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A NEW TYPE OF TAPERED STEEL PIPE PILE FOR TRANSPORTATION APPLICATIONS

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ABSTRACT: Piles with a variable perimeter over all or part of their length are generically called *tapered piles*. The benefit of using tapered piles when axial-compressive loads predominate, especially in 'friction' situations involving coarse-grain soils, has been recognized in principle for a long time. However, this benefit does not appear to have been fully exploited in practice, especially in transportation applications.

Several recent events have produced a rebirth of interest in tapered piles, at least in U.S. practice. One was the development and commercial introduction of a new type of proprietary tapered steel pipe pile called the *Tapertube*™. It was developed primarily to provide commercial competition to the long-established *Monotube* pile but it has also demonstrated that it is a structurally robust pile capable of withstanding the stresses of today's high-capacity design requirements. Of relevance to this conference is that *Tapertube* piles were essentially developed for, and eventually used extensively on, one of the larger transportation-related projects in the New York City metropolitan area in recent years, the major renovation and expansion work at the John F. Kennedy International Airport. This work included both terminal buildings and several kilometres of elevated light-rail structures as well as project-wide design for seismic loading. As a result, a comprehensive pile-load-test program was conducted to verify the performance of *Tapertube* piles under compressive, uplift and lateral loads.

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BACKGROUND

Overview

The geotechnical benefit of pile taper in efficiently resisting axial-compressive loads was recognized in principle at least as far back as the 1950s when Peck (1958) stated:

"…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."

However, experience suggests that tapered piles are generally underutilized, at least in U.S. practice, for several reasons that include:

- lack of knowledge and education about their basic existence;
- lack of knowledge and education about the various types of tapered piles that are available or can be created commercially;
- lack of a modern, reliable analytical method for estimating their axial geotechnical capacity, both in compression and tension (uplift);
- lack of marketplace competition with regard to pile types to avoid sole-source specification (always a problem on publicly funded projects as is typically the case for transportation-related projects) and minimize costs by making a wider variety of alternative types of tapered piles available commercially; and
- lack of commercially available tapered piles that have the sufficiently high structural capacity, both during driving and under service loads, required both by current design requirements and to compete economically with other deep-foundation alternatives.

In the last years of the 20th century, the issues of geotechnical-capacity calculation and increased structural capacity became problematic even in those markets such as the New York City metropolitan area where tapered piles historically enjoyed widespread knowledge and usage. There have been significant efforts in recent years to address these issues through both academic research and commercial development of new types of tapered piles. The latter issue in particular is the focus of this paper.

Geotechnical Capacity Calculation Methods

For decades, the only analytical method that specifically addressed the geotechnical axial capacity of tapered piles was that developed by Nordlund (1963) in the early days of modern soil mechanics. Recent research (Horvath 2002) suggests that Nordlund's method is deficient in several respects, the most important being that it does not correctly model the way in which a tapered deep-foundation element derives its axial capacity. The work of Kodikara (Kodikara and Moore 1993) demonstrated conclusively that there is a third capacity mechanism called *cylindrical-cavity* *expansion* that defines the axial-compressive behavior of any type of tapered deep foundation. This mechanism is in addition to the classical mechanisms of side friction and end bearing that have long been recognized for deep foundations.

In addition to Kodikara's rigorous solution, there have been efforts to develop a relatively simple solution that could be solved manually if desired (Horvath 2002; Horvath 2003). An important element of this latter solution is the explicit integration of a modern site-characterization algorithm directly into the analytical process. A recent study (Horvath and Trochalides 2004) that involved a wide variety of tapered piles demonstrated that this is a promising analytical method for practical use.

Pile Alternatives

The issues of marketplace competition and increased structural capacity that were identified previously were addressed simultaneously during the 1990s as a result of the commercial development and introduction of a new type of tapered steel pipe pile called the *Tapertube*™. This is a patented pile (although it can be installed by any piling contractor under license) that provides both a design alternative and marketplace competition to the proprietary *Monotube* pile that has been available since the early 20th century (Chellis 1961). A choice in tapered steel piles has not existed since the demise of the *Raymond* line of true- and pseudo-tapered piles decades ago. A complete discussion of the evolution of the *Tapertube* pile can be found in Horvath et al. (2004). Only a brief summary of its key components is presented here.

The *Tapertube* is similar to the *Monotube* in terms of its overall geometry and components, i.e. it has a tapered lower section and constant-diameter upper section. The tapered lower section of the *Tapertube* consists of a steel plate that is bent so that it has 12 flat faces or sides to create an approximately circular cross section. The constant-diameter upper section is a section of standard circular 'pipe' pile. Figure 1 shows several *Tapertube* piles assembled and ready for installation.

FIG. 1. *Tapertube*™ Piles Stockpiled at Job Site and Ready for Installation

Despite their overall similarity in appearance, there are important structural differences between the two piles. The primary one is that the *Tapertube* is made entirely of hot-rolled components whereas the *Monotube* is fabricated from cold-rolled members. Thus there is no inherent technical barrier to pile size (length and diameter) and structural capacity with the *Tapertube* as exists currently with the *Monotube*. This has already been found to be a significant advantage in practice.

APPLICATION

Introduction

As a way of introducing the *Tapertube* pile as a viable deep-foundation alternative for transportation-related projects, an overview of its relatively recent extensive application at the John F. Kennedy International Airport (JFKIA) in New York City is presented here. JFKIA provides an unusually good setting for discussing tapered piles in coarse-grain soil as a wide variety of such piles have been tested and utilized there in the more than 50 years the airport has existed (Horvath and Trochalides 2004). In fact, the demanding pile-design requirements at JFKIA are directly responsible for both advancing the state of art of tapered-pile technology in general and the development of the *Tapertube* pile in particular. In addition, there has been significant study of the time-dependent axial compressive capacity of piles at JFKIA (York et al. 1994). It is now recognized that this phenomenon, which is often referred to colloquially as *setup* or *freeze*, is apparently universal in coarse-grain soils although it historically has not been considered in routine practice and the exact reasons for it are still poorly understood (Chow et al. 1997).

The recent work at JFKIA highlighted in this paper encompassed a variety of new structures with the highlight being the construction of *AirTrain*™ *JFK*, a light-rail system approximately 13 km (8 mi) long that connects the airport with nearby regional transportation hubs. This system is largely on elevated structure throughout its alignment and that fact coupled with a project-wide seismic design criterion resulted in design loads that involved significant uplift and lateral components in addition to the usual axial compression.

Figure 2 shows a representative soil profile within the Central Terminal Area (CTA) of JFKIA. Conditions in other parts of the airport and adjacent transportation corridors north of the airport that were traversed by *AirTrain JFK* are similar but without the Holocene fill and organic strata and with somewhat denser and coarser Pleistocene sands. Also shown are typical results for Standard Penetration Test (SPT) field N values (N_f) and cone-penetrometer test (CPT) tip resistance, q_c. The former were obtained using a hammer system with approximately 45% driving efficiency (N_{45}) and the latter are non-dimensionalized using atmospheric pressure, p_{atm}.

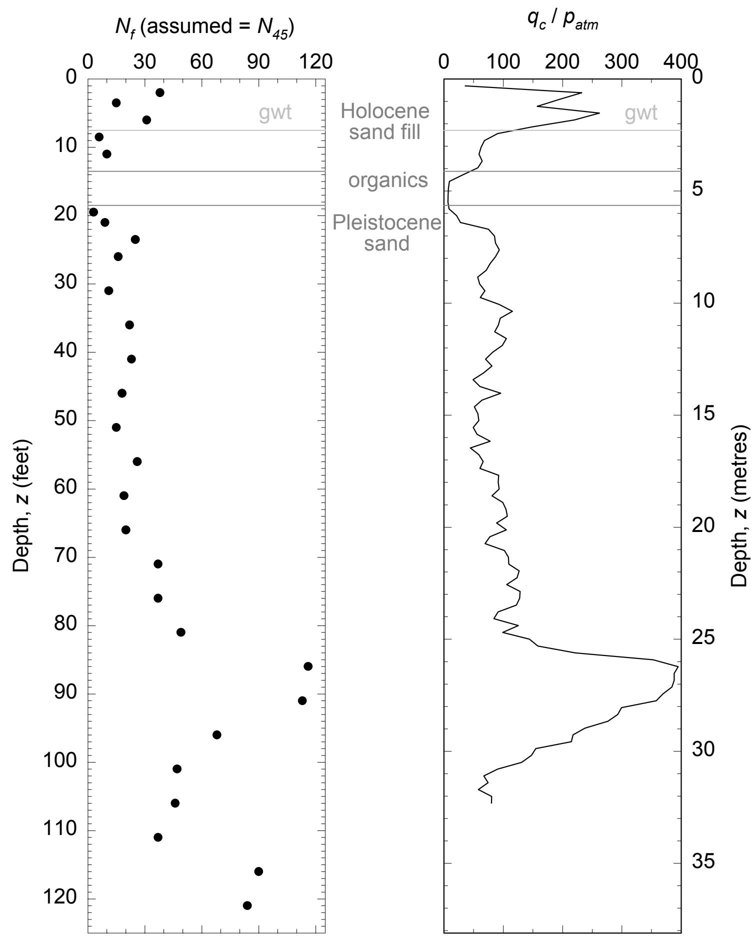

FIG. 2. Typical JFKIA CTA Subsurface Stratigraphy and In-Situ Test Results

Axial Loading

Compression

The majority of load testing performed on *Tapertube* piles at JFKIA involved axial-compressive loading. A variety of testing methodologies were employed both real-time during driving as well as after driving. In many cases, the tests were conducted at or to geotechnical failure which provided an opportunity to compare measured results with those calculated using the analytical methodology presented originally in Horvath (2002) and updated in Horvath (2003). This methodology was recently found to give overall very good results (typically within 15% plus or minus) for a wide variety of tapered pile types and capacities at JFKIA (Horvath and Trochalides 2004). Figure 3 shows the comparison between a typical static maintained-load (ML) test and estimated load-settlement behavior made using this analytical methodology. A detailed presentation and discussion of the axial-compressive load testing program and analytical comparison for the *Tapertube* piles at JFKIA can be found in Horvath et al. (2004).

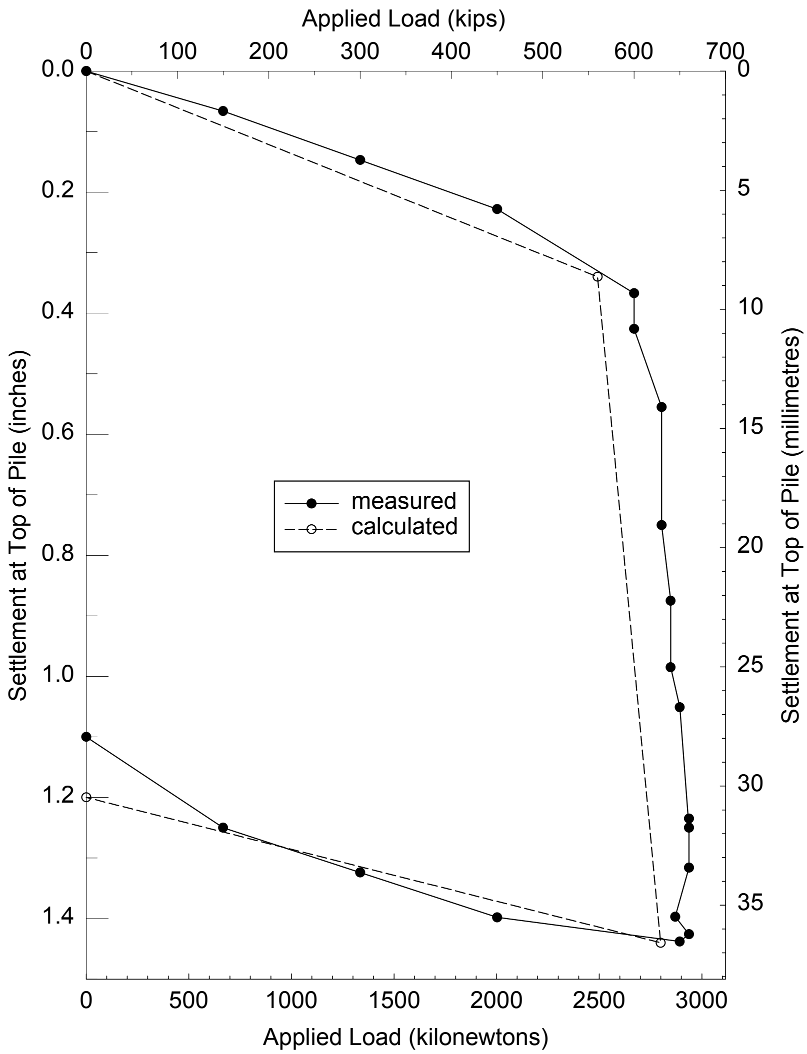

FIG. 3. Measured Versus Calculated Load-Settlement Curves for a Typical *Tapertube* Pile at JFKIA

All production piles installed at JFKIA had a tapered lower section that was 25 ft (7620 mm) long with a diameter that varied from 8 in (203 mm) at the tip to 18 in (457 mm) at the connection with the constant-diameter upper section. The length of the constant-diameter upper section varied throughout the project site depending on the specific geotechnical capacity desired and variations in subsurface conditions but was typically of the order of 25 ft (8 m).

The key conclusion reached by Horvath et al. (2004) was that, for conditions similar to those shown in Figure 2, it is now possible to routinely install piles that have ultimate axial-compressive geotechnical capacities per pile of up to 1000 kips (4450 kN) if desired although the targeted capacity of production piles at JFKIA was somewhat less than this.

Tension (Uplift)

One of the 'negatives' that is sometimes expressed concerning tapered piles is that they are presumed to have little or no axial-tensile (uplift) capacity. This is based on the perception that a tapered pile will neatly and instantaneously separate from the soil when subjected to an uplift force due to the fact that is occupies a conical or wedge-shaped volume in the ground.

This visualization is overly simplistic and needlessly conservative. It ignores the fact that the soil will rebound as it is unloaded and thus will remain in contact with the pile shaft although the radial stresses would be expected to decrease (this is discussed in more detail subsequently). In addition, it ignores the fact that most modern tapered piles such as the *Tapertube* have a constant-diameter upper section that can provide substantial uplift capacity. All in all, tapered piles usually have more than enough uplift capacity to satisfy design requirements. To illustrate this point, two uplift tests performed on *Tapertube* piles for the work at JFKIA are summarized. The piles were relatively close to each other and their overall results were very similar so only averages of the two tests are discussed.

With reference to Figure 2, the piles that were tested in uplift were located several kilometres north of the airport CTA and off airport property along the *AirTrain JFK* route. In this area the Holocene fill and organic strata are absent and the Pleistocene sands are somewhat denser and coarser due to being closer to the glacial terminal moraine that traverses Long Island in a roughly east-west orientation. Each test pile was at the center of a five-pile cluster at the time of load testing and there was likely some beneficial group effect (i.e. a group efficiency > 1) that contributed to axial capacities, a phenomenon that is common for coarse-grain soils. The test piles were relatively short with only about 10 ft (3 m) of a constant-diameter (18 in (457 mm)) upper section. Each was load tested in axial compression and had an ultimate geotechnical capacity in that mode of the order of 900 kips (4000 kN), most of which was likely due to cylindrical-cavity expansion within the 25-ft (7620-mm) long tapered lower section. The uplift load test on each pile was carried to 300 kips (135 kN) and maximum upward displacements were 0.62 and 0.74 in (16 and 19 mm). Residual displacements upon load removal were 0.53 and 0.60 in (13 and 15 mm), respectively. Calculations using the methodology presented in Horvath (2002) as updated in Horvath (2003) suggest that no more than about 100 kips (445 kN) of the applied uplift-load resistance could be attributed to the short constant-diameter upper section which means that the tapered lower section must have had a significant contribution.

This latter observation is not surprising. Applying an uplift load to the tapered portion of any type of deep-foundation element represents *cylindrical-cavity contraction*, a phenomenon that is conceptually identical to the unloading of an expanded pressuremeter. It is well established that a contracting pressuremeter does not lose its radial stress against the surrounding ground instantaneously but over some range of radial strain. So it makes sense that an uplifted tapered deep foundation would continue to provide resistance along its tapered section for some magnitude of upward displacement. In fact, it can be argued that the resistance along the tapered section would never become zero in most cases but would stabilize at some residual magnitude that would correlate conceptually to the active earth pressure state. Clearly, the subject of cylindrical-cavity contraction and its application to uplifted tapered deep foundations is an area of useful future research that would complement the cylindrical-cavity expansion work of Yu and Houlsby (1991) that was a key component of Kodikara's seminal work (Kodikara and Moore 1993) on tapered piles in axial compression.

Lateral Loading

Lateral loading is often a significant design issue for transportation-related structures. There are two key differences between axial and lateral loading for deep foundations in general. First, the mechanism by which any type of deep foundation develops resistance to lateral loading is completely different from the mechanisms that provide axial capacity. The response to lateral loading is governed solely by:

- the flexural stiffness of the upper portion of the deep-foundation element and
- ground conditions within a relatively shallow depth below the ground surface.

Thus a modern tapered pile like the *Tapertube* is at no inherent disadvantage compared to constant-diameter piles when it comes to resisting lateral loads. This is because the constant-diameter upper section of a *Tapertube* pile typically extends to a depth below that which governs resistance to lateral loads.

The second difference is that, at least for typical 'on-land' piles, the allowable lateral load is almost always governed by serviceability considerations (allowable lateral displacement) whereas the allowable axial loads in both compression and tension are governed by maintaining an adequate safety factor against ultimate geotechnical capacity. Thus lateral-load tests are rarely performed to geotechnical failure.

The load-testing program for the work at JFKIA included several lateral-load tests on *Tapertube* piles. Note that for the typical subsurface conditions as reflected in Figure 2 the lateral capacity was governed largely by the Holocene sand fill which had been placed in an uncontrolled fashion by hydraulic filling during the original airport construction in the late 1940s. Where present, the Holocene organic stratum, which consists primarily of organic clay with little or no peat, was a secondary influence on performance under lateral loading.

Two specific lateral-load tests are discussed here. In one area located within the CTA, the desired service lateral load for design purposes was 25 kips (111 kN). A test was performed on a *Tapertube* pile with a constant-diameter upper section that was 18 in (457 mm) diameter by 0.375 in (9500 μm) wall thickness. The interior of the pile was filled with portland-cement concrete after driving and before testing. The constant-diameter section extended to a depth of 34 ft (10 m) so the tapered lower section did not influence pile response. The pile was loaded to its design capacity and 0.4 in (10 mm) of lateral displacement was measured. It was then unloaded and a residual displacement of 0.1 in (2 mm) was measured. It was then loaded and unloaded several times in a rather complex protocol than involved loading to 150% of the design load (37.5 kips (167 kN)), then 200% of the design load (50 kips (223 kN)), and followed by cyclic loading at 150% of design load. The maximum lateral displacement achieved (at 200% of design load) was 1 in (25 mm) and the residual displacement at the conclusion of the test was 0.35 in (9 mm).

In another area several kilometres from the CTA but still within airport property (the Holocene fill stratum was denser and the Holocene organic stratum was virtually absent relative to the CTA conditions as shown in Figure 2), an essentially identical pile had a design lateral load of 23 kips (102 kN) and was loaded monotonically to 400% of that load (92 kips (409 kN)). The displacement at design load was approximately 0.25 in (6 mm), the maximum displacement at four times the design load was 1.9 in (48 mm), and there was 0.4 in (10 mm) of residual displacement upon load removal. The force-displacement response of this pile was both noticeably stiffer than the one at the CTA site (due, no doubt, to the denser consistency of the Holocene fill) and linear up to about twice the design load (the pile at the CTA site exhibited some nonlinearity even at design load).

CONCLUSIONS

Tapertube piles have been used now for several years on a number of projects in a variety of geographic locations in addition to their significant use at JFKIA as discussed in this paper. They have demonstrated their ability to successfully resist the entire spectrum of axial and lateral loading that is normally encountered in transportation applications. Because *Tapertube* piles are made of hot-rolled steel components there is no inherent limitation on the size and capacity of piles that might ultimately be developed. This plus the fact that the pile can be made available for driving anywhere combines to offer a promising new driven-pile alternative in a wide variety of applications.

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