# Tapered Driven Piles: New Directions for an Old Concept

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**ABSTRACT:** Driven piles with a depth-variable circumference or perimeter over all or at least part of their length are called *tapered driven piles* or simply *tapered piles*. Although they have been used for thousands of years (timber (wood) piles used by many ancient cultures and civilizations are naturally tapered) and have long been recognized as the most cost effective driven-pile alternative in many "friction pile" applications, they are not as well known and utilized as they could be. This paper is intended to be a contribution toward changing this state of affairs. A brief review of past tapered pile usage and technological development is presented to provide a basis for understanding the current state of practice for both available pile types and analytical methods. Perhaps the single most important fact to come out of this review is that it is now clear that there is a third mechanism for the axial-compressive geotechnical capacity of deep foundations, that of *cylindrical-cavity expansion*. This newly defined mechanism is the predominant way in which tapered piles develop their axial-compressive geotechnical capacity and is in addition to the traditional deep foundation mechanisms of side friction and end bearing. The paper concludes with a discussion of possible future trends regarding tapered deep foundations in general and includes greater use of drilled piles or shafts with taper.

**KEY WORDS:** deep foundations, piles, driven piles, tapered piles, drilled piles, drilled shafts, axial-compressive capacity, cylindrical cavity expansion

## INTRODUCTION

Driven piles with a depth-variable circumference or perimeter over all or at least part of their length are called *tapered driven piles* or simply *tapered piles*. They are usually installed using some type of impact (as opposed to vibratory) hammer and have long been recognized as the most cost effective driven pile alternative to use in applications calling for "friction piles", especially in coarse-grain soil conditions (Peck 1958). It is interesting to note that, on one hand, tapered piles are the oldest type of pile, indeed perhaps the oldest type of deep foundation in general, because humans have been using naturally-tapered timber (wood) piles for thousands of years. On the other hand, in many countries tapered piles are relatively unknown and have been underutilized to date. This appears to be due to a combination of several factors:

- lack of knowledge and education about their existence and/or the various types of tapered piles that are available or can be created commercially;
- lack of a reliable analytical method for estimating their axial geotechnical capacity, especially in compression; and
- lack of marketplace competition to minimize cost by making a wider variety of alternative types of tapered piles available commercially.

However, there is evidence that this overall underappreciation and underutilization of tapered piles is slowly changing as the result of renewed interest and technical developments during the past decade from several independent sources. In particular, education and research 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 were addressing the third issue, in the U.S.A. at least [Horvath et al. 2004].

This paper is intended primarily to be a contribution toward informing those involved in the design and installation of deep foundations about tapered piles. In particular, this paper is intended to present a summary of recent developments related to tapered piles, and offer some thoughts and suggestions as to where future research and development efforts might be directed. Hopefully, sharing information about the current state of knowledge concerning tapered piles will encourage their greater consideration in practice. However, a brief review of the past will first be presented as it provides useful evolutionary insight for the present and future.

# A LOOK AT THE PAST

## A Brief History of Tapered Driven Piles

*Overview*

The following discussion covers the main types of tapered piles that have figured into the evolution of tapered-pile technology and as such is considered comprehensive for the purposes of this paper. However, there are undoubtedly individual pile designs or design variations that were developed at some time in the past that are not mentioned. Some of these are covered in older texts on piles, e.g. Chellis (1961).

Before continuing, it is necessary to define the term *taper angle*, $\omega$, which is the single most important parameter for tapered piles. This 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 as a baseline reference a non-tapered (i.e. constant-diameter) pile has a $\omega = 0°$.

One of the interesting aspects of tapered piles is that a remarkably small taper angle, typically less than $1°$, is required to develop significant benefits of taper. In fact, for almost a century now the de facto "optimum" taper angle for tapered steel piles in the U.S.A. has been a slope of 1 (vertical) to 60 (horizontal) which is $\omega \cong 0.95°$. In addition, the axial-compressive geotechnical capacity is relatively sensitive to changes in taper angle, at least within some range of angles.

*Timber*

As noted previously, timber (wood) piles, which are simply the trunks of trees minus branches and bark, are the oldest type of pile in general for the obvious reason of natural availability. It is happenstance that they are tapered over their entire length by virtue of the way trees grow. Although they were the only type of pile for centuries and numerous different kinds of hard- and softwood have been used regionally over time (Chellis 1961), in recent decades the use of timber piles has been limited to geographic areas where the use of softwoods such as Southern Yellow Pine and Douglas Fir in the U.S.A. was still competitive economically. In addition, for some decades now it has been customary to treat timber piles with a preservative such as creosote to enhance their durability in unsaturated soils and open air and water (wood is naturally quite durable when kept perfectly dry or buried within saturated soil).

Fig. 1 shows a typical timber pile with creosote preservative being readied for driving in the U.S.A. some time during the latter part of the $20^{th}$ century. The power auger mounted on the side of the leads is for predrilling for obstructions, etc. prior to placing and driving the pile.

**FIG. 1. Creosote-Treated Timber Pile Being Readied for Installation**

The taper angle of timber piles can be highly variable, not only between different types of wood and length of piles but even between similar piles on a given project and along a given pile. For example, recent studies (Horvath 2002, Horvath and Trochalides 2004) of timber piles used at the John F. Kennedy International Airport

(JFKIA) in New York City during the 1970 to 1990 time frame found that ω varied between 0.2° and 0.3° for piles of similar length. In fact, for one 18-m (60-ft) long pile for which relatively detailed measurements were made ω was found to vary between 0.15° and 0.27° along the pile with an average of 0.21°. Only very recently has it been fully appreciated that these unavoidable variations in taper angle have a significant effect on calculating the axial-compressive geotechnical capacity of timber piles.

It appears that timber pile usage has been declining in recent years, even in areas such as the Eastern U.S.A. where timber piles were always an economically viable alternative when lightly-loaded piles were required. It is likely that the use of timber piles will continue to decline both from purely economic perspectives (various types of ground improvement, including minipiles, now provide alternatives) as well as the fact that it is becoming increasing difficult to find preservative treatments that are environmentally acceptable.

*Steel Shell and Pipe*

In general, tapered steel piles developed and used to date consist of a hollow, closed-end section that is nominally circular in cross section. In almost all cases (certainly for piles driven on land or close to shore in a marine environment) the inside of the pile is filled with portland-cement concrete (PCC) after the pile is driven. Depending on the specific type of steel pile used, filling with PCC is either a necessity or highly desirable from a structural-capacity perspective.

From these common elements, the distinction is made here between what will be referred to as steel *shell* piles and *pipe* piles. The steel wall of shell piles is so thin (it is usually corrugated to give it some nominal stiffness for handling) that the pile hammer cannot drive on the shell directly. Rather, a temporary steel insert, called a *mandrel*, is placed within the shell and the hammer actually impacts on the mandrel which essentially drags the shell into the ground with it. In essence, then, the shell has negligible structural capacity and serves only as a form for the poured-in-place PCC. On the other hand, a pipe pile has a sufficiently thick and robust wall so that the pile hammer can impact on it directly. The pipe also has some permanent structural capacity once installed in the ground. However, whether or not the design engineer considers all or some of this capacity depends on site- and project-specific concerns over long-term corrosion.

It appears that the first tapered steel piles developed were of the shell variety and grew out of a patent issued at the end of the 19th century (Chellis 1961). These were the *Raymond Standard*™ pile and the *Raymond Step-Taper*® pile. The former was a "true" tapered pile in that was tapered continuously and over its entire length, essentially mimicking a timber pile. The taper angle was fixed at 0.95° (which limited the maximum length of pile that could ever be driven) which seems to have set a de-facto standard for subsequent tapered-steel-pile development in the U.S.A. that continues into the 21st century. The latter pile was a pseudo-tapered pile in that it was an assemblage of several constant-diameter segments, each with a different diameter, so that the diameter changed along the longitudinal axis of the pile in discrete steps as the pile's tradename states.

Fig. 2 shows a *Raymond Step-Taper* pile being readied for driving. Note the steel mandrel being inserted into the thin, corrugated-steel shell of the pile, a process that was referred to colloquially as "shelling up". Note also again the auger mounted on the side of the leads, a not-uncommon practice in the U.S.A.

**FIG. 2. *Raymond Step-Taper* Pile Being Readied for Installation**

Both of the Raymond shell piles were proprietary with regard to both the piles themselves as well as the contractor who installed them, i.e. in general only Raymond would install them. This significantly limited opportunities for these piles to be used and also linked their usage to a single business entity. As the fortunes of this business entity declined during the latter decades of the 20th century, these piles essentially disappeared from the marketplace. It should be noted that the need to drive these piles with a mandrel, a process that is both cumbersome and time consuming, severely affects their application and overall economics so it is doubtful that the specific concepts on which these piles were based would ever be worthwhile to resurrect given all the other alternatives available to the modern-day foundation engineer and contractor.

On the other hand, tapered steel pipe piles appear to represent the future, at least as far as high-capacity tapered piles are concerned. Since the early part of the 20th century, the only tapered steel pipe pile has been the *Monotube*™ brand. The company actually making and distributing this pile in the U.S.A. has gone through several corporate changes over the years. However, the *Monotube* (as it is colloquially referred to) has always been a pile that any pile-driving contractor can purchase and install.

The *Monotube* always consists of a tapered lower section and constant-diameter upper section, with both sections made of cold-rolled steel and possessing vertical fluting that has always been the visual hallmark of this pile. The tapered sections come in three standard tapers or "types", designated 'F', 'J' and 'Y' with $\omega$ = 0.33°, 0.57° and 0.95° respectively. A variety of diameters and pipe wall thickness are available.

Fig. 3 shows a partially-driven *Monotube*. The signature vertical fluting of the cold-rolled pipe sections used for both the tapered lower section and constant-diameter upper section (extension) are readily apparent.

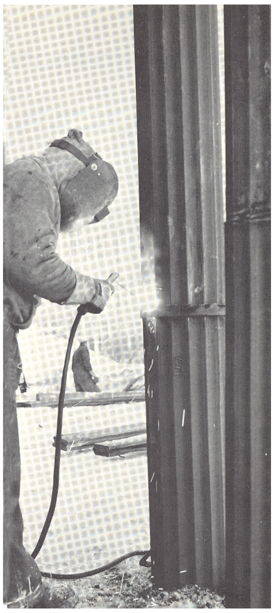

**FIG. 3. Partially-Driven *Monotube* Pile Having a Constant-Diameter Upper Section (Extension) Being Field Welded to the Tapered Lower Section**

As the years went on, foundation engineers in the U.S.A. pushed the edge of the tapered-steel-pile design envelope so that by the end of the 20th century on a project at JFKIA it became increasingly difficult to consistently achieve allowable axial-compressive service loads per pile of 1335 kN (300 kips), even using the heaviest *Monotube* sections available. This fact directly led to the development of the *Tapertube*™ pile as an alternative (Horvath et al. 2004). The *Tapertube* pile is identical to the *Monotube* in terms of its overall shape, geometry and components (i.e. a tapered lower section and constant-diameter upper section). However, the *Tapertube* is made of hot-rolled steel which results in a pile that is structurally more robust than the *Monotube*. In fact, within a relatively short time after introduction and use of the *Tapertube* pile allowable axial-compressive service loads per pile were increased to in excess of 1800 kN (400 kips). In some cases, net ultimate axial-compressive geotechnical capacities per pile approaching 4500 kN (1000 kips) have been measured.

Fig. 4 shows a *Tapertube* pile being positioned for driving on a very recent project in the New York City area. Note the ubiquitous power auger attached to the leads that is still being used in U.S. practice. However, now the pile-driving rig was of a more-modern type from Finland compared to those shown in Figs. 1 and 2. Not only are the leads of a completely different design but a hydraulic hammer was used to install the pile. The steam/air hammer, and the diesel hammer to a lesser extent, had been predominant in U.S. practice ever since mechanized pile-driving hammers began to be used there.

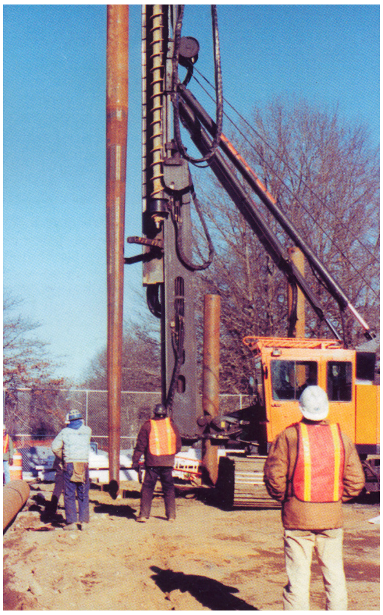

**FIG 4.** ***Tapertube*** **Pile Being Positioned for Driving**

*Portland-Cement Concrete*

Precast and later precast/prestressed PCC piles have often been the driven pile of choice in most countries outside of the U.S.A. as they are more economical than steel piles. In the vast majority of cases, PCC piles are generic in both their manufacture and installation, and can be manufactured locally to some standard design that is generally widely available.

Unfortunately, it is this generic, localized nature of PCC piles that makes it difficult to identify and trace their use as tapered piles. In the absence of a proprietary business interest, there is no organization to document their designs and usage in this manner. At the present time, only relatively spartan and anecdotal information was available to the author to indicate that tapered PCC piles have indeed been used. Kodikara and Moore (1993) and Fellenius (2002) make reference to their use in the former Soviet Union and Norway respectively. The author has heard reports of their use in the State of Florida, U.S.A.

Separate from the typical PCC pile that is relatively long and slender in shape is a variant called the *bulb pile*. Such piles have a lower portion ("bulb") that is block-like in shape as opposed to the rod-like shape of a typical pile. The particular shape of the bulb may be roughly spherical or cylindrical depending on whether it is formed in place or precast, respectively. It is the precast version, which was developed in the U.S.A. ca. 1970 as a proprietary pile called the *Tapered Pile Tip® (TPT)* pile, that is of interest here. This is because the precast bulb has the shape of a tapered, right-circular cylinder so can be classified as a tapered pile. The *TPT* pile came (it does not appear to be actively marketed at the present time) in a variety of sizes with taper angles in the range of 2.7° to 5.7°. It was used mainly in the Northeastern U.S.

It might be argued that the *TPT* pile is in a gray area categorically as it can be considered a type of *composite pile* (discussed in the following section). This is because a section of traditional piling is always required to connect the precast PCC bulb to the surface. A variety of piles, including timber and constant-diameter steel shell and pipe segments (the latter filled with PCC after driving in all cases), have been used for this purpose over the years. However, for the purposes of this paper the *TPT* is not considered to be a composite pile as for all practical purposes all axial-compressive capacity is derived, by assumption if not in actuality, by the precast bulb portion alone.

Fig. 5 shows a *TPT* pile being readied for installation. This particular tip (bulb) is typical of *TPT* piles in terms of its overall shape and size. This is one of the earliest projects to use the *TPT* pile as a steel shell (note the characteristic spiraled corrugations) is being used for the extension. The photo shows the shell being connected to the precast *TPT* tip to prepare a complete pile for driving. Note that this type of shell is very thin and required a mandrel to be inserted within it in order to drive the pile. This is one reason why the design of *TPT* piles was changed soon after their invention to using a steel pipe section for the extension as it eliminated the need for a mandrel. Note also in Fig. 5 that the top of the precast bulb is considerably larger in diameter than the outside diameter of the shell extension. This design detail resulted in the creation of an annulus around the shell as the pile was driven. This annulus was backfilled manually with soil and is one reason why any side friction along the constant-diameter extension was neglected in determining the axial-compressive geotechnical capacity of the installed pile.

**FIG. 5. An Early Version of a *TPT* Pile Being Assembled Prior to Driving**

*Composite*

As the name implies, these are piles consisting of two different types of pile materials connected axially so as to result in one pile once installed. The basic reason for doing this is purely economics and the practice has largely been abandoned for the very reason that it is no longer economical. However, it is mentioned here for the sake of completeness.

Chellis (1961) illustrates a number of variations that were used for creating composite tapered piles in the early decades of the 20th century. Each involved the use of one type of Raymond shell pile that was placed on top of either a timber pile (usually untreated as it would be below the permanent ground-water table) or section of constant-diameter steel pipe pile. A much more recent (late 20th century) example of composite tapered piles was the use of a constant-diameter steel pipe pile that was used as the extension of a *Monotube* tapered lower section (Brand 1997).

**Analysis of Geotechnical Axial Capacity**

*Compression: Introduction*

Given that humans having been installing driven piles for thousands of years, calculating the geotechnical axial capacity of piles is a relatively new endeavor. As recently as the 1960s, Terzaghi and Peck (1967) wrote the following with regard to "friction piles" in sand:

*"Attempts to predict the ultimate bearing capacity of such piles on a semi-empirical basis appear promising but as yet the procedures are in a formative stage."*

Essentially they were saying that calculating the post-driving axial-compressive geotechnical capacity of piles driven into coarse-grain soil was an unreliable, still-evolving technology. However, they did note that taper was one of several parameters that could influence the capacity of driven piles in coarse-grain soil and, therefore, a factor to be considered in design. In fact, a few years earlier it was Peck (1958), in what may be the earliest published detailed assessment of tapered piles, said:

*"…it is obvious from an inspection of Figure…that taper has a beneficial influence on the capacity of piles in sand…it would appear reasonable to conclude that a taper of 1 percent or more is likely to increase the capacity of a pile, for a given length of embedment, between $1^1/_2$ and $2^1/_2$ times."*

*Compression: Static Approach*

It appears that the first significant effort to develop an analytical method for the axial-compressive geotechnical capacity of tapered piles was the work of Nordlund (1963, with an updated presentation in Hannigan et al. 1998a). He used what will be referred to herein as the "static approach" to pile capacity, i.e.

applying fundamental soil-mechanics concepts and principles to the pile after installation. This is the same basic procedure for calculating the static capacity of piles after driving that is still used today. Nordlund assumed that resistance along the side of a pile, whether tapered or not, was derived from the traditional mechanism of side friction and resistance at the tip of the pile was from the traditional mechanism of end bearing. His contribution to the state of knowledge was the hypothesis that the lateral earth pressure coefficient that produces side friction is strongly influenced by pile taper. Specifically, he modeled pile taper using classical lateral earth pressure concepts by assuming that loading a tapered pile in axial compression was equivalent to rotating a planar "wall" through the soil. In this way, he came up with lateral earth pressure coefficients for tapered piles that were greater than those for constant-diameter piles.

Subsequent to Nordlund's work, the published record suggests that relatively little new research into the subject of calculating tapered-pile capacity was done for almost 30 years. Meyerhof (1976) was one of the few researchers who even mentioned tapered piles and even then he did so in a very simplistic manner by suggesting that the side resistance of tapered piles in coarse-grain soil was uniformly 1.5 times that of a constant-diameter pile in the same soil (this turns out to be grossly conservative and doesn't do justice to tapered piles).

It was not until ca. 1990 that significant and, as it turned out, landmark work related to taper piles was done by Kodikara (Kodikara and Moore 1993). For the first time, the true way in which tapered piles develop their axial-compressive capacity was identified. Specifically, Kodikara demonstrated that along the tapered portion of a pile the primary soil-mechanics mechanism was not the traditional sliding friction as Nordlund and Meyerhof had postulated but that of *cylindrical-cavity expansion*. In essence, as a tapered pile is pushed into the ground the soil around it is undergoing radial expansion, similar to what occurs in a pressuremeter (PMT) test. It is this radial expansion that results in the increased lateral earth pressure that provides the relatively large axial-compressive capacities of tapered piles.

Note that this cavity expansion is a unique mechanism that is fundamentally different than the traditional deep foundation capacity mechanisms of side friction and end bearing. As such, cylindrical-cavity expansion represents a new, third capacity mechanism for deep foundations. It is interesting to note that the basic manner in which tapered piles develop capacity, by lateral expansion of the soil surrounding a pile, had been correctly conceptualized by Nordlund ca. 1960. However, at that time modern soil mechanics had not advanced to the point where physical mechanisms such as cavity expansion had been identified and researched to provide the analytical results that were available to Kodikara. As a result, Nordlund did not have the theoretical resources to properly model what he visualized. Nevertheless, Nordlund deserves credit for his basic insights which ultimately proved correct.

At the present time, Kodikara's solution appears to be the state of art for calculating the axial-compressive capacity of tapered piles. However, his solution is mathematically very complex and always requires a numerical solution using a computer. While these are not insurmountable obstacles nowadays, experience suggests that until software containing Kodikara's solution is widely available to engineers his analytical methodology will not see widespread use.

To overcome this pragmatic handicap, the author developed an interim improved method for analyzing tapered piles with the intention that it would provide a methodology that was both immediately available and relatively easy to use. This interim method was part of a larger research project to better integrate site characterization and geotechnical analysis that was first applied to the problem of shallow-foundation bearing capacity (Horvath 2000a, 2000b). This interim analytical method for piles was first presented in Horvath (2002) and was recently updated (Horvath 2003a). A discussion of how to use the current version of this method can be found in Horvath (2003b).

*Compression: Dynamic Approach*

An alternative to the "static approach" to pile capacity that was used by Nordlund, Meyerhof, Kodikara and the author as described above is the "dynamic approach". This approach uses the familiar one-dimensional wave equation as the fundamental theoretical model and solution, and is based on the philosophy that resistance encountered during driving relates to static axial-compressive capacity afterward.

In practice, this dynamic approach is used in two distinct ways:

- as an office tool using commercially produced and widely available wave-equation software to perform capacity and/or drivability assessments using assumed hammer performance, etc. and
- as a field tool for obtaining and interpreting actually measured results using proprietary hardware and software such as the Pile Driving Analyzer® (PDA) and CAPWAP®, both from Pile Dynamics, Inc.

Each of these uses is now considered to be a normal part of routine driven-pile practice worldwide (Hannigan et al. 1998a, 1998b).

Regardless of the specific manner in which the dynamic approach is used in practice, it is important to note that it is always built around the basic model that resistance of the portion of the pile that is embedded in the ground is provided only by the two traditional mechanisms of side friction and end bearing. This is now recognized as an incorrect model for tapered piles in view of the preceding discussion concerning the now-recognized third capacity mechanism of cylindrical-cavity expansion. Recent studies conducted for the new *Tapertube* pile suggest that the failure of these dynamic-capacity methods to properly model how a tapered pile develops axial-compressive resistance is at least part of the reason for the relatively poor correlation between geotechnical capacity estimates made using dynamic methodologies such as the PDA and CAPWAP, and capacities measured in traditional maintained-load tests (Horvath et al. 2004).

*Uplift (Tension)*

One of the arguments heard at times as to why tapered piles are not used more widely is that they have negligible uplift capacity. Many foundation engineers simplistically (and incorrectly) visualize a tapered pile that is subjected to an uplift force as immediately and neatly separating from its tapered hole in much the same way that end bearing of a deep or shallow foundation is assumed (again simplistically and incorrectly) to immediately disappear under uplift-force application.

There has been relatively little need to date to develop a theoretically sound model for the uplift behavior of tapered piles to counteract this misconception and, as far as is known, none has been developed. There have been some small-scale model tests of the uplift behavior of tapered piles but these tests have been heavily criticized in discussion and do not appear to provide a sound basis for developing even an interim empirical model and solution for calculating the uplift capacity of a tapered pile.

## AN ASSESSMENT OF THE PRESENT

In view of the preceding presentation and discussion, it appears that as a result of several significant developments in recent years tapered-pile technology has the potential for significant increase in recognition and growth worldwide. At the present time, there is marketplace competition for steel piles and, as always, there is the ability to develop locally-manufactured precast, prestressed PCC piles with a shape and taper to fit local needs. With particular regard to the steel *Tapertube* piles, because they are made of hot-rolled components there is significant room for growth in terms of pile diameters and wall thicknesses. This means that there is the potential for much larger axial-compressive capacities than have been exploited to date, especially in the offshore environment.

Analytically, there is now a currently-available, generic methodology for estimating the axial-compressive geotechnical capacity of tapered piles in coarse-grain soil that shows acceptable correlation with measured capacities (Horvath 2003b). There is also a more-general and theoretically-rigorous analytical method (Kodikara and Moore 1993) that can be developed for routine practice with some additional effort by developing a commercially available computer code.

## A VIEW TO THE FUTURE

### Introduction

As noted in the preceding section, there has never been a more conducive climate than at present for using tapered driven piles installed in the traditional manner using impact hammers. However, there is also no reason to limit the development of tapered deep-foundation geotechnology where it is at present. Therefore, as a conclusion to this paper it is useful to suggest areas where additional research and development may be useful and productive.

### Research

The following topics are suggested for conducting future research and development of tapered driven piles. No attempt has been made to assemble them in any order of importance as importance is highly subjective. For example, a foundation engineer may consider capacity calculation a critical need whereas a pile-installation contractor may consider optimization of pile design critical for their interests:

- Computer software should be developed and made available commercially that implements Kodikara's solution. Strong consideration should be given to integrating site characterization into the overall solution algorithm along the lines of what was done for the author's interim improved analytical method (Horvath 2003b).

- Fine-grain soils should be considered in any solution methods developed in the future. There does not appear to have been any systematic study to date to indicate whether or not taper is beneficial in fine-grain soil conditions. This is something that should be explored.
- An analytical methodology should be developed for estimating the geotechnical uplift (tension) capacity in all soil conditions. There is evidence that this type of loading may be of greater interest in the future as presently available information suggests that tapered piles have been used or at least are being considered for use in high-capacity offshore applications (M. Randolph, personal communication, 2003).
- The capability of assessing the effect of group behavior on pile capacity in all soil conditions and for both types of axial loading should be developed. There is very limited evidence that suggests in coarse-grain soil at least there is a significant increase in lateral earth pressures due to group effects that translates into increased axial-compressive capacity (Horvath et al. 2004). While such increases have long been known for constant-diameter piles, it is possible that they may be even more significant for tapered piles.
- For both compression and tension loading in coarse-grain soils, the effect of time on capacity should be considered in any analytical methods as well as when interpreting any actual load measurements that are used to validate analytical methods. Time effects are now recognized as important even for piles bearing in coarse-grain soil (York et al, 1994, Chow et al. 1997).
- One of the more-intriguing issues is whether or not there is a *limiting taper angle*. This is defined herein as a taper angle beyond which no additional benefit of taper develops. Nordlund concluded there was such a value but this was due to the conceptual model of a retaining wall that he used, i.e. there is always an upper bound on passive earth pressure. For both simplicity and the fact that it rarely controlled a problem solution this concept of a limiting taper angle was retained for the author's interim improved analytical method (Horvath 2002, 2003b). On the other hand, Kodikara's work (Kodikara and Moore 1993) is interpreted by the author as indicating that there is no such limiting value. However, there must be some limit. If for no other reason, as the taper angle increases from 0° to 90° the mechanism of cylindrical-cavity expansion must transition to the classical mechanism of end bearing (which, interestingly Vesic modeled as *spherical-cavity expansion* when he developed his bearing-capacity solution (Vesic 1975)). Thus at some point the behavior assumed by Kodikara simply no longer exists. So it would appear that fundamental research would be useful to determine the taper angle at which one mechanism transitions to the other.
- Given the strong theoretical link between tapered piles and the PMT test, it would be useful to explore using the PMT test to develop input parameters for tapered-pile analytical methods.
- As discussed in Horvath and Trochalides (2004), the axial-compressive resistance from the tapered portion of a pile is primarily a function of three variables: taper angle, length of the tapered section, and embedment depth of the tapered section. Because most of the axial-compressive capacity of a tapered pile comes from its tapered section, it would be useful to develop an algorithm to optimize pile design for a given project application, e.g. is it better to use a shorter pile with more taper or a longer pile with less taper. The purpose of this would be to minimize costs.
- It appears that a complete and fundamental reassessment of the classical one-dimensional wave equation and the various dynamic methods that derive from it is required. Specifically, this equation needs to be modified so that pile resistance during driving from the cylindrical-cavity-expansion capacity mechanism is correctly accounted for in the model which it is not at present. Given the widespread use of the various dynamic methods in current practice worldwide this is a critical need.

**Broader Applications**

This paper has intentionally focused on tapered driven piles installed using impact hammers as this is where the vast majority of usage with regard to tapered deep foundations appears to have occurred to date and where the greatest potential exists in the near term. However, the axial-compressive capacity mechanism of cylindrical-cavity expansion is completely general (as are the two traditional capacity mechanisms of side friction and end bearing). This means that many of the concepts discussed in this paper are applicable to:

- preformed piles that are installed using vibratory as opposed to impact hammers,
- helical piles that are screwed into the ground,
- drilled piles (defined for the purposes of this paper as deep-foundation elements that are created in place using a cement grout injected under pressure) and
- drilled shafts (defined for the purposes of this paper as deep-foundation elements that are created in place by placing high-slump PCC under gravity into preformed holes).

The broader potential for developing tapered deep foundations that are efficient at carrying axial-compressive loads was noted by Kodikara (Kodikara and Moore 1993). He discussed a drilled-in type of deep-foundation element that was used in the former Soviet Union that had a circular cross section. Clearly, there is a significant, broad potential for developing other types of tapered deep foundations. Whether such foundations would be economically viable in the marketplace is, of course, some that would have to be assessed on a local or regional basis.

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