the soil plug. Other studies have shown that, even if the pile is re-driven, a significant reduction in the overall pile capacity results from jetting [18]. More recent studies also show that removing the plug decreases the pile capacity by 45% to 79% in sand specifically [19]. Therefore, it is necessary to understand the conditions that may lead to plugging, in order to avoid them; or to have an appropriate hammer available to drive the pile to the required depth.

Pile plugging could be quantified using the Incremental Filling Ratio (IFR), which represents the amount of soil plugging in a pile, or the Plug Length Ratio (PLR), which is a global indicator of pile plugging, that is easier to measure at the end of driving [20]. IFR and PLR are not necessarily correlated, especially because IFR can change rapidly from near zero to much greater values, or vice versa, while the PLR remains largely unchanged [21]. Methods to predict and account for pile plugging on capacity based on the IFR and PLR have been proposed by Paik and Salgado [3], Yu and Yang [22], and Jeong et al. [23]. In addition, methods to predict the contribution of the plug to the pile capacity have also been developed [24,25]; however, the required information is typically not available during initial design required to size piles.

The relationship between pile plugging and geometrical properties of the pile such as diameter (D), length (L), and L/D was also explored. The occurrence of plugging was identified using load test data. Interpreted (measured) capacities are compared to the computed capacities for the three plugging conditions: (1) Plugged, (2) Unplugged, and (3) Internal Plugged. The plugging condition during loading is assumed to be that which corresponds to the calculated capacity from one of the three aforementioned conditions and is closest to the interpreted capacity.

This study employs data-driven decisions to identify plugging. In the past, other studies have employed experimental and theoretical approaches and the matter remains unresolved, thus we employed tools of data science. The onset of plugging is identified by comparing the measured (i.e., interpreted) pile capacity to that obtained from static analyses; however, there is a great difference between the pile capacities computed with the many available design methods. Therefore, four commonly used design methods were employed, and the analysis was repeated separately for each design method. Next, the plugging condition is identified via simple voting from the four methods. Finally, a methodology is
proposed to forecast the plugging condition of a pile based on its geometrical dimensions in an effort to shed some light on the pile plugging phenomenon.

2. Load Test Data

A dataset of 74 piles compiled from the FHWA Deep Foundation Load Test Database (DFLTD) v.2 [26] and Olson’s Database [27–30] was employed in this study. Dimensions of piles employed for analysis along with associated soil conditions are summarized in Appendices A and B, for DFLTD and Olson databases, respectively. These load tests were ported to a relational database for easy access [31]. The scope of this paper was limited to statically loaded steel pipe piles and hollow concrete piles with ample soil profile data for capacity calculations ($Q_c$), and interpretable compression load tests for capacity measurement ($Q_m$). The piles ranged between 0.25–2.54 m (10–100 in) in diameter and 7.5–113 m (24.6–370 ft) in length. The distribution of the diameter and length of the studied piles is shown in Figure 1. A summary of the bearing layer of the piles in the dataset is also shown in Figure 1, showing that nearly 65% of the pile toes employed in this study bear in sand, while approximately 35% bear in clay. All load tests were carried in compression according to ASTM D1143 [32], but information regarding the time duration between installation and load testing was not always available.

![Figure 1. Distribution of pile diameter and length of load tests employed in this study. The distribution of the bearing layer is also depicted in the top right.](image)

Missing or misinterpreted data is one of the dominant issues when dealing with geotechnical databases. Therefore, all the soil data associated with the chosen piles were reviewed by the research team to check its integrity and usability. Available geotechnical design parameters were employed to compute $Q_c$ where possible, but many pile cases lacked sufficient measurements, so the team used empirical relationships from established guidelines such as those provided by The Naval Facilities Engineering Command Design Manual 7.01 [33] and Peck et al. [34] to supplement laboratory data. More details about data handling are available in Rizk et al. [35].
3. Plugging and Capacity

The ultimate bearing capacity of the pile \( Q_c \) is typically calculated by adding the shaft resistance \( R_s \) and the toe resistance \( R_t \). Open-ended piles experience one of three possible plugging conditions: (i) unplugged, (ii) plugged, or (iii) internal plug. Designers are typically unable to predict which condition will prevail, and thus check all conditions and adopt the minimum capacity as a conservative approach. Paikowsky and Whitman [20] presented equations to calculate the pile capacity if the pile is plugged (Equation (1)) or if the pile is partially plugged or unplugged (Equation (2)).

\[
Q_c = \sum f_{so} A_{so} + q_p A_{pp} - W_p \\
Q_c = \sum f_{so} A_{so} + \sum f_{si} A_{si} + q_p A_p - W_p
\]

where \( f_{so} \) is the exterior unit shaft resistance, \( A_{so} \) is the pile exterior surface area, \( q_p \) is the unit toe resistance, \( A_{pp} \) is the cross-sectional area of the pile and soil plug at pile toe \( \left( \pi D^2 / 4 \right) \), \( D \) is pile outer diameter, \( f_{si} \) is the interior unit shaft resistance, \( A_{si} \) is the pile interior surface area, \( A_p \) is the pile toe cross-sectional area \( \left( \pi (D^2 - D_i^2) / 4 \right) \), \( D_i \) is pile inner diameter and \( W_p \) is the weight of the pile and soil plug.

In the unplugged condition, the pile is assumed to behave as a “cookie-cutter” coring through the soil without exhibiting internal friction. The pile capacity is the summation of exterior skin friction and end bearing of the pile annulus section (i.e., \( f_{si} \) in Equation (2) is taken as 0). For the plugged condition, the pile is assumed to behave as a full displacement pile and hence the capacity is the summation of exterior skin friction and end bearing of the entire toe area (Equation (1)). Finally, in the internal plug condition, it is theorized that the pile might experience interior skin friction. The capacity is taken as the summation of exterior skin friction and the lesser of: (1) the end bearing of the entire toe area; or (2) the end bearing of the pile annulus section plus the interior skin friction. Interior skin friction \( (f_{si}) \) is typically taken as 40% of the exterior skin friction \( (f_{so}) \) in cohesive soils, and as 100% of the exterior skin friction in cohesionless soil \( (f_{si} = f_{so}) \) [36].

4. Pile Design Methods Employed for Identification of Plugging

Four classic design methods are implemented in this study for the purpose of computing the capacity \( Q_c \), namely: (1) United States Federal Highway Administration, FHWA [36]; (2) United States Army Corps of Engineers [37]; (3) Revised Lambda [38,39]; and (4) American Petroleum Institute [40]. These four methods were chosen for their wide acceptance and use by many institutions and engineering firms. Many of the design methods have well-recognized limitations, which may potentially be addressed through stochastic analysis; however, this is beyond the scope of this work. This study is addressed primarily to practicing engineers, and therefore focuses on using the available design methods and design tools. Comprehensive description of these design methods can be found in Reese et al. [41], Hannigan et al. [36], or Wang et al. [42]. Note that more recent design methods require the use of CPT data, which were not available for the majority class of the data. Thus, these four classic methods were used to develop the methodology and for CPT methods were used for validation. The following is a brief description of the similarities and difference between the methods.

4.1. Federal Highway Administration (FHWA) Method

For piles smaller than 18 inches in diameter, the FHWA recommends using the \( \alpha \)-method [43] for cohesive soils and the Nordlund method [44] for cohesionless soils. The \( \alpha \)-method applies a reduction factors that are directly proportional to the undrained shear strength \( s_u \) for cohesive soil to calculate the adhesion between the pile side and the surrounding soils. It also provides other reduction factors to account for drag-down, a phenomenon that occurs during pile driving in mixed soil profiles and results in a side resistance reduction. For the cohesionless soils, the Nordlund method, detailed in
Hannigan et al. [36], uses several complex charts to account for the effects of pile type, taper, slenderness ratio, material, friction angle, and soil displacement to acquire the design parameters.

4.2. United States Army Corps of Engineers (USACE) Method

The USACE method suggests that the pile skin friction increases linearly up to an assumed critical depth ($D_c$) and remains constant below that depth in cohesionless soils [43]. $D_c$ depends on the relative density of sand and the pile diameter. Similar, but not identical, to the FHWA method, the USACE employs the $\alpha$-method and bearing resistance for cohesive soils.

4.3. Revised Lambda Method

Kraft et al. [39] revised the original Lambda method after it was deemed “grossly conservative by industry” [45]. The pile penetration coefficient $\lambda$, employed by the original Lambda method for side friction in cohesive soils, was revised to account for the relative pile stiffness by proposing that $\lambda$ be made a function of the term $\pi_3$ [46], which describes soil’s compressibility normalized by the pile’s compressibility. For the cohesionless soils, APILE converts the sand layers in a soil profile to equivalent clay layers and computes the side resistance using the same set of equations. Additionally, no equations for toe resistance in all soils have been proposed by the Revised Lambda method. Hence, the APILE software computes the end bearing in sands and clays using the equations proposed by the API method.

4.4. American Petroleum Institute (API) Method

Obtaining the soil properties for the design of offshore platforms can be difficult. This was the motivation behind developing the API RP2A [40], which depends on visual description of soils. For cohesive soils, the API method uses the $\alpha$-method for side resistance similar to the FHWA and USACE methods, but uses its own set of equations to calculate the adhesion between the piles sides and the surrounding soil based on the ratio of undrained shear strength ($s_u$) to effective overburden stress. For cohesionless soil, the API method uses a table that presents friction angles and skin friction limits to aid in computing the skin friction based on the sand classification (gravel, sand, silt), and the relative density of the soil. The table also provides end bearing limits and a bearing capacity factor, $N_q$, for computing the end bearing.

5. Analysis

ENSOFT’s APILE Offshore 2019 software [42] was utilized for all capacity computations. APILE was selected because: (1) the design methods are pre-programmed; and (2) it is widely used among practicing geotechnical engineers. Some design methods, employ plugging assumptions inherent to their formulation. Nevertheless, APILE calculations were carried out assuming the three aforementioned plugging conditions. The authors decided to use the pre-programmed design methods in APILE to: (1) help ensure that the results are easily adopted in practice, (2) comply with the current practice; and (3) avoid claims of possible computational errors by the authors.

The authors also used python scripts to: (1) automatically generate input files for the analysis from the database; (2) extract results from APILE output files; and (3) combine the results in a single spreadsheet. This was done to automate the analysis process and speed up the calculation process.

Interpreted (measured) capacities ($Q_m$) were obtained from the load-settlement curves using the NYU interpretation criterion [47,48], where the capacity is that corresponding to the smallest of the following settlements: (1) the load corresponding to a settlement equal to the elastic shortening of the pile ($\Delta L_E$) plus 0.75 inches (20 mm) per the 2014 New York City Building Code; (2) 5% of the pile diameter; or (3) settlement corresponding to
first incidence of plunging or strain-softening resulting in loss of more than 5% of capacity. Calculated and computed capacities are summarized for the 74 piles in Appendix C.

5.1. Performance of Design Methods

All capacities presented in this study are unfactored (i.e., Characteristic) capacities. Calculated capacities ($Q_c$) using the four chosen design methods were plotted versus the interpreted capacities ($Q_m$) obtained from the NYU criterion for all possible plugging conditions in Figure 2. The 1:1, 1:2, and 1:0.5 lines were also plotted to underline the ideal relation between $Q_c$ and $Q_m$ and its boundaries. The 1:1 line represents an ideal scenario where $Q_c$ is equal to $Q_m$, while the 1:2 line and the 1:0.5 line indicate over or underestimation by a factor of 2, respectively. Additionally, key statistics are listed for each design method, such as the mean, standard deviation, and the coefficient of determination ($R^2$). The mean and standard deviation are the descriptive statistics describing the data distribution with the mean representing the central value, and the standard deviation representing the variation in the data. $R^2$ is used to describe how well the fitted line, the 1:1 line, in this case, captures the behavior of the real data. Note that $R^2$ can have a negative value when the model selected does not follow the trend of the data. This can be clearly noticed in Figures 2 and 3 for the FHWA design method in the unplugged condition, where it is clear that the 1:1 line (chosen model) does not follow the trend of the data (red dots).

**Figure 2.** Calculated ($Q_c$) vs. interpreted (aka measured, $Q_m$) capacities for all plugging conditions for each design method. Statics of $Q_c/Q_m$ are shown in the inset tables.
Figure 3. Calculated ($Q_c$) vs. interpreted (aka measured, $Q_m$) capacities for the best plugging conditions for each design method. Statics of $Q_c/Q_m$ are shown in the inset tables.

A uniform datum of comparison between the performance of the various methods was established by normalizing the calculated capacities by the interpreted capacities ($Q_c/Q_m$), for each test, which also helps to better visualize the target value of 1. Values higher than 1 indicate that the design method is over-estimating the pile capacity, while values less than 1 indicate that the design method is conservative in its capacity estimation.

5.2. Identification of Plugging Based on $Q_c/Q_m$

The best-calculated capacity and the associated plugging condition were determined using each design method for each pile individually. This was determined based on the performance of $Q_c/Q_m$ and how close is the value to the ideal value of 1. For example, for a certain pile, if the $Q_c/Q_m$ values for a design method for the unplugged, plugged, and internal plug conditions were 1.10, 1.85, and 1.47, respectively, it was assumed that this pile was unplugged since 1.10 is closest to the ideal value of 1.00.

The measured capacity ($Q_m$) was plotted versus the best-calculated capacity ($Q_c$) in Figure 3 along with the identified plugging condition which helps identify the overall performance of all design methods and their average. It is noteworthy that the data showed significant scatter with a standard deviation ranging between 0.53 and 1.01. The scatter is attributed to a combination of factors including (1) significant variation in the calculated...
capacities using the different plugging conditions and design methods, (2) quality of the geotechnical data, (3) differences in the procedures employed to conduct the static load tests; and (4) absence of information related to pile setup. Nevertheless, Figure 3 was considered as the reference for comparing any guidance resulting from this analysis, since it represents the best achievable performance given the available data. Once again, inset tables summarize the plugging condition as well as the overall performance of each design method are presented in Figure 3. Several observations are possible. First, the majority of cases are classified as unplugged. Second, only a few cases are classified as internal plug, with only 3–12% of cases being classified as internal plug. Finally, the data in Figure 3 exhibit less scatter than Figure 2, but that is to be expected.

The data in Figure 3 represent the capacity corresponding to the plugging condition closest to the interpreted value, for each design method. It was observed that the unplugged condition had superior performance compared to the other plugging conditions. This was further investigated and statistically proven for large diameter open-ended piles in the analysis presented by Rizk et al. [49].

Design methods did not always agree on whether a pile is plugged, unplugged, or internally plugged, so a voting system was used to identify the onset of plugging based on the majority of votes by the four design methods.

5.3. Relationship between Plugging Condition and the Pile Diameter, Length, and L/D Ratio

Paikowsky et al. [8] concluded that beyond a certain penetration depth to diameter ratio (L/D) most piles plug. Ko and Jeong [50] also determined that as the pile diameter increases, open-ended piles tend to become unplugged; however, these studies did not examine a large number of piles. Thus, the relationship between the plugging condition and piles’ geometric properties namely diameter (D), length (L), and L/D ratio was explored in Figure 4, where piles are tagged by their voted overall plugging condition. It should be noted that important information needed to investigate plugging, such as the Plug Length Ratio (PLR), and the Incremental Filling Ratio (IFR) was not available in the databases. Hence, the discussion herein is limited to observed $Q_p/Q_m$ values and their respective pile properties.

![Figure 4](image-url)

Figure 4. Relationship between: (a) L/D ratio and pile diameter, (b) L/D ratio and pile length, and (c) pile length and diameter, for the average $Q_p/Q_m$ ratio, by the best plugging condition for each pile.

The L/D ratio was plotted against the pile diameter in Figure 4a. Multiple observations were made. It was observed that piles larger than or equal to ~0.9 m (36 in) in diameter are likely to be unplugged (31 out of 39 cases), irrespective of L/D ratio, while piles with diameters less than 0.5 m (20 in) are likely to be plugged (12 out of 15 cases), which is expected since small diameter piles have a higher likelihood of being plugged and vice versa. This observation has critical implications for the design of large diameter open-ended piles (LDOEPs), since these are typically defined as piles larger than 36 in (~0.9 m) in diameter. It was also noted that the piles in between vary in terms of plugging conditions,
which suggests that this could be a transition zone between the plugged and unplugged conditions. This is shown in the figure where the shading represents the transition from a zone of plugged high likelihood, to a transition and uncertain zone, and finally a high likelihood unplugged zone. The authors also attempted to separate unplugged from internal plug, as well as internal plug from plugged; however, this was difficult due to the small number of load tests (8 cases) coded as internal plug. Using these two major zones, nearly 80% of the cases in these zones were identified correctly, which is encouraging.

The relationship between L/D and length for all piles under consideration coded by the voted plugging conditions is presented in Figure 4b. Similarly, the relationship between length and diameter is presented in Figure 4c. It was observed that the majority of the plugged piles are small diameter piles with low L/D ratios (L/D <~ 50). No further pattern of plugging is discernable, as the data scatter makes it hard to make conclusive observations regarding pile plugging. In particular, the available data do not support the popular notion that most piles plug beyond a certain L/D ratio. Notably, Paikowsky et al. [8] suggest that piles with L/D smaller than 75 are unlikely to plug, but it is difficult for us to agree considering the data presented in Figure 4. In addition, prior studies suggest that when a pile plugs, load is transferred by arching to the inner pile surface within the first two pile diameters [51]; thus, it was concluded that soil, driving, and load testing conditions have significant effects on plugging of piles, and recommendations based solely on length or L/D are difficult to formulate based on the available data.

5.4. Relationship between Plugging Condition and Soil Information

The relationship between the plugging condition and soil properties was investigated next. Histograms for the voted plugging condition with respect to the predominant soil type along the pile length and the bearing soil layer are presented in Figure 5a,b, respectively. The predominant soil type was determined by taking the weighted average of the heights of the soil layers along the depth of the piles. Predominant soil types were classified into three arbitrary groups depicting sand (0–30% clay), mixed soils (30–70% clay) and clayey soils (70–100% clay). Once again, no clear inference could be drawn, except that (1) piles bearing in sand had a higher tendency to be unplugged, which could be attributed to the frictional resistance of clay, increasing the likelihood of the pile being plugged in clay; and (2) that the predominant soil type does not materially influence the analysis. This observation is somewhat surprising, and the occurrence of plugging in sand is likely related to its relative density, a factor that is not accounted for in Figure 5.

![Figure 5.](image)

Figure 5. Histograms of (a) the predominant soil type, and (b) the bearing soil layer for each plugging condition.
6. Proposed Interaction Diagram for Plugging

6.1. Development of Interaction Diagram

The authors explored if plugging could be better forecasted using an interaction diagram that separates piles into two zones (plugged and unplugged) based on both the values of the pile diameter and the L/D ratio. Multiple interaction diagrams with D = 0.5–1.78 m (20–70 in) and L/D = 75–125 were explored (121 interaction diagrams in total), and their performance was evaluated by computing the number of cases correctly forecasted based on the voted overall plugging condition. The authors also explored the use of two lines to separate the cases into three zones representing plugged, internally plugged, and unplugged; however, the accuracy was lower than using a single line separating the plugged from unplugged conditions. This could be attributed to the small number of internally plugged cases.

The highest achieved forecasting accuracy using an interaction diagram was 74.3% (55 out of 74 cases forecasted correctly) and was achieved by five possible lines. These five lines are plotted in Figure 6a where the shaded zone is where the piles are likely to be plugged. The initial proposal was to find the line with the highest accuracy and use it; however, upon finding 5 lines achieving identical accuracies, it was theorized that the area created by the union of these 5 lines would give more confidence in the likelihood of the plugging occurrence. This union zone is presented in Figure 6b along with the associated accuracy.

The authors theorized that the area created by the union of these 25 lines would give more confidence in the likelihood of the plugging occurrence. This union zone is presented in Figure 6d along with the associated accuracy.

![Figure 6. Performance of various interaction diagrams for forecasting pile plugging based on pile dimensions. (a) The top performing 5 interaction diagrams; (b) The union zone created by the top 5 interactive diagrams and their respective accuracy; (c) The top achieving 25 interaction diagrams; (d) The union zone created by the top 25 interactive diagrams and their respective accuracy.](image-url)
The second highest accuracy was 73% (54 out of 74) and was achieved by 20 possible lines. All 25 lines are plotted in Figure 6c, where the shaded zone is where the piles are likely to be plugged. Again, upon finding 25 lines achieving nearly identical accuracies, it was theorized that the area created by the union of these 25 lines would give more confidence in the likelihood of the plugging occurrence. This union zone is presented in Figure 6d along with the associated accuracy.

6.2. Diameter Criterion

Using both interaction diagrams resulted in the same accuracy of 74.3%, which means that the plugging condition of the pile could be forecasted approximately 3 out of 4 times. This occurs because no interaction diagram was able to increase the rate of positive identification of plugging while reducing the rate of false identification. A much larger dataset is likely needed to overcome this challenge. At any rate, interaction diagrams do not represent an improvement over using the straightforward diameter criterion (Figure 4a). Hence, the authors chose the original diameter criterion proposed in Figure 4a for a couple of reasons. First, the diameter criterion is a more discreet and intuitive concept, and easier to comprehend. Second, the diameter criterion resulted in a higher accuracy, rendering the Diameter–L/D interaction diagram inferior to the diameter criterion.

6.3. Testing of the Diameter Criterion & Interaction Diagram

DFLTD contained 23 tests where CPT data were available [Appendices A and B]. These load tests were initially excluded from the analysis because they lacked the SPT data required for computing the capacity using the FHWA, USACE, Revised Lambda, and API design methods. Therefore, the author used these 23 cases to test the diameter criterion (Figure 4) and the interaction diagrams (Figure 6). A similar methodology and voting routine were used and APILE was again utilized. Four CPT design methods were employed namely: (i) the Norwegian Geotechnical Institute (NGI) method [52,53]; (ii) the Imperial College Pile (ICP) method [54]; (iii) the Fugro method [55]; and (iv) the University of Western Australia (UWA) method [56]. It is essential to acknowledge that, while APILE employs FUGRO-04 and UWA-05, updated methods (FUGRO-10, and UWA-13) have since been developed. Some design methods employ plugging assumptions inherent to their formulation. Nevertheless, APILE calculations were carried out assuming the three aforementioned plugging conditions [Appendix D]. The authors decided to use the pre-programmed design methods in APILE to: (1) help ensure that the results are easily adopted in practice, (2) comply with the current practice; and (3) avoid claims of possible computational errors by the authors.

The capacities corresponding to the three plugging conditions and their statistics for the four CPT methods are presented in Figure 7. On average, the performance statistics in terms of average $Q_c/Q_m$ and its standard deviation (Target 1 and 0) is somewhat better than the classic methods presented earlier (Figure 3), but scatter between measured and calculated capacities persists.

The relationship between L/D and diameter for all CPT tests is presented in Figure 8, with the presumed plugging condition obtained via voting identified using the symbols U for unplugged, P for plugged. The diameter criterion and the two previously identified interaction diagrams are also superimposed on the data. One difference is that the CPT methods can in fact identify internal plugged cases and two piles were identified as internally plugged. These two cases are shown in the figures, designated by the letter I, but excluded when computing accuracy. The accuracy of the diameter criterion was found to be 60% while the accuracy of the two interaction diagrams was found to be 60.9% and 56.5%. These results suggest that the diameter criterion offers results that are as good as the interaction diagrams. More importantly, it suggests that the accuracy of the diameter criterion is in the order of 70 ± 10%.
The relationship between L/D and diameter for all CPT tests is presented in Figure 8, showing the correlation between these parameters. The authors performed sensitivity analyses and the results of the analyses remained consistent with the proposed criterion. The new piles in the test dataset ranged in diameter from 0.33 to 1.58 inches.

Validation of the Proposed Diameter Criterion

Figure 7. Calculated (Qc) vs. interpreted (aka measured, Qm) capacities for the best plugging conditions for the CPT design methods. Statics of Qc/Qm are shown in the inset tables.

Figure 8. Testing the performance of the diameter criterion and two interaction diagrams using a dataset of CPT piles (a) The proposed diameter criterion and its respective accuracy; (b) The proposed interaction diagram created by the union of the top 5 interactive diagrams and its respective accuracy; (c) The proposed interaction diagram created by the union of the top 25 interactive diagrams and its respective accuracy.

7. Validation of the Proposed Diameter Criterion

The performance of the diameter only criterion was validated using 24 published load tests where in-situ plugging performance was reported. None of these piles were...
employed previously in our analyses, so this represents a true arm’s length check on the proposed criterion. The new piles in the test dataset ranged in diameter from 0.33 to 1.58 m (13–62 inches), and in length from 9 to 86 m, (30–282 ft). All chosen piles included information about either the Incremental Filling Ratio (IFR), or the Plug Length Ratio (PLR). An IFR of 1.00 indicates that the pile is completely unplugged, while an IFR of 0 represents a completely plugged pile, and anything in between implies a partially plugged pile. Since the measured IFR values are not always 0 s and 1 s, and since the proposed interaction diagram does not account for the partially plugged condition, it was decided that an unplugged pile is any pile with an IFR > 0.3, and a plugged pile is any pile with an IFR < 0.3. The authors performed sensitivity analyses and the results of the analyses remained consistent when the plugging threshold was set to IFR in the range of 0.2 to 0.6.

The test piles are summarized in Table 1 and are plotted in Figure 9, with the actual plugging condition identified using the symbols U for unplugged, P for plugged. The actual plugging condition based on the recorded IFR value, along with the forecasted plugging condition based on the diameter criterion are also shown in Table 1. The proposed criterion successfully forecasted the plugging condition in 10 cases out of the 14 test cases that plot in the plugged and the unplugged zones with an accuracy of 71%. The authors performed sensitivity analyses and the results of the analyses were off in 4 cases. The remaining 10 cases are scattered in the transition zone, and hence the plugging condition cannot be determined with confidence since the likelihood of being plugged and unplugged are equal.

![Figure 9](image-url)

**Figure 9.** Test Piles used to evaluate the performance of the proposed diameter criterion, showing the actual plugging condition and the resulting accuracy.

These observations, confirm that the proposed diameter criterion can be employed for preliminary determination of plugging, factoring in that its accuracy is on the order of 70%; however, the results are somewhat skewed by only 3 out of 24 tests in the validation data set exhibiting in-situ plugging.

**Table 1.** Test Piles used to evaluate the performance of the proposed interaction diagram, and the actual and forecasted plugging condition.

| #  | Reference                | Pile ID | Diameter m (in) | Length m (ft) | L/D | IFR (%) | Plugging Condition Actual | Forecasted |
|----|--------------------------|---------|-----------------|---------------|-----|---------|---------------------------|------------|
| 1  | Jeong and Ko [23]        | TP-2    | 0.7 (27.6)      | 11.4 (37.4)   | 16.3| 60.0    | Unplugged                 | N/A        |
| 2  |                          | TP-3    | 0.9 (36)        | 15.5 (50.9)   | 17.0| 60.0    | Unplugged                 | Unplugged  |
Table 1. Cont.

| #  | Reference                  | Pile ID | Diameter m (in) | Length m (ft) | L/D | IFR (%) | Plugging Condition Actual | Forecasts |
|----|----------------------------|---------|-----------------|---------------|-----|---------|----------------------------|------------|
| 3  | Jardine et al. [54]        | -       | 0.8 (30)        | 47 (154.2)    | 61.7 | 89.0    | Unplugged                 | N/A        |
| 4  | Kikuchi [57]               | TP4     | 1.5 (58.8)      | 73.5 (241.1)  | 49.2 | 100.0   | Unplugged                 | Unplugged |
| 5  |                            | TP5     | 1.5 (58.8)      | 86 (282.2)    | 57.6 | 100.0   | Unplugged                 | Unplugged |
| 6  | De Nicola and Randolph [24]| LOD1    | 1.6 (62.4)      | 15.7 (51.5)   | 9.9  | 65.0    | Unplugged                 | Unplugged |
| 7  |                            | MOD1    | 1.6 (62.4)      | 15.2 (49.9)   | 9.6  | 85.0    | Unplugged                 | Unplugged |
| 8  |                            | DOD2    | 1.6 (62.4)      | 16.7 (54.8)   | 10.5 | 115.0   | Unplugged                 | Unplugged |
| 9  | Han et al. [58]            | -       | 0.6 (24)        | 30.5 (100)    | 50.0 | 70.0    | Unplugged                 | N/A        |
| 10 | Liu et al. [59]            | P1      | 0.5 (19.2)      | 22 (72.2)     | 45.1 | 0.0     | Plugged                   | Plugged    |
| 11 |                            | P2      | 0.5 (19.2)      | 22 (72.2)     | 45.1 | 0.0     | Plugged                   | Plugged    |
| 12 |                            | P3      | 0.5 (19.2)      | 22 (72.2)     | 45.1 | 0.0     | Plugged                   | Plugged    |
| 13 | Olson and Shantz [29]      | Bent E31R | 0.6 (24)      | 13.3 (43.6)   | 21.8 | 83.0    | Unplugged                 | N/A        |
| 14 | Tveldt et al. [60]         | 16      | 0.8 (32.0)      | 11 (36.1)     | 13.5 | 88.0    | Unplugged                 | N/A        |
| 15 |                            | 25      | 0.8 (32.0)      | 16 (52.5)     | 19.7 | 88.0    | Unplugged                 | N/A        |
| 16 |                            | 25      | 0.8 (32.0)      | 25 (82.0)     | 30.8 | 88.0    | Unplugged                 | N/A        |
| 17 | Jardine and Standing [61]  | C1      | 0.5 (18.0)      | 10 (32.8)     | 21.9 | 78.0    | Unplugged                 | Plugged    |
| 18 | Williams et al. [62]       | P       | 1.2 (48.0)      | 26 (85.3)     | 21.3 | 95.0    | Unplugged                 | Unplugged |
| 19 | Yang et al. [63]           | K24-1   | 0.6 (24)        | 33 (108.3)    | 54.2 | 74.0    | Unplugged                 | N/A        |
| 20 |                            | K24-2   | 0.6 (24)        | 39.8 (130.6)  | 65.3 | 74.0    | Unplugged                 | N/A        |
| 21 |                            | K24-3   | 0.5 (19.2)      | 39.8 (130.6)  | 81.6 | 73.0    | Unplugged                 | Plugged    |
| 22 |                            | K34-1   | 0.6 (24)        | 29.3 (96.1)   | 48.1 | 82.0    | Unplugged                 | N/A        |
| 23 | Mayne [64]                 | AL 1    | 0.3 (13.2)      | 15.2 (49.9)   | 45.4 | 71.0    | Unplugged                 | Plugged    |
| 24 |                            | AL 2    | 0.3 (13.2)      | 42.7 (140.1)  | 127.4| 71.0    | Unplugged                 | Plugged    |

8. Practical Significance of Results

The data presented in this study suggest that forecasting the plugging of pipe piles based solely on pile dimensions and the geotechnical profile is difficult. This is not surprising considering that plugging is influenced by a myriad of installation effects that are not captured by many of the design methods in common use. Nevertheless, forecasting the plugging before driving is necessary not only to correctly compute the capacity, but also to ensure drivability to the desired depth, especially for cases of non-uniform pile wall thickness.

The presented results have two implications. The first is that large diameter piles, piles with diameters larger than ~0.9 m (36 inches), are highly likely to be unplugged. The second is that piles smaller than 0.5 m (20 inches) are likely to be plugged. The design engineer has two options. The first is to assume that all piles are unplugged. This approach is in our opinion best when estimation of the correct ultimate capacity is desirable. Our opinion is based on the mean normalized capacity being closest to 1 for the unplugged assumption when considering the 74 cases examined in Figure 2 using the 4 design methods. This opinion is also supported by examining the capacities computed in Appendix D using the CPT design methods. Alternatively, the proposed diameter criterion can be used to forecast the onset of plugging when determination of plugging is paramount, for example to size the driving equipment. Utilization of the proposed diameter criterion should however be limited to piles in the same size ranges considered here in (L > 9 m (30 ft), D = 0.25–2.5 m (10–100 inches), and L/D = 6–150).

9. Limitations

Several limitations were encountered in this study. The first was the lack of plugging information such as the soil column depth inside the piles, or the Incremental Filling
Ratio (IFR). This information is necessary to positively identify the onset of plugging in pipe piles. Because nearly all the piles were not instrumented, the authors are unable to separate the effects of plugging on base and shaft resistance. In addition, the authors are unable to discern when plugging occurred. Some piles may have driven as coring, and plugged during load testing (Static Plugging), while others may have plugged during driving (Dynamic Plugging). Similarly, partial/intermittent plugging is not considered; the analysis presumes a PLR of 1 or 0, while field data generally suggest PLRs between 0.5 and 1 [3]. Finally, plugging may also influence both stiffness and load transfer, but the nature of the analysis precludes identifying these effects. Consequently, that limited the analysis to being a statistical evaluation based on the pile properties and the observed measured and computed capacities only.

A second limitation was that only a few piles (8 cases) were identified as developing an internal plugging condition, leading to the decision to marginalize the internal plugging condition in the process of developing the proposed diameter criterion and in the analysis overall.

The third limitation was the lack of information about the age of testing for some cases in the employed dataset. Age of testing affects pile capacity significantly, which is also associated with the actual plugging condition. Hence, the authors opted for employing the pile geometric properties. Finally, the quality of the available data is not always excellent, and in many cases lacks vital information regarding either the driving system or the soil conditions.

Finally, on average the performance of the design methods used to deduce the plugging condition has been less than optimal (Table 2). All methods appear to consistently overestimate the capacity of unplugged piles and underestimate the capacity of plugged and internally plugged piles (Figures 3 and 7). Many individual cases are overestimated or underestimated by a factor of two. Some design methods overestimate the capacity by nearly 90% under certain conditions (e.g., FHWA Unplugged in Figure 3). These shortcomings stem from design methods having well-recognized limitations which are beyond the scope of this work. Therefore, the authors refrained from offering any design method-specific recommendations and opted for general recommendations based on the voted plugging condition.

Table 2. Average performance statistics of all design methods employed in this study.

| Method       | Average $Q_c/Q_m$ | Std. Dev. $Q_c/Q_m$ |
|--------------|-------------------|---------------------|
| FHWA         | 1.54              | 1.01                |
| USACE        | 1.28              | 0.82                |
| Revised Lambda | 1.15           | 0.53                |
| API          | 1.2               | 0.62                |
| NGI-04       | 0.99              | 0.35                |
| ICP-05       | 1.18              | 0.84                |
| FUGRO-04     | 1.13              | 0.80                |
| UWA-05       | 1.15              | 0.82                |

10. Conclusions

The propensity for plugging based on basic pile properties such as pile diameter, length, and L/D ratio was investigated using a database of load tests on 74 open-ended pipe piles. The closeness between the capacity interpreted from a load test and that computed for three plugging conditions was used to identify plugging for each design method, then a voting system was employed to decide the overall plugging condition of a pile. Four commonly used designed methods were used to compute the calculated capacity including: (1) FHWA, (2) USACE, (3) Revised Lambda, and (4) API. The results
were checked using 23 load tests where CPT soundings were available and a similar voting methodology was employed but using four CPT-based pile design methods including (i) NGI-04, (ii) UWA-05, (iii) FUGRO-04 and (iv) UWA-05 methods. Finally, the results were validated using 24 case histories where plugging records have been reported. A summary of the findings is presented below:

Most of the piles in the database of 74 piles used in this study appear to be unplugged, evidenced by that condition providing the closest capacity to the one interpreted from the load test. This was also the case for the test dataset of 24 case histories where plugging records have been reported;

No plugging pattern was found based on a diameter-length relationship or a length-L/D ratio relationship, or soil condition, as data was largely scattered;

Piles larger than 0.9 m (36 inches) in diameter have higher likelihood of being unplugged, while piles smaller than 0.5 m (20 inches) tend to be plugged. These dimensions are proposed as a diameter criterion for preliminary determination of the plugging condition of a pile with an average accuracy of 70 ± 10%.

Author Contributions: Both authors contributed to the study conception and design. The specific roles are: data manipulation, software development, investigation, formal analysis, methodology, visualization, writing original draft, A.K.; conceptualization, supervision, validation, project administration, writing review and editing, M.I. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data used during the study appears in the submitted article.

Acknowledgments: This study employed data from FHWA DFLTD v2 as well as Roy Olson piling database. The authors are grateful to Roy Olson and FHWA for providing the data. The databases were ported from their original sources to a relational database by Nick Machairas, now Data and Analytics Leader at Haley and Aldrich, as part of his doctoral dissertation at NYU. Drew Rizk, PE, now Associate Principal/Vice President GZA Geoenvironmental, reviewed the geotechnical data of all load tests as part of his master’s thesis at NYU. The authors gratefully acknowledge these previous efforts, without which this work would not have been possible.

Conflicts of Interest: The authors declare no conflict of interest and certify that they have no affiliations with or involvement in any entity with any financial, or non-financial, interest in the subject matter or materials discussed in this manuscript.
## Appendix A. Open-Ended Pipe Piles Adopted into This Study from the FHWA DFLTD v.2 Database

| ID   | Project ID | Project                                   | Material | Pile ID | Load Test ID | OD (in) | ID (in) | L (ft) | CPT Data | Soil Profile ID | Major Soil Type | Ref. |
|------|------------|-------------------------------------------|----------|---------|--------------|---------|---------|--------|----------|----------------|----------------|------|
| N-1  | 234        | Salinas River Bridge, USA                 | S        | 1       | 1            | 60      | 59      | 130    | No       | B-5            | Sand           | [26] |
| N-2  | 843        | 108 GRL Piles-3rd Lake Wash. BR, WA, USA  | S        | 1       | 1            | 48      | 46      | 160    | No       | GRL Piles #108 | Sand           |      |
| N-3  | 1001       | Port Mann Bridge, Canada                  | S        | 5       | 1            | 72      | 70      | 246    | No       | DFSL           | Mixed          | [65] |
| N-4  | 1002       | Red Sea Coast, Saudi Arabia               | S        | 1       | 1            | 56      | 54      | 240    | No       | Boring-A       | Sand           | [66] |
| N-5  | 1002       | Red Sea Coast, Saudi Arabia               | S        | 2       | 1            | 56      | 54      | 217    | No       | Boring-B       | Sand           |      |
| N-6  | 1002       | Red Sea Coast, Saudi Arabia               | S        | 4       | 1            | 56      | 54      | 135    | No       |                |                |      |
| N-7  | 1002       | Red Sea Coast, Saudi Arabia               | S        | 5       | 1            | 56      | 54      | 72     | No       |                |                |      |
| N-8  | 1003       | Louisiana Highway 1 Improvements Phase 1B, USA | S      | 1       | 1            | 30      | 29      | 195    | Yes      | 1              | Clay           | [67] |
| N-9  | 1004       | Tokyo Port Bay Bridge, Japan              | S        | 1       | 1            | 59      | 57      | 261    | Yes      | Generalized    | Mixed          | [57] |
| N-10 | 1005       | Salinas River Bridge, USA                 | S        | 1       | 1            | 72      | 71      | 118    | No       | UTB-44         | Mixed          | [68] |
| N-11 | 1006       | I-880 Port of Oakland Connector Viaduct, USA | S      | 1       | 1            | 42      | 41      | 88     | Yes      | 1              | Clay           |      |
| N-12 | 1006       | I-880 Port of Oakland Connector Viaduct, USA | S      | 1       | 1            | 42      | 41      | 88     | Yes      | Generalized    | Clay           | [26] |
| N-13 | 1007       | I-880 Oakland Bridge Replacement, USA     | S        | 1       | 1            | 42      | 41      | 106    | No       | UTB-12B        | Clay           |      |
| N-14 | 1008       | Santa Clara River Bridge, USA             | S        | 1       | 1            | 84      | 81      | 69     | No       | 00-2           | Mixed          | [68] |
| N-15 | 1009       | Noto Peninsula New Highway Route Bridges, Japan | S      | 1       | 1            | 31      | 31      | 36     | Yes      | DFSL           | Clay           | [69] |
| N-16 | 1009       | Noto Peninsula New Highway Route Bridges, Japan | S      | 2       | 1            | 31      | 31      | 36     | Yes      |                |                |      |
| ID   | Project ID | Project                                           | Material | Pile ID | Load Test ID | OD (in) | ID (in) | L (ft) | CPT Data | Soil Profile ID | Major Soil Type | Ref. |
|------|------------|---------------------------------------------------|----------|---------|--------------|---------|---------|--------|----------|----------------|-----------------|------|
| N-19 | 1010       | Pentre Site, Great Britain                        | S        | 1       | 1            | 30      | 28      | 192    | No       | 101            | Clay            | [70] |
| N-20 | 1011       | Woodrow Wilson Bridge over Potomac River, VA and MD, USA | S        | 1       | 1            | 54      | 52      | 165    | No       | ID-63          | Mixed           | [68] |
| N-21 | 1011       | Jin Mao Building, China                           | S        | 1       | 1            | 36      | 34      | 96     | No       | ID-65          | Sand            | [71] |
| N-22 | 1012       | Hokkaido, Japan                                   | S        | 1       | 1            | 40      | 38      | 135    | No       | Generalized Boring | Mixed           | [77] |
| N-23 | 1013       | Chiba, Japan                                      | S        | 1       | 1            | 31      | 30      | 157    | No       | Generalized Boring | Sand            | [72] |
| N-24 | 1019       | EURIPIDES Joint Industry Project-Offshore test piles, Netherlands | S        | 1       | 1            | 30      | 27      | 101    | Yes      | CPT-36         | Sand            | [26] |
| N-28 | 1020       | Sakonnet River Bridge (Route 138), USA            | S        | 1       | 1            | 72      | 69      | 136    | No       | Generalized Boring | Sand            | [73] |
| N-29 | 1021       | Annacis Throughway Bridge Project-Highway 91, Canada | S        | 1       | 1            | 36      | 35      | 221    | No       | Generalized CPT | Clay            | [74] |
| N-32 | 1023       | Berenda Slough Bridge, USA                        | S        | 1       | 1            | 42      | 41      | 106    | No       | 98-5           | Sand            | [68] |
| N-33 | 1024       | Gulf Intracoastal Waterway West Closure Complex Test Site 3 | S        | 1       | 1            | 96      | 93      | 137    | No       | Generalized Boring | Clay            | [76] |
| ID  | Project ID | Project                                                                 | Material | Pile ID | Load Test ID | OD (in) | ID (in) | L (ft) | CPT Data | Soil Profile ID | Major Soil Type | Ref. |
|-----|------------|-------------------------------------------------------------------------|----------|---------|--------------|---------|---------|--------|-----------|----------------|----------------|------|
| N-38| 1035       | Highway 32 Stony Creek Bridge (No. 11-0029), USA                       | S        | 1       | 1            | 100     | 96      | 170    | No        | 00-6          | Mixed          | [77] |
| N-39| 1055       | Feather River Bridge (Caltrans Bridge No. 18-0009), USA                | S        | 1       | 1            | 48      | 46      | 173    | No        | 1             | Sand           | [78] |
| N-40| 1056       | Mad River Bridge (Caltrans Bridge No. 04-0025L), USA                   | S        | 1       | 1            | 87      | 84      | 136    | No        | 1             | Sand           | [79] |
| N-41| 1057       | Russian River Bridge, USA                                              | S        | 1       | 1            | 66      | 64      | 121    | No        | 1             | Sand           | [80,81] |
| N-42| 1060       | Russian River Bridge, USA                                              | S        | 1       | 1            | 48      | 46      | 143    | No        | 1             | Sand           | [80,81] |
| N-43| 1061       | Feather River Bridge, USA                                              | S        | 2       | 1            | 90      | 87      | 202    | No        | 1             | Sand           | [26] |
| N-44| 1061       | Feather River Bridge, USA                                              | S        | 2       | 1            | 90      | 87      | 202    | No        | 1             | Sand           | [26] |
| N-45| 1062       | Santa Clara River Bridge, USA                                          | S        | 1       | 1            | 72      | 69      | 129    | No        | 1             | Sand           | [82] |
| N-46| 1063       | Port of Oakland, USA                                                   | S        | 2       | 1            | 42      | 41      | 98     | No        | 1             | Mixed          | [83] |
| N-47| 1064       | Port of Toamasina Offshore Jetty                                       | S        | 3       | 1            | 42      | 41      | 97     | No        | 3             | Mixed          | [84] |
| N-48| 1068       | Port of Toamasina Offshore Jetty                                       | S        | 2       | 1            | 40      | 38      | 213    | No        | NP-04         | Sand           | [84] |
| N-50| 1069       | Trans-Tokyo Bay Highway, Japan                                         | S        | 1       | 1            | 79      | 76      | 203    | Partial   | DFSL          | Sand           | [85] |
| N-51| 1070       | Legislative Route 795 section B-6 Philadelphia, USA                    | S        | 1       | 1            | 30      | 29      | 96     | No        | PLT-E         | Mixed          | [86] |
| N-52| 1070       | Legislative Route 795 section B-6 Philadelphia, USA                    | S        | 2       | 1            | 30      | 29      | 64     | No        | PLT-C         | Sand           | [86] |
| N-53| 1070       | Legislative Route 795 section B-6 Philadelphia, USA                    | S        | 3       | 1            | 30      | 29      | 86     | No        | B-620         | Mixed          | [86] |
| N-54| 1071       | Nippon Steel Blast Furnace Foundations, Japan                          | S        | 2       | 1            | 47      | 46      | 81     | No        | DFSL          | Sand           | [87] |
| ID | Project ID | Project Description | Material | Pile ID | Load Test ID | OD (in) | ID (in) | L (ft) | CPT Data | Soil Profile ID | Major Soil Type | Ref. |
|----|------------|---------------------|-----------|---------|-------------|---------|---------|-------|----------|----------------|----------------|------|
| N-56 | 1072 | Tilbrook Grange Site, Great Britain | S | 1 | 1 | 30 | 27 | 110 | No | 201 | Clay | [70] |
| N-57 | 1102 | I-664 Bridge, USA | C | 1 | 1 | 54 | 44 | 48 | No | B-66 | Sand | [68] |
| N-58 | 1103 | San Mateo-Hayward Bridge, USA | C | 1 | 1 | 42 | 28 | 139 | No | DFSL-1 | Clay | [68] |
| N-59 | 1104 | St. George Island Bridge Replacement. Pier 20 (Test Pile LT-1), USA | C | 1 | 4 | 54 | 38 | 80 | Partial | B-20 | Sand | [69] |
| N-60 | 1105 | US 13 Chesapeake Bay Bridge—Tunnel, USA | C | 6 | 1 | 54 | 42 | 96 | Partial | DFSL-6 | Mixed | [68] |
| N-61 | 1106 | Crossbay Blvd. Bridge Over North Channel, USA | C | 1 | 1 | 54 | 44 | 89 | No | DFSL | Sand | [88] |
| N-62 | 1116 | St. George Island Bridge Replacement. Pier 124 (Test Pile LT-5), USA | C | 1 | 2 | 54 | 38 | 80 | Partial | 1 | Sand | [68] |
| N-63 | PHC-2 | Wuhu Bridge, China | C | - | - | 31.5 | 21 | 96 | Yes | K27 | Sand | [82] |
| N-64 | 10 | Seismic Retrofit Program-Hwy 280, USA | S | 14 | 2 | 16 | 15 | 109 | No | B2 | Mixed | [26] |
| N-65 | 10 | Seismic Retrofit Program-Hwy 280, USA | S | 28 | 1 | 13 | 12 | 83 | No | B8 | Mixed | [26] |
| N-66 | 10 | Seismic Retrofit Program-Hwy 280, USA | S | 29 | 2 | 16 | 15 | 204 | No | B2 | Mixed | [26] |
| N-67 | 10 | Ventura Underpass Br # 52-178, USA | S | 30 | 1 | 16 | 15 | 200 | No | B2 | Mixed | [26] |
| N-68 | 124 | Ventura Underpass Br # 52-178, USA | S | 69 | 1 | 12 | 11.7 | 30 | No | B-1A | Sand | [26] |
| N-69 | 129 | Nyeland Acres O.C Sta103+00, USA | S | 24 | 1 | 11 | 10.5 | 35 | No | B-2 | Sand | [26] |
| N-70 | 228 | Bayshore Fwy Viaduct Site C, USA | S | 1 | 1 | 16 | 15 | 58 | No | B-5 | Sand | [26] |
| N-71 | 228 | Bayshore Fwy Viaduct Site C, USA | S | 2 | 1 | 16 | 15 | 52 | No | B-5 | Sand | [26] |
| ID   | Project ID | Project                                | Material | Pile ID | Load Test ID | OD (in) | ID (in) | L (ft) | CPT Data | Soil Profile ID | Major Soil Type | Ref. |
|------|------------|----------------------------------------|----------|---------|--------------|---------|---------|--------|----------|----------------|-----------------|------|
| N-73 | 229        | Bayshore Fwy Viaduct Site B, USA       | S        | 2       | 1            | 24      | 23      | 64      | No       | B-4            | Clay            | [26] |
| N-74 | 230        | Bayshore Fwy Viaduct Site D, USA       | S        | 2       | 1            | 24      | 23      | 53      | No       | 95-2           | Sand            | [26] |
| N-75 | 231        | Bayshore Fwy Viaduct Site E, USA       | S        | 2       | 1            | 24      | 23      | 98      | No       | 95-3           | Clay            | [26] |
| N-76 | 231        | Bayshore Fwy Viaduct Site F, USA       | S        | 2       | 1            | 24      | 23      | 97      | No       | 95-3           | Clay            | [26] |
| N-77 | 235        | Bayshore Fwy Viaduct Site F, USA       | S        | 2       | 1            | 24      | 23      | 73      | Yes      | CPT-1          | Mixed           | [26] |
| N-78 | 235        | ABEF Research on Foundation # 84, Great Britain | C     | 2       | 1            | 24      | 23      | 72      | Yes      | CPT1           | Sand            | [26] |
| N-79 | 707        | ABEF Research on Foundation # 84, Great Britain | C     | 2       | 2            | 20      | 13      | 30      | Yes      | CPT1           | Sand            | [26] |
| N-80 | 707        | ABEF Research on Foundation # 84, Great Britain | C     | 2       | 2            | 20      | 13      | 25      | Yes      | CPT1           | Sand            | [26] |
| N-81 | 788        | GRL Piles-LTV Cont. Caster, Ohio, USA   | S        | 2       | 1            | 18      | 17      | 120     | No       | GRL 42         | Mixed           | [26] |
| N-82 | 789        | GRL Piles-ODOT State Rte 22, Ohio, USA  | S        | 1       | 1            | 12      | 11.6    | 40      | No       | GRL 44         | Sand            | [26] |
| N-83 | 1024       | Gulf Intracoastal Waterway West Closure Complex Test Site 3, USA | S      | 1       | 1            | 24      | 23      | 190     | Yes      | ALGSGS-08-10U  | Clay            | [74] |
### Appendix B. Open-Ended Steel Pipe Piles Adopted into This Study from the Olson’s Database

| ID    | Olson Project ID | Project Location    | OD (in) | ID (in) | L (ft) | CPT Data | Major Soil Type | Original Source |
|-------|------------------|---------------------|---------|---------|--------|----------|-----------------|-----------------|
| N-84  | 43               | British Columbia, CAN | 24      | 23      | 100    | No       | Clay            | [89]            |
| N-85  | 44               | British Columbia, CAN | 24      | 23      | 153    | No       | Clay            |                 |
| N-86  | 68               | Alsancak Harbor, Turkey | 20.8    | 18.2    | 98     | No       | Clay            | [90]            |
| N-87  | 70               | Alsancak Harbor, Turkey | 20.8    | 18.2    | 92     | No       | Clay            |                 |
| N-88  | 487              | Empire, Louisiana   | 14      | 11.4    | 177    | No       | Clay            |                 |
| N-89  | 489              | Empire, Louisiana   | 14      | 9.75    | 267    | No       | Clay            |                 |
| N-90  | 491              | Empire, Louisiana   | 14      | 9.75    | 322    | No       | Clay            |                 |
| N-91  | 493              | Empire, Louisiana   | 14      | 9.75    | 370    | No       | Clay            |                 |
| N-92  | 494              | Empire, Louisiana   | 14      | 9.75    | 370    | No       | Clay            |                 |
| N-93  | 495              | Kontich, Belgium    | 24      | 22      | 79     | Yes      | Clay            | [92]            |
| N-94  | 497              | Kontich, Belgium    | 24      | 22      | 68     | Yes      | Clay            |                 |
| N-95  | 527              | British Columbia, CAN | 24      | 23      | 149    | No       | Clay            | [89]            |
| N-96  | 868              | Eugene Island, USA  | 24      | 18.75   | 357    | No       | Clay            | Unpublished Data, Source: Confidential |
| N-97  | 869              | Eugene Island, USA  | 24      | 18.75   | 282    | No       | Clay            | Confidential     |
### Appendix C. Calculated Capacities for the SPT Design Methods

| Case ID | Nominal Resistance (kips) | Max. Applied Load (kips) | Load Test Information | Calculated Capacities (kips) |
|---------|---------------------------|--------------------------|-----------------------|------------------------------|
|         |                           |                          | FHWA                  | USACE                        | REVISED LAMBDA               | API                           |
| N-1     | 2100                      | 2100                     | 6338                  | 17,831                       | 11,352                       | 5390                          |
| N-2     | 1030                      | 2000                     | 599                   | 5290                         | 917                          | 539                           |
| N-3     | 10,022                    | 12,061                   | 7937                  | 11,594                       | 8901                         | 5037                          |
| N-4     | 1328                      | 1417                     | 7855                  | 21,809                       | 12,204                       | 6857                          |
| N-5     | 1296                      | 1382                     | 5547                  | 16,590                       | 9864                         | 5076                          |
| N-6     | 1084                      | 1458                     | 2442                  | 6054                         | 3413                         | 2839                          |
| N-7     | 354                       | 611                      | 511                   | 3098                         | 891                          | 533                           |
| N-11    | 1513                      | 1513                     | 2952                  | 9788                         | 4355                         | 2845                          |
| N-13    | 875                       | 875                      | 1409                  | 2313                         | 1691                         | 1003                          |
| N-14    | 1209                      | 1209                     | 1422                  | 2731                         | 1697                         | 1000                          |
| N-15    | 1995                      | 1995                     | 3330                  | 7016                         | 5746                         | 2639                          |
| N-16    | 5680                      | 8000                     | 12,263                | 24,165                       | 20,669                       | 8596                          |
| N-19    | 1349                      | 1349                     | 2206                  | 2313                         | 2313                         | 1427                          |
| N-20    | 2905                      | 2925                     | 6329                  | 7655                         | 7391                         | 4365                          |
| N-21    | 2899                      | 2920                     | 4319                  | 4649                         | 4610                         | 2825                          |
| N-22    | 1764                      | 1764                     | 1475                  | 3278                         | 2018                         | 1214                          |
| N-25    | 3195                      | 3552                     | 2058                  | 5923                         | 3093                         | 2044                          |
| N-26    | 1666                      | 1866                     | 750                   | 3164                         | 1322                         | 997                           |
| N-28    | 3453                      | 5193                     | 3499                  | 7335                         | 4573                         | 1651                          |
| N-29    | 3581                      | 4766                     | 3448                  | 7238                         | 4523                         | 1637                          |
| N-30    | 4517                      | 6699                     | 3448                  | 7238                         | 4523                         | 1637                          |
| N-31    | 2394                      | 2990                     | 9455                  | 16,382                       | 13,558                       | 7302                          |
| Case ID | Nominal Resistance (kips) | Max. Applied Load (kips) | FHWA | USACE | REVISED LAMBDA | API |
|---------|--------------------------|--------------------------|-------|-------|----------------|-----|
|         |                          |                          | U     | P     | I              | U   |
| N-32    | 1651                     | 1693                     | 2241  | 3603  | 2475           | 2461|
| N-33    | 1551                     | 1610                     | 2784  | 4146  | 3018           | 3140|
| N-35    | 1618                     | 1618                     | 1479  | 5748  | 2493           | 2473|
| N-37    | 5793                     | 6742                     | 8953  | 21,296| 14,985         | 6835|
| N-38    | 7859                     | 7859                     | 10,556| 13,548| 12,141         | 6830|
| N-39    | 2254                     | 2500                     | 8709  | 15,027| 9124           | 5526|
| N-40    | 5421                     | 7191                     | 9131  | 11,938| 9644           | 5485|
| N-41    | 3200                     | 3200                     | 8212  | 18,485| 14,201         | 6284|
| N-42    | 3377                     | 3975                     | 6100  | 14,052| 9199           | 3928|
| N-43    | 3351                     | 4090                     | 13,950| 21,159| 17,606         | 11,028|
| N-44    | 7725                     | 8000                     | 26,709| 37,589| 31,105         | 18,169|
| N-45    | 6565                     | 8045                     | 10,048| 19,095| 16,500         | 6524|
| N-46    | 834                      | 845                      | 1516  | 3040  | 2034           | 1127|
| N-47    | 1037                     | 1037                     | 1262  | 2602  | 1854           | 1041|
| N-48    | 1288                     | 1288                     | 1416  | 3022  | 1918           | 1068|
| N-49    | 1988                     | 2029                     | 2966  | 7445  | 4288           | 2349|
| N-51    | 1176                     | 1436                     | 1296  | 2517  | 1357           | 1363|
| N-52    | 1499                     | 1499                     | 919   | 3069  | 1218           | 1017|
| N-53    | 878                      | 896                      | 1378  | 2586  | 1439           | 1354|
| N-54    | 1148                     | 1239                     | 1181  | 7360  | 1803           | 1308|
| N-55    | 1425                     | 1456                     | 742   | 4264  | 1127           | 702 |
| N-56    | 3619                     | 3619                     | 1722  | 2069  | 2069           | 3179|
| N-57    | 1300                     | 1300                     | 1175  | 2635  | 1499           | 852 |
| Case ID | Nominal Resistance (kips) | Max. Applied Load (kips) | Load Test Information | Calculated Capacities (kips) |
|---------|--------------------------|--------------------------|-----------------------|------------------------------|
|         |                          |                          |                       | FHWA                         |
|         |                          |                          |                       | U   | P  | I  | U   | P  | I  | U   | P  | I  | U   | P  | I  |
| N-58    | 1350                     | 1350                     |                       | 5211 | 6950 | 6141 | 3087 | 4903 | 4229 | 1619 | 2724 | 2724 | 1888 | 2992 | 2992 |
| N-59    | 1545                     | 1545                     |                       | 1950 | 2173 | 1989 | 1408 | 1447 | 1447 | 1285 | 1324 | 1324 | 1209 | 1248 | 1248 |
| N-62    | 1431                     | 1560                     |                       | 2166 | 2987 | 2723 | 2449 | 3868 | 3151 | 1400 | 2270 | 2190 | 1409 | 2279 | 2199 |
| N-65    | 219                      | 219                      |                       | 123  | 254  | 135  | 149  | 214  | 171  | 251  | 279  | 279  | 143  | 219  | 171  |
| N-66    | 341                      | 398                      |                       | 115  | 304  | 155  | 117  | 138  | 138  | 166  | 229  | 229  | 182  | 245  | 245  |
| N-67    | 355                      | 390                      |                       | 498  | 1935 | 577  | 499  | 575  | 575  | 1045 | 1167 | 1167 | 914  | 1037 | 1037 |
| N-68    | 489                      | 550                      |                       | 470  | 1812 | 550  | 481  | 557  | 557  | 985  | 1107 | 1107 | 874  | 997  | 997  |
| N-69    | 88                       | 180                      |                       | 19   | 116  | 34   | 62   | 110  | 92   | 54   | 84   | 84   | 54   | 84   | 84   |
| N-70    | 163                      | 180                      |                       | 19   | 181  | 31   | 38   | 88   | 56   | 41   | 71   | 71   | 43   | 88   | 73   |
| N-71    | 876                      | 933                      |                       | 161  | 911  | 232  | 238  | 440  | 333  | 228  | 346  | 346  | 250  | 475  | 369  |
| N-72    | 600                      | 627                      |                       | 161  | 911  | 232  | 238  | 440  | 333  | 228  | 346  | 346  | 250  | 475  | 369  |
| N-73    | 484                      | 487                      |                       | 608  | 2165 | 872  | 1015 | 1641 | 1289 | 775  | 1181 | 1181 | 821  | 1439 | 1225 |
| N-74    | 800                      | 800                      |                       | 345  | 2223 | 532  | 562  | 1262 | 784  | 415  | 776  | 776  | 462  | 1019 | 823  |
| N-75    | 208                      | 213                      |                       | 109  | 124  | 118  | 122  | 138  | 132  | 194  | 204  | 204  | 111  | 126  | 120  |
| N-76    | 180                      | 180                      |                       | 104  | 119  | 112  | 117  | 132  | 125  | 189  | 197  | 197  | 105  | 120  | 113  |
| N-81    | 564                      | 766                      |                       | 602  | 1163 | 712  | 591  | 737  | 694  | 529  | 672  | 672  | 648  | 963  | 782  |
| N-82    | 161                      | 184                      |                       | 18   | 66   | 31   | 50   | 73   | 72   | 74   | 100  | 100  | 100  | 65   | 92   | 92   |
| N-84    | 440                      | 440                      |                       | 540  | 540  | 540  | 462  | 462  | 462  | 537  | 537  | 537  | 508  | 508  | 508  |
| N-85    | 594                      | 594                      |                       | 990  | 990  | 990  | 795  | 795  | 795  | 927  | 927  | 927  | 1070 | 1070 | 1070 |
| N-86    | 315                      | 322                      |                       | 419  | 957  | 461  | 297  | 527  | 330  | 342  | 386  | 386  | 277  | 496  | 321  |
| N-87    | 180                      | 211                      |                       | 195  | 218  | 218  | 190  | 213  | 213  | 225  | 248  | 248  | 161  | 183  | 183  |
| N-88    | 225                      | 225                      |                       | 185  | 191  | 191  | 142  | 148  | 148  | 174  | 180  | 180  | 126  | 131  | 131  |
| N-89    | 439                      | 439                      |                       | 272  | 277  | 277  | 147  | 152  | 152  | 228  | 233  | 233  | 164  | 169  | 169  |
### Load Test Information

| Case ID | Nominal Resistance (kips) | Max. Applied Load (kips) | FHWA | USACE | REVISED LAMBDA | API |
|---------|---------------------------|--------------------------|------|-------|----------------|-----|
|         |                           |                          | U    | P     | I              | U   | P | I |
| N-90    | 481                       | 481                      | 237  | 248   | 248            | 145 | 156 | 155 | 205 | 216 | 216 | 141 | 152 | 152 |
| N-91    | 537                       | 537                      | 237  | 246   | 246            | 146 | 154 | 154 | 206 | 214 | 214 | 141 | 150 | 150 |
| N-92    | 383                       | 383                      | 237  | 246   | 246            | 146 | 154 | 154 | 206 | 214 | 214 | 141 | 150 | 150 |
| N-95    | 353                       | 353                      | 504  | 2317  | 536            | 727 | 685 | 954 | 1346 | 1346 | 1149 | 1541 | 1507 |
| N-96    | 1697                      | 1872                     | 2604 | 2860  | 2652           | 1941 | 1989 | 1989 | 3578 | 3626 | 3626 | 3466 | 3514 | 3514 |
| N-97    | 1542                      | 1676                     | 2014 | 2270  | 2062           | 1390 | 1439 | 1439 | 2195 | 2243 | 2243 | 2365 | 2413 | 2413 |

### Appendix D. Calculated Capacities for the CPT Design Methods

| Case ID | Nominal Resistance (kips) | Max. Applied Load (kips) | NGI-04 | ICP-05 | FUGRO-04 | UWA-05 |
|---------|---------------------------|--------------------------|--------|--------|----------|--------|
|         |                           |                          | U      | P      | I        | U      | P | I |
| N-8     | 1350                      | 1597                     | 972    | 1050   | 1050     | 671    | 687 | 687 | 658 | 840 | 766 | 668 | 707 | 697 |
| N-9     | 5089                      | 7194                     | 6111   | 8667   | 8667     | 7452   | 9305 | 9305 | 7442 | 10,033 | 10,033 | 6306 | 11,783 | 8990 |
| N-10    | 6417                      | 8093                     | 7815   | 10,588 | 10,588   | 8791   | 9709 | 9709 | 6348 | 8541 | 8541 | 6701 | 9411 | 8050 |
| N-12    | 1245                      | 1245                     | 905    | 1089   | 1089     | 748    | 958  | 925  | 715  | 933  | 900  | 742  | 954  | 920 |
| N-17    | 1046                      | 1057                     | 229    | 307    | 307      | 187    | 299  | 264  | 187  | 299  | 264  | 187  | 299  | 264 |
| N-18    | 832                       | 835                      | 229    | 307    | 307      | 185    | 298  | 263  | 185  | 298  | 263  | 185  | 298  | 263 |
| N-23    | 2717                      | 3698                     | 2289   | 3247   | 3247     | 2768   | 2926 | 2926 | 1467 | 2138 | 2138 | 2224 | 2751 | 2581 |
| N-24    | 2952                      | 4073                     | 2287   | 3245   | 3245     | 2759   | 2918 | 2918 | 1443 | 2114 | 2114 | 2217 | 2744 | 2574 |
| N-27    | 1660                      | 2653                     | 1880   | 1722   | 1722     | 2157   | 2157 | 2157 | 2101 | 2426 | 2426 | 2126 | 2789 | 2655 |
| N-34    | 1477                      | 1797                     | 2974   | 3134   | 3134     | 6975   | 7348 | 7135 | 6770 | 7142 | 6929 | 6909 | 7281 | 7068 |
| N-36    | 1171                      | 1215                     | 1360   | 1436   | 1436     | 912    | 1012 | 989  | 912  | 1012 | 989  | 912  | 1012 | 989 |
| Case ID | Nominal Resistance (kips) | Max. Applied Load (kips) | NGI-04 | ICP-05 | FUGRO-04 | UWA-05 |
|---------|--------------------------|-------------------------|--------|--------|----------|--------|
|         |                          |                         | U      | P      | I        |        |
| N-50    | 7324                     | 7592                    | 6349   | 8816   | 8816     | 7442   |
| N-60    | 1953                     | 2109                    | 1855   | 1193   | 1193     | 2014   |
| N-61    | 746                      | 932                     | 897    | 679    | 679      | 1337   |
| N-63    | 2844                     | 2762                    | 1891   | 1526   | 1526     | 2036   |
| N-64    | 986                      | 1214                    | 956    | 898    | 898      | 1172   |
| N-77    | 900                      | 900                     | 517    | 698    | 698      | 593    |
| N-78    | 321                      | 380                     | 491    | 668    | 668      | 566    |
| N-79    | 680                      | 719                     | 610    | 365    | 365      | 669    |
| N-80    | 731                      | 742                     | 528    | 260    | 260      | 562    |
| N-83    | 687                      | 811                     | 893    | 964    | 964      | 623    |
| N-93    | 1096                     | 1096                    | 1175   | 1283   | 1283     | 1290   |
| N-94    | 767                      | 767                     | 835    | 905    | 905      | 932    |
References

1. Paikowsky, S. The Mechanism of Pile Plugging in Sand. In Proceedings of the All Days, OTC, Houston, TX, USA, 2–5 May 1990.
2. Paik, K.; Salgado, R. Determination of Bearing Capacity of Open-Ended Piles in Sand. J. Geotech. Geoenvironmental Eng. 2003, 129, 46–57. [CrossRef]
3. Raines, R.D.; Ugaz, O.G.; O’Neill, M.W. Driving Characteristics of Open-Toe Piles in Dense Sand. J. Geotech. Eng. 1992, 118, 72–88. [CrossRef]
4. Iskander, M. Behavior of Pipe Piles in Sand: Plugging and Pore-Water Pressure Generation during Installation and Loading. Springer Series in Geomechanics and Geogiotechnique; Springer: Berlin/Heidelberg, Germany, 2011.
5. Paik, K.; Lee, S. Behavior of soil plugs in open-ended model piles driven into sands. Mar. Georesour. Geotechnol. 1993, 11, 353–373. [CrossRef]
6. Smith, I.M.; Chow, Y.K. Three-dimensional analysis of pile drivability. In Proceedings of the 2nd International Conference on Numerical Methods in Offshore Piling, Austin, TX, USA, 18–22 May 1982; pp. 1–19.
7. Smith, I.M.; To, P.; Wilson, S.M. Plugging of pipe piles. In Proceedings of the 3rd International Conference on Numerical Method in Offshore Piling, Nantes, France, 21–22 May 1986; pp. 53–73.
8. Paikowsky, S.G.; Whitman, R.V.; Baligh, M.M. A new look at the phenomenon of offshore pile plugging. Mar. Geotechnol. 1989, 6, 213–230. [CrossRef]
9. Randolph, M.F.; Leong, E.C.; Houlsby, G.T. One-dimensional analysis of soil plugs in pipe piles. Géotechnique 1991, 41, 587–598. [CrossRef]
10. Randolph, M.F.; Leong, E.C.; Houlsby, G.T. One-dimensional analysis of soil plugs in pipe piles. Géotechnique 1991, 41, 587–598. [CrossRef]
11. Choi, Y.; O’Neill, M.W. Soil Plugging and Relaxation in Pipe Pile during Earthquake Motion. J. Geotech. Geoenvironmental Eng. 1997, 123, 975–982. [CrossRef]
12. Murff, J.; Raines, R.; Randolph, M. Soil Plug Behavior of Piles in Sand. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 2–5 May 1990.
13. Miller, G.A.; Lutenegger, A.J. Influence of Pile Plugging on Skin Friction in Overconsolidated Clay. J. Geotech. Geoenvironmental Eng. 1997, 123, 525–533. [CrossRef]
14. Henke, S.; Grabe, J. Numerical investigation of soil plugging inside open-ended piles with respect to the installation method. Acta Geotech. 2008, 3, 215–223. [CrossRef]
15. Henke, S.; Grabe, J. Field measurements regarding the influence of the installation method on soil plugging in tubular piles. Acta Geotech. 2013, 8, 335–352. [CrossRef]
16. Randolph, M.F. Science and empiricism in pile foundation design. Géotechnique 2003, 53, 847–875. [CrossRef]
17. Bracy, F.; Meunier; J.; Nauroy, J.-F. Behavior of Pile Plug in Sandy Soils During and After Driving. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 6–9 May 1991.
18. Focht, J.A.; McClelland, B. Analysis of Laterally Loaded Piles by Difference Equation Solution. Tex. Eng. 1955, 25, 7–9.
19. Fattah, M.Y.; Al-Soudani, W.H. Behavior of soil plugs in open-ended model piles driven into sands. Mar. Georesour. Geotechnol. 1993, 11, 353–373. [CrossRef]
20. Paikowsky, S.G.; Whitman, R.V.; Baligh, M.M. A new look at the phenomenon of offshore pile plugging. Mar. Geotechnol. 1989, 6, 213–230. [CrossRef]
21. Paikowsky, S.G.; Whitman, R.V. The effects of plugging on pile performance and design. Can. Geotech. J. 1990, 27, 429–440. [CrossRef]
22. Lehane, B.M.; Gavin, K.G. Discussion of “Determination of Bearing Capacity of Open-Ended Piles in Sand” by Kyuho Paik and Rodrigo Salgado. J. Geotech. Geoenvironmental Eng. 2004, 130, 656–658. [CrossRef]
23. Yu, F.; Yang, J. Base Capacity of Open-Ended Steel Pipe Piles in Sand. J. Geotech. Geoenvironmental Eng. 2012, 138, 1116–1128. [CrossRef]
24. Jeong, S.; Ko, J.; Won, J.; Lee, K. Bearing capacity analysis of open-ended piles considering the degree of soil plugging. Soils Found. 2015, 55, 1001–1014. [CrossRef]
25. De Nicola, A.; Randolph, M.F. The plugging behaviour of driven and jacked piles in sand. Géotechnique 1997, 47, 841–856. [CrossRef]
26. Lehane, B.; Randolph, M.F. Evaluation of a Minimum Base Resistance for Driven Pipe Piles in Siliceous Sand. J. Geotech. Geoenvironmental Eng. 2002, 128, 198–205. [CrossRef]
27. Dennis, D.N.; Olson, R.E. Axial Capacity of Steel Pipe Piles in Clay. In Proceedings of the Conference on Geotechnical Practice on Offshore Engineering, Austin, TX, USA, 27–29 August 1983; pp. 370–388.
28. Dennis, D.N.; Olson, R.E. Axial Capacity of Steel Pipe Piles in Clay. In Proceedings of the Conference on Geotechnical Practice on Offshore Engineering, Austin, TX, USA, 27–29 April 1983; pp. 389–402.
29. Olson, R.E.; Shantz, T.J. Axial Load Capacity of Piles in California in Cohesionless Soils. In Current Practices and Future Trends in Deep Foundations; American Society of Civil Engineers: Reston, VI, USA, 2004; pp. 1–15.
30. Iskander, M.; Garlanger, J.E.; Hussein, M.H. From Soil Behavior Fundamentals to Innovations in Geotechnical Engineering. In Geo-Congress 2014 Technical Papers; American Society of Civil Engineers: Reston, VI, USA, 2014; pp. 209–220.
90. Toğrol, E. Bearing capacity by load tests. *Int. J. Rock Mech. Min. Sci. Géoméch. Abstr.* **1975**, *12*, 101. [CrossRef]

91. Cox., W.; Kraft, L.M.; Verner, E. Axial Load Tests on 14-inch Pipe Piles in Clay. In *Proceedings of the Offshore Technology Conference*, Houston, TX, USA, 30 April–30 May 1979; pp. 1147–1158.

92. Heenema, E. Pile Driving And Static Load Tests On Piles In Stiff Clay. In *Proceedings of the Offshore Technology Conference*, Houston, TX, USA, 30 April–30 May 1979.