15 Apr 2004, 10:45am - 12:00pm

A Half Century of Tapered-Pile Usage at the John F. Kennedy International Airport

John S. Horvath
Manhattan College, Bronx, New York

Thomas Trochalides
Underpinning & Foundation Constructors, Inc., Queens, New York

Proceedings: Fifth International Conference on Case Histories in Geotechnical Engineering
New York, NY, April 13-17, 2004

A Half Century of Tapered-Pile Usage at the John F. Kennedy International Airport

John S. Horvath, Ph.D., P.E.
Manhattan College
Bronx, New York 10471-4098, U.S.A.

Thomas Trochalides
Underpinning & Foundation Constructors, Inc.
Queens, New York 11378, U.S.A.

ABSTRACT

Tapered driven piles have been the deep foundation of choice ever since construction of and at the well-known John F. Kennedy International Airport (JFKIA) in New York City began in the late 1940s. Timber piles were used primarily for many decades but various brands of closed-end steel pipe piles have become preferred in recent years as engineers have sought ever-increasing allowable axial-compressive loads per pile. With currently available pile types it is now possible to routinely install tapered piles that have an allowable axial-compressive service-load capacity per pile in excess of 400 kips (1780 kN), with net ultimate axial-compressive geotechnical capacities of the order of 1000 kips (4450 kN).

Fortunately, the use and load testing of piles at JFKIA has been relatively well documented. This extensive history and record of tapered-pile usage in one geologic setting provides an unusual opportunity to evaluate a new (in 2002) method for estimating the axial-compressive geotechnical capacity of tapered piles. The results of this evaluation are summarized in this paper and indicate very good agreement between measured and calculated capacities.

INTRODUCTION

The cost effectiveness of using tapered driven piles, especially as "friction piles" in coarse-grain soils, was recognized at least as far back as the 1950s when Peck authored his landmark report on the subject [Peck 1958]. Of course humans had been using tapered driven piles for thousands of years before that by virtue of using naturally tapered timber piles.

Despite the proven cost effectiveness of tapered driven piles, experience suggests that they are underutilized in practice. This appears to be due to a combination of several factors:

- lack of knowledge and education about their existence,
- lack of a reliable analytical method for estimating their axial-compressive geotechnical capacity and
- lack of marketplace competition to minimize their cost.

Work at the Manhattan College School of Engineering Center for Geotechnology (CGT) was initiated in recent years to address the first two issues. Coincidentally, during roughly the same time frame market forces in the U.S.A. were addressing the third issue [Horvath et al. 2004].

BACKGROUND

Historically, the use of tapered driven piles in the New York City metropolitan area has been very common. This is due to a combination of appropriate geologic conditions (sands from Pleistocene glaciation are encountered in many areas) and local piling suppliers and contractors who have been proactive in advancing the states of practice and art for tapered piles.

In view of these factors, it is no surprise that tapered driven piles have been the deep foundation of choice ever since the well-known John F. Kennedy International Airport (JFKIA, originally named New York International ("Idlewild") Airport) was first developed in the 1940s by The Port Authority of New York and New Jersey (PANYNJ, originally named the Port of New York Authority). The only thing that has changed in the more than 50 years of construction at JFKIA is the type of tapered pile used, beginning with generic, naturally tapered timber piles and evolving through several types of closed-end steel shell and pipe piles that are filled with portland-cement concrete (PCC) after driving. Many of these piles were load tested to geotechnical failure. Fortunately, much of this work was well documented.

PURPOSE AND SCOPE OF PAPER

The extensive experience with tapered driven piles at JFKIA offered a unique opportunity for the ongoing CGT research into tapered piles. As discussed subsequently, the geologic conditions at JFKIA are remarkably uniform throughout most of the airport area so it is possible to easily compare load-test results from various structures and locations throughout the airport. In addition, because a variety of tapered piles with ever-increasing geotechnical capacity have been driven and load tested over the years there is a unique opportunity to compare various measured and calculated results. In particular, the comprehensive experience with tapered driven piles allows an opportunity to investigate the effect of taper angle which is probably the single most important variable in determining the axial-compressive geotechnical capacity of such piles.

The purpose of this paper is to present the outcomes of recent CGT research that involved a retrospective assessment of the axial-compressive geotechnical capacities of several different types of tapered piles that were driven at JFKIA since 1972. This research also allowed further validation of an interim improved analytical method for tapered driven piles that was developed by the first author of this paper and first reported in Horvath [2002]. This method offers good analytical accuracy, requires nothing more sophisticated than Standard Penetration Test (SPT) *N* values as input, and can be solved manually if desired.

GEOLOGIC AND SUBSURFACE CONDITIONS

Despite the relatively large area covered by JFKIA (almost 8 square miles (20 square kilometres)), the overall geologic setting and subsurface conditions are surprisingly uniform. A general description can be found in York et al. [1994] and is synopsized here.

Figure 1 was taken from Horvath [2002] and illustrates typical subsurface conditions within the Central Terminal Area (CTA) where most of the piles considered in this paper were driven. Also shown are SPT field *N* values, N_f, and cone penetrometer (CPT) tip resistances, q_c, (the latter normalized to atmospheric pressure, p_{atm}) that are typical of conditions within the CTA. Note that the assumed SPT hammer efficiency of 45% shown in this figure is representative of SPT driving systems used up to ca. 1990 when this particular boring was drilled. The SPT driving system used in recent years has an efficiency of the order of 60% as verified by field measurements.

Virtually the entire airport property was originally a marine tidal wetland bordering on Jamaica Bay which is part of the Atlantic Ocean. Within the depth of interest for foundation purposes (approximately 100 ft (30 m)), the original Holocene wetland soils (mostly organic clay with some peat) are underlain by a stratum of sand (predominantly fine but grading coarser with depth) that is a kame (outwash) glacial-drift deposit from the recent Pleistocene glaciation that terminated several miles (kilometres) north of the airport. The current JFKIA property was developed in the 1940s by dredging similar sands from within Jamaica Bay and hydraulically pumping them over the wetland. The resulting surface topography is quite flat. Some of the piles discussed in this paper are located at the northern edge of the JFKIA property, at or just north of the former shoreline. The Holocene organic stratum in these areas becomes very thin and eventually disappears entirely. In addition, the Pleistocene sand stratum becomes both overall denser and coarser in gradation as it approaches and eventually transitions into the terminal-moraine glacial-drift deposits north of the airport.

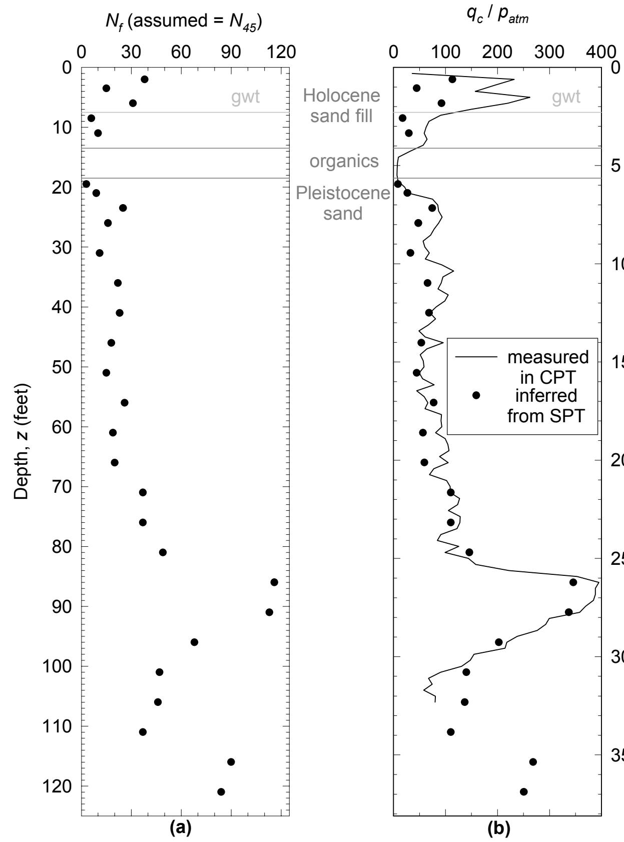

Fig. 1. Typical JFKIA CTA Subsurface Stratigraphy and In-Situ Test Results.

As shown in Fig. 1, the current ground-water table is located within the Holocene sand-fill stratum. The piezometric level within the underlying Pleistocene sand stratum is close to that in the Holocene fill and was assumed so for all calculations reported in this paper.

PILES STUDIED

Introduction and Overview

At various times in the history of JFKIA, comprehensive test-pile programs (broadened to include drilled shafts beginning in the late 1980s) have been conducted to determine the most cost-effective deep-foundation alternative for use in major construction programs at the airport. Three of these programs were selected for the work reported in this paper.

Pile Taper Angle

The taper angle, ω, of a tapered pile, or the tapered portion of a pile that has both tapered and constant-diameter portions, plays a significant role in axial-compressive geotechnical capacity. Taper angle is defined as the angle, typically expressed using the imperial unit of degrees, that the planar outside surface of a pile makes with respect to its longitudinal axis. Thus a constant-diameter pile has a $\omega = 0°$. As will be seen, what is rather remarkable is that:

- small taper angles (typically $\omega < 1°$) have significant beneficial impact on axial-compressive geotechnical capacity and
- small changes in taper angle can have a significant effect on axial-compressive geotechnical capacity.

Test-Pile Programs

1972-1973 "IAB-STRAP". The primary purpose of this program was to refine timber-pile design for a parking garage (referred to by its acronym STRAP) that was planned in the CTA in the vicinity of what was then called the International Arrivals and Departures Building (IAB). Thus only timber piles were load tested and these results were used for the study reported in this paper. By this era, a 60 kip (267 kN) maximum allowable axial-compressive capacity under service-load conditions was considered standard for timber piles at JFKIA although there was some consideration to trying to raise this to perhaps 80 kips (356 kN) if structural capacity of the piles would allow it.

An interesting, secondary aspect of this program was that several examples of each of two different types of closed-end steel shell piles (the constant-diameter *Cobi Helcor* and the quasi-tapered *Raymond Step-Taper*®) and one type of pipe pile (the tapered *Monotube*™) were also installed. A maximum allowable axial-compressive capacity of 120 kips (534 kN) under service-load conditions was desired for these piles. However, none was ever load tested.

In retrospect, there were several items of particular interest in this program:

- Some of the timber piles had unusually shallow penetrations into the Pleistocene sand bearing stratum, as little as about 3 ft (1 m) in one case.
- Dynamic measurements were made on several piles using what would later be known as the Pile Dynamics, Inc. (PDI) *Pile Driving Analyzer*®. PDI *CAPWAP* analyses were also performed. This was certainly one of the earliest commercial applications of this equipment and procedures, and may have been their first use in the New York City metropolitan area.
- The installation of several *Raymond Step-Taper* piles may have represented one of the last commercial uses of this pile in the New York City metropolitan area. The *Raymond Step-Taper* pile was unusual in that it achieved an overall taper in a series of constant-diameter steps. The *Raymond Step-Taper* and its "true" tapered companion, the *Raymond Standard* pile, were some of the earliest tapered piles that were developed commercially in the U.S.A. [Chellis 1961].
- The installation of several *Monotube* piles, which have a tapered lower section and a constant-diameter upper section, requires some further comment. *Monotube* piles come in three standard taper angles or "types": Type F ($\omega = 0.33°$), Type J ($\omega = 0.57°$), and Type Y ($\omega = 0.95°$). Only Type Y piles with the largest taper angle were driven, and both 14- and 16-inch (356- and 406-mm) constant-diameter upper sections were tried. What is interesting is that piles with $\omega = 0.95°$ would ultimately emerge as the taper angle of choice at JFKIA but not until more than a quarter-century later.

1988-1990 "JFK 2000". This program was much more comprehensive than the preceding in that a variety of driven piles (timber, *Monotube* Type J, constant-diameter steel pipe) as well as drilled shafts were driven/installed and load tested as part of a planned reconstruction of JFKIA that was called JFK 2000. Only the results from the timber and *Monotube* testing were relevant for the study reported in this paper.

It is interesting to note that only the intermediate (Type J) taper of the *Monotube* line, with a 14-inch (356-mm) constant-diameter upper section, was chosen for this program. As noted above, the earlier 1972-1973 program had used the largest (Type Y) taper but had not explored its capacity. By the 1988-1990 time frame, designers were looking for allowable *Monotube* pile capacities under service loads in the range of 200 to 240 kips (890 to 1068 kN).

1998-2000 AirTrain and CTA Terminals. The very end of the 20th century saw extensive construction at JFKIA and vicinity for several new terminals as well as a light-rail system called AirTrain to connect JFKIA with nearby transit hubs. By this time, designer engineers were looking for piles with allowable axial-compressive service-load capacities of at least 300 kips (1335 kN). *Monotube* piles with the greatest taper (Type Y) and an 18-inch (457-mm) constant-diameter upper section was the initial choice.

These design requirements, which pushed the edge of the deep-foundation envelope at JFKIA, ultimately led to the development of the *Tapertube*™ pile which essentially mimics the *Monotube* in terms of its overall shape, geometry and dimensions but has several structural features that seem to provide better performance under demanding driving and static-load conditions. This is supported by the fact that allowable axial-compressive service-load capacities in excess of 400 kips (1780 kN) were eventually used for *Tapertube* piles within a relatively short time after they appeared commercially. In some cases, net ultimate axial-compressive geotechnical capacities per pile of the order of 4500 kN (1000 kips) have been measured.

The evolution of the *Tapertube* pile is discussed in detail by Horvath et al. [2004]. However, key aspects of these piles for the purposes of this paper are:

- There were two early, experimental versions that are referred to herein as Type Ia ($\omega = 1.6°$) and Type Ib ($\omega =$

0.95°). Note that the Type Ia had a taper angle greater than any commercially available *Monotube* pile while the Type Ib had the same taper angle as the *Monotube* Type Y. The common element between the *Tapertube* Ia and Ib is the connection detail between the tapered lower portion and constant-diameter upper portion of the pile. This detail was subsequently changed on the "production" version.

- The production version of the *Tapertube* with the changed connection detail is referred to herein as Type II. It has the same taper angle as the experimental Type Ib and *Monotube* Type Y ($\omega = 0.95°$).

It is important to note that the *Tapertube* "type" designations (Ia, Ib, II) used in this paper are unofficial terms created by the authors solely to facilitate reference to the different versions of this pile. At the time this paper was written (July 2003), there is no known official nomenclature for the different sizes of *Tapertube* piles as there is for *Monotube* piles.

ANALYTICAL METHOD USED

Introduction

A detailed discussion of the analytical method used to calculate the axial-compressive geotechnical capacities of the piles reported herein is beyond the length-limits of this paper but can be found in Horvath [2002]. However, a summary of key elements of this method is presented here for information.

Background

Traditional Analytical Methods. One of the factors that has hampered the wider use of tapered driven piles has been the lack of reliable analytical methods for calculating their axial-compressive geotechnical capacities. A survey of published analytical methods for driven piles in coarse-grain soils indicates that most researchers have not considered tapered piles at all. When they have, it is often in a very conservative, simplistic fashion, e.g. Meyerhof [1976] recommended that tapered-pile side friction simply be 150% (i.e. an increase of 50%) that of a constant-diameter pile (but only for tapered piles with $\omega > 1\%$ which would actually eliminate most of the piles discussed in this paper). This recommended increase was not a function of taper angle (which turns out to be a significant variable) and is also very conservative (the increase can be of the order of ten times what Meyerhof suggested) so that the benefit of taper is seriously underestimated. Interestingly, this suggested taper benefit was dropped entirely in the presentation of Meyerhof's method contained in Hannigan et al. [1998].

Historically, the primary analytical method mentioned whenever the subject of tapered driven piles arises is work published by Nordlund [1963]. A somewhat-updated version of his work is contained in Hannigan et al. [1998]. In many ways, Nordlund's work was ahead of his time. He recognized that there was something special about the way in which tapered piles derived their axial-compressive geotechnical capacity. Unfortunately, at that time (ca. 1960) soil mechanics had not advanced to the point where there were the analytical solutions and tools necessary to properly model the special behavior of tapered piles. Nordlund viewed (incorrectly as it turns out) the capacity mechanism of a tapered pile section as one of side friction. As is well known, side friction is one of the two classical capacity mechanisms for any deep foundation in axial compression, the other being end bearing. He accounted for the benefit of taper by increasing the lateral earth pressure coefficient acting on the pile side that produces the side friction.

The Third Capacity Mechanism. The landmark breakthrough in correctly understanding the behavior of tapered deep foundations in general, and tapered driven piles in particular, was the work of Kodikara [Kodikara and Moore 1993]. Using modern soil mechanics concepts and solutions, he demonstrated for the first time that to properly understand the behavior of tapered piles a new, third deep-foundation capacity mechanism must be defined. This mechanism is called "cylindrical cavity expansion". Thus a tapered pile develops support in axial compression not so much from sliding friction along its side (as Meyerhof and Nordlund assumed) but by expanding a cylindrically-shaped volume within the soil, identical to what happens in a pressuremeter (PMT) test. It should be noted in retrospect that Nordlund had, some 30 years earlier, identified some of the basic components of this new capacity mechanism in that he used classical passive earth pressure theory for an infinitely long planar surface to develop his lateral earth pressure coefficients.

Interim Improved Analytical Method

At the present time, Kodikara's method represents what is believed to be the most-correct analytical model for use with tapered deep foundations of any kind. However, it is extremely complex mathematically and requires a numerical solution. While this is certainly not an insurmountable obstacle nowadays, its development represents a significant effort. In addition, to advance the state of practice in tapered-pile analysis any computer software encompassing Kodikara's solution would have to be made available commercially. Again, this is not insurmountable but does represent significant effort. Therefore, implementation of Kodikara's method into routine foundation-engineering practice remains a goal yet to be achieved.

As a way to advance the state of practice for tapered-pile capacity analysis in more-manageable increments, an interim improved analytical methodology was developed by the first author of this paper and presented in detail in Horvath [2002]. They key elements of this methodology are:

- A theoretical, as opposed to empirical, basis for the two traditional deep-foundation capacity mechanisms (side friction and end bearing) was used. The work of Kulhawy [1984] was used for this.

- The third capacity mechanism of cylindrical cavity expansion was approximated using empirical equations derived from Nordlund's original work as presented in Hannigan et al. [1998].
- An integrated site-characterization algorithm that was developed by the first author and first presented in Horvath [2000] was used to generate all required stress-state and shear-strength soil properties. This was considered a major aspect of the overall method as it eliminates the soil-property guesswork that is a staple of most geotechnical analyses. It is of interest to note that although this site-characterization algorithm uses state-of-art empirical relationships and produces relatively sophisticated results it requires nothing more than CPT q_c data as input and can even be used with SPT N values if no CPT data are available.
- Both the site-characterization and pile-capacity components of this interim improved method can be solved by manual calculation although using a computer solution greatly reduces the time required. Experience indicates that commercially available spreadsheet and mathematics software can be used for this purpose.

This interim improved analytical method was used for all analyses reported in this paper. One important change was that the site-characterization algorithm in Horvath [2002] was updated as discussed in Horvath [2003].

PRESENTATION AND DISCUSSION OF RESULTS

Measured Versus Calculated Capacities

Background Comments re Load Tests. Before comparing measured and calculated pile capacities, it is important to understand the limitations and shortcomings of the measured results. The load tests used for the study reported in this paper were mostly, if not exclusively, traditional maintained load (ML) tests using dead-weight reaction. There is a tendency to view results from such tests as "the answer", i.e. the absolute, single-valued geotechnical capacity of the pile. In reality, there are many reasons involving both the test procedures themselves as well as the interpretation of the measured load-settlement curve that make pile load test results really more of a range of capacities and only at some point in time at that. A detailed discussion of this topic is beyond the scope of this paper but can be found in Horvath [2002].

Overall Results. Figure 2 shows the comparison between measured and calculated net ultimate axial-compressive geotechnical capacities for the piles studied. Data points with arrows indicate piles that were judged not to have failed at the maximum load applied. However, in all such cases it appeared that the pile was close to its failure load. The trend in ever-increasing pile capacities at JFKIA is quite apparent from this figure, roughly an order of magnitude in a span of 30 years.

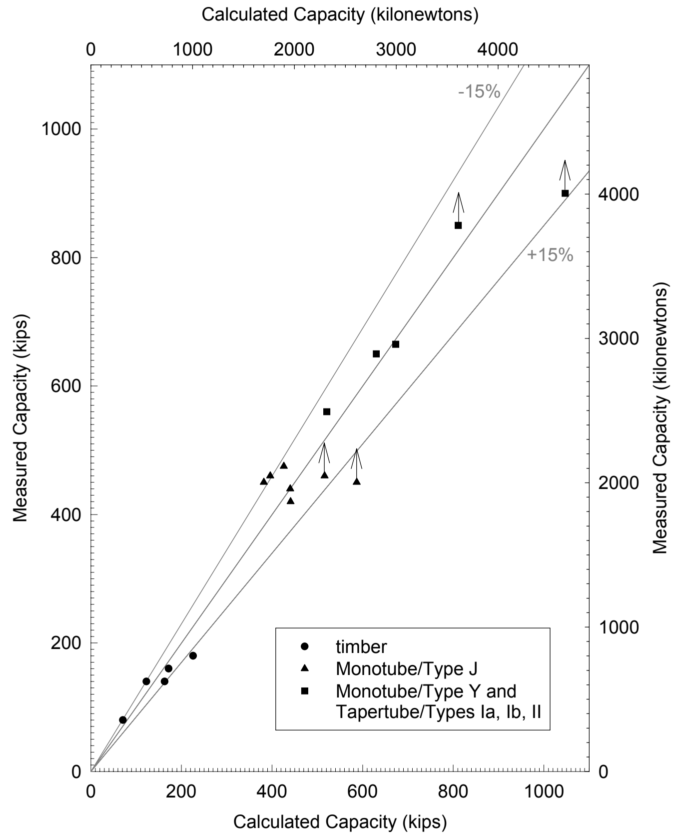

Fig. 2. Measured versus Calculated Net Ultimate Axial-Compressive Geotechnical Capacities.

The agreement between calculated and measured results is generally within ±15% and is considered to be quite good. However, one additional comment is warranted concerning timber piles. Calculated capacities using the interim improved analytical method used in this study are sensitive to the taper angle. The same is true if Kodikara's method were used. Taper angle is rather variable for timber piles because of their natural, non-manufactured origin. For example, for the piles shown in Fig. 2 ω was found to vary between 0.2° and 0.3°. In fact, for one 60 ft (18 m) long pile for which relatively-detailed physical measurements were made ω was found to vary between 0.15° and 0.27° along the pile with an average of 0.21°.

Load v. Settlement. One of the ancillary capabilities of the interim improved analytical method used to develop the results presented in Fig. 2 is the ability to generate a theoretical load-settlement curve. The curve is actually a series of line segments connecting a series of points defined on the following basis:

- Zero load and pile settlement at the origin initially.
- The load corresponding to the peak side resistance of both the constant-diameter and tapered portions plus 10% of the peak tip capacity. This occurs at a downward movement of the top of the pile equal to the theoretical elastic compression plus 0.12 inches (3 mm).

- The load corresponding to the constant-volume (critical-state) side resistance of the constant-diameter section, the peak side resistance of the tapered section plus the peak tip capacity. This occurs at a downward movement of the top of the pile equal to the theoretical elastic compression plus 15% of the pile tip diameter (1.2 inches (30 mm) for the majority of the piles shown in Fig. 2).
- When all load is removed, there is a net settlement equal to 15% of the pile tip diameter (1.2 inches (30 mm) for the majority of the piles shown in Fig. 2).

Figure 3 shows the typical results obtained using this procedure for one pile, a Type Ia *Tapertube*.

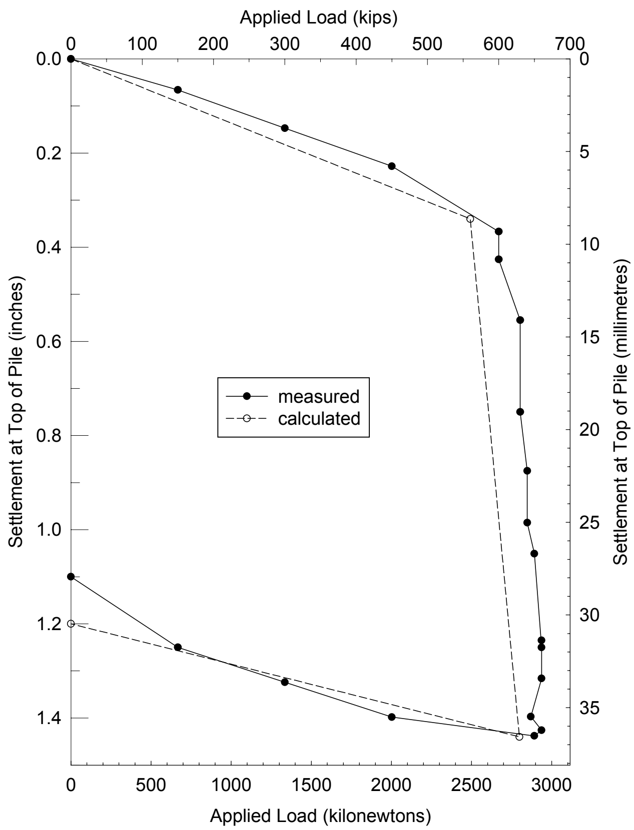

Fig. 3. Measured versus Calculated Load-Settlement Curves.

SPT v. CPT Input Data. As noted previously, the site-characterization algorithm that provides all the necessary input for the pile-capacity calculations was developed to use CPT q_c values as the preferred input data. However, the ability to use SPT field N values as an alternative was provided for in the solution algorithm as a pragmatic necessity.

An obvious question is to what extent are calculated results sensitive to the use of N values as opposed to q_c. This is especially important here as only about 40% of the pile capacities shown in Fig. 2 were based on q_c values. The rest used only N_f values. Experience to date indicates the following:

- Results based on N_f values are considered to always be more approximate simply because fewer data points are available. N values can never be closer than 18 inches (457 mm) whereas with modern CPT equipment q_c data less than 1 inch (25 mm) apart are easily obtained (the circa-1988 CPT data available for this study were spaced 12 inches (305 mm) apart).
- The empirical conversion from N_f to q_c is sensitive to the assumed SPT hammer efficiency and gradation of the soil. Therefore, all reasonable efforts should be made in practice to maximize the accuracy of these parameters. As a minimum, this means the SPT hammer system should be clearly documented on boring logs so that appropriate correlations with observed average hammer efficiencies can be used and sieve analyses should be performed on representative specimens taken from SPT samples. If these guidelines are followed, reasonable correlation between measured and inferred q_c values can be expected as shown in Fig. 1(b).
- If reasonable approximations of q_c are obtained using N_f values, then calculated pile capacities based on these N values should also be close to what would be calculated if actual q_c data were available. This is illustrated in Table 1 for one timber (TR) and one *Monotube* (MT) pile from the 1988-1990 program. In this case, the same boring and CPT sounding were close to each of these piles which makes the comparison all the more interesting.

Table 1. Comparison of Calculated Pile Capacities

Pile Number	Pile Capacity, in kips (kN)		
	Measured	Calculated	
		based on CPT	based on SPT
TR-LT10-172	180 (801)	226 (1006)	214 (952)
MT-LT2-172	420 (1869)	442 (1967)	423 (1882)

Effect of Taper Angle

Kodikara [Kodikara and Moore 1993] demonstrated conclusively that taper angle is an important variable in the axial-compressive geotechnical capacity of tapered piles. This verified the assumption made by Nordlund and supports the assumption made in developing the interim improved analytical method for tapered piles that was used in the study reported herein.

In looking toward the future, it is clear that further study centered around taper angle is desirable to optimize pile design not only at JFKIA but in any application of tapered piles. This is because the majority of the axial-compressive geotechnical capacity of a tapered pile comes from its tapered portion. Thus future research into optimizing tapered-pile design should consider the variables of:

- taper angle,
- length of tapered section and
- depth of embedment of the tapered section (due to its effect on vertical effective overburden stresses).

Initial considerations suggested that the contributions of these variables to capacity can be expressed using the dimensionless parameter β. This parameter is the basis for a popular analytical method for axial geotechnical capacity that is called the β Method [Hannigan et al. 1998, Horvath 2002]. An overview of the parameter β is as follows.

The contribution to net ultimate geotechnical pile capacity in axial compression, Q_c, that comes from the side of the pile is defined as Q_{sc} and is equal to

$$Q_{sc} = \int_0^L f_s(z) \cdot dz \qquad (1)$$

where f_s is the pile-soil friction stress, L is embedded length of the pile and z is the depth variable. The parameter f_s can be further defined as

$$f_s(z) = \beta(z) \cdot \sigma_{v_o}(z) \qquad (2)$$

where $\sigma_{v_o}(z)$ is the vertical effective overburden stress. Finally, the parameter β can be defined as

$$\beta(z) = K_h(z) \cdot \tan\delta(z) \qquad (3)$$

where K_h is the lateral earth pressure coefficient after pile installation and δ is the pile-soil friction angle. However, in the context of the interim improved analytical method used in this paper β is better defined as

$$\beta(z) = \left[\frac{K_h}{K_o}\right](z) \cdot K_o(z) \cdot \tan\delta(z) \qquad (4)$$

where K_h/K_o is the ratio of the lateral earth pressure coefficient after pile installation to the coefficient of earth pressure at rest prior to driving (K_o).

As discussed in detail in Horvath [2002], for tapered piles the ratio K_h/K_o can be visualized as having a base component equal to that for a constant-diameter pile plus an additional component that is a function of taper angle. In any event, the importance of K_o to pile capacity, whether the pile is tapered or not, is obvious from Eq. 4.

As can be seen from the above discussion in general and Eq. 4 in particular, it would thus appear that the parameter β provides a useful way to compare the relative efficiency of various types of tapered piles. This is explored in Fig. 4 in which the values of β calculated using the interim improved method are plotted as function of depth along the tapered portion of each pile (for the continuously tapered timber piles this was only the portion within the Pleistocene sand stratum).

The results shown in Fig. 4 are disappointing. Although there is an overall trend of increasing β values with increasing taper angle, there is significant overlap between results from distinctly different taper angles.

A review of Eq. 4 suggests that natural variations in K_o (which is reflected in the K_h/K_o ratio) may be masking the effect of taper. Therefore, it was decided that Fig. 4 might be better replotted using the dimensionless ratio β/K_o. This was done and the results are shown in Fig. 5. Here the effect of taper angle is somewhat clearer.

ACKNOWLEDGEMENTS

The work reported in this paper was performed as a contribution to the Integrated Site Characterization and Foundation Analysis Research Project of the CGT. The first author is the Founding Director of the CGT. The second author was an undergraduate student at Manhattan College at the time the work for this paper was performed.

The pile-capacity calculations summarized in this paper were performed by Mr. Thomas Mortko, a graduate student at Manhattan College, as part of his work for the course CIVG 757-99 (Advanced Study in Civil Engineering) during the Spring 2003 semester. Mr. Mortko's work was conducted under the personal direction and supervision of the first author.

Finally, the data on which most of this paper was based were graciously provided to the first author by the PANYNJ. Geotechnical engineers at the PANYNJ deserve credit for their decades-long proactive efforts to routinely test piles driven at JFKIA as a contribution to the state of foundation-engineering knowledge. This paper would not have been possible without their generous sharing of technical information. Additional data and information used or referred to in this paper was provided by Underpinning & Foundation Constructors, Inc. (UFC) of New York City. This material is acknowledged with gratitude. The civil engineers at UFC also deserve credit for the many deep-foundations innovations they have developed over many years.

DISCLAIMER

Reference in this paper to tradenamed products and technologies is solely for informational purposes necessary for the objectives of this paper and does not constitute an endorsement of these products and technologies by the first author, CGT or Manhattan College. No financial compensation was made to the first author, the CGT or Manhattan College by any outside party involved in the work reported herein with exception that the first author was an employee of the PANYNJ at the time of the 1972-1973 test program described in this paper. Finally, all opinions expressed in this paper are strictly those of the first author and do not necessarily reflect those of the PANYNJ, UFC or any of their employees.

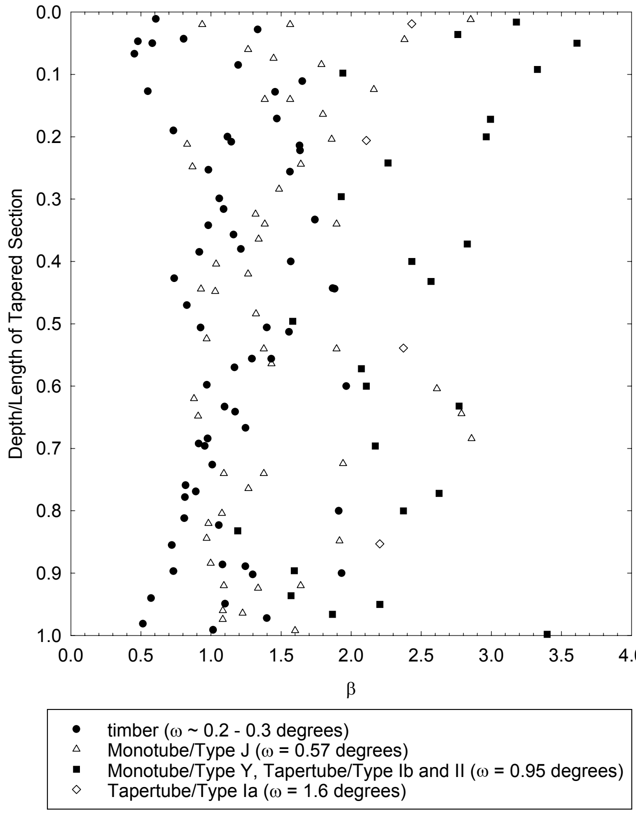

Fig. 4. Calculated β *Values as a Function of Taper Angle.*

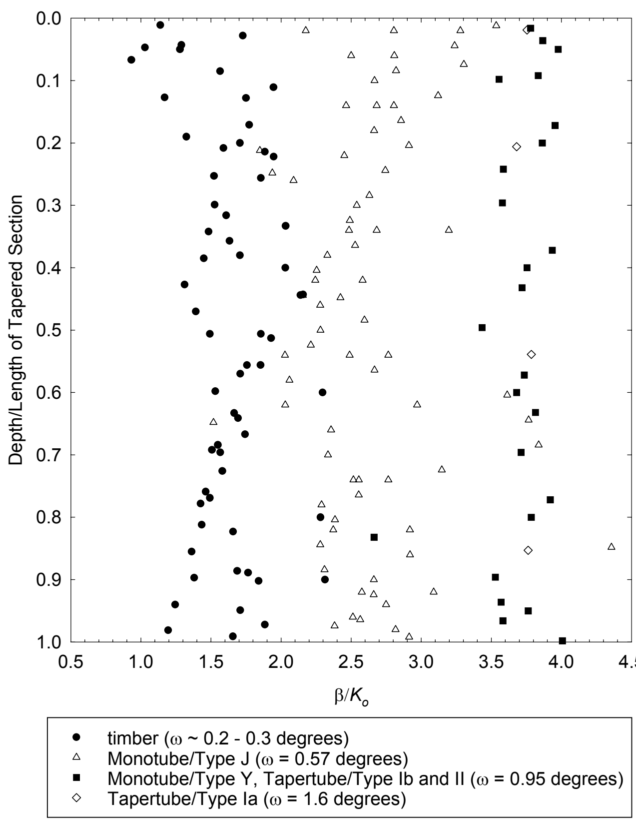

Fig. 5. Calculated β/K_o *Values as a Function of Taper Angle.*

REFERENCES

Chellis, R. D. [1961]. "*Pile Foundations*", 2nd ed., McGraw-Hill, N.Y., NY, U.S.A.

Hannigan, P. J., G. G. Goble, G. Thendean, G. E. Likins and F. Rausche [1998]. "*Design and Construction of Driven Pile Foundations - Volume I*", Rpt. No. FHWA-HI-97-013, U.S. Dept. of Trans., Fed. Hwy. Admin., Wash., DC, U.S.A.

Horvath, J. S. [2000]. "*Coupled Site Characterization and Foundation Analysis Research Project - Rational Selection of* φ *for Drained-Strength Bearing Capacity Analysis*", Res. Rpt. No. CE/GE-00-1, Manhattan Coll., Sch. of Engr., Civil Engr. Dept., Bronx, NY, U.S.A.

Horvath, J. S. [2002]. "*Integrated Site Characterization and Foundation Analysis Research Project; Static Analysis of Axial Capacity of Driven Piles in Coarse-Grain Soil*", Res. Rpt. No. CGT-2002-1, Manhattan Coll., Sch. of Engr., Ctr. for Geotechnology, Bronx, NY, U.S.A.

Horvath, J. S. [2003]. "*Integrated Site Characterization and Foundation Analysis Research Project; Updated Site-Characterization Algorithm for Coarse-Grain Soils*", Res. Rpt. No. CGT-2003-2, Manhattan Coll., Sch. of Engr., Ctr. for Geotechnology, Bronx, NY, U.S.A.

Horvath, J. S., T. Trochalides, A. Burns and S. Merjan [2004]. "Axial-Compressive Capacities of a New Type of Tapered Steel Pipe Pile at the John F. Kennedy International Airport", paper No. 11-02, Fifth Case Hist. Conf. on Geotech. Engrg., N.Y., NY, U.S.A.

Kodikara, J. K. and I. D. Moore [1993]. "Axial Response of Tapered Piles in Cohesive Frictional Ground", *J. of Geotech. Engrg.*, ASCE, N.Y., NY, U.S.A., 119 (4), 675-693.

Kulhawy, F. H. [1984]. "Limiting Tip and Side Resistance: Fact or Fallacy?", *Analysis and Design of Pile Foundations*, (J. R. Meyer, ed.) ASCE, N.Y., NY, U.S.A., 80-98.

Meyerhof, G. G. [1976]. "Bearing Capacity and Settlement of Pile Foundations", *J. of the Geotech. Engrg. Div.*, ASCE, N.Y., NY, U.S.A., 102 (GT3), 195-228.

Nordlund, R. L. [1963]. "Bearing Capacity of Piles in Cohesionless Soils", *J. of the Soil Mech. and Fndns. Div.*, ASCE, N.Y., NY, U.S.A., 89 (SM3), 1-35. [Authors' note: Nordlund's surname was misspelled in the original paper.]

Peck, R. B. [1958]. "*A Study of the Comparative Behavior of Friction Piles*", Special Rpt, 36, Hwy. Res. Bd., Wash., DC, U.S.A.

York, D. L., W. G. Brusey, F. M. Clemente and S. K. Law [1994]. "Setup and Relaxation in Glacial Sand", *J. of Geotech. Engrg.*, ASCE, N.Y., NY, U.S.A., 120 (9), 1498-1513.