A New Analytical Method for the Axial-Compressive Static Capacity of Tapered Driven Piles in Coarse-Grain Soil

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ABSTRACT: Tapered driven piles have been used for thousands of years and are often the most cost-effective driven-pile alternative for "friction piles" in coarse-grain soil. However, for a variety of reasons they remain relatively unknown and underutilized in many areas. One reason is the lack of a relatively simple yet reliable analytical method for calculating their axial-compressive geotechnical capacity under static load conditions. This paper outlines a newly developed analytical methodology that seeks to overcome this. This methodology integrates a state-of-art site-characterization algorithm with a capacity-calculation algorithm that approximately models cylindrical-cavity expansion. As demonstrated conclusively by Kodikara ca. 1990, cylindrical-cavity expansion is the true way in which tapered piles develop their capacity under axial-compressive loading. As such it represents what is now recognized as the third capacity mechanism for deep foundations in addition to the traditional mechanisms of side friction and end bearing. An important aspect of the analytical methodology outlined in this paper is that it only requires typical site-exploration and laboratory testing data as input and can be solved by manual calculation if desired. This paper concludes by showing the results of applying this analytical methodology to a variety of tapered piles that were driven and load tested to geotechnical failure at the John F. Kennedy International Airport in New York City over a period of 30 years. The agreement between measured and calculated capacities is considered very good.

KEY WORDS: tapered piles, driven piles, piles, deep foundations, axial-compressive capacity, cylindrical cavity expansion, site characterization

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 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 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/or have been underutilized to date for a variety of reasons.

There is evidence that this current state of tapered-pile underutilization is slowly changing as the result of recent renewed interest and development from several independent sources. These overall developments are discussed in detail by Horvath (2003b) as part of a larger discussion of tapered piles. This paper focuses on one aspect of these recent developments, an improved analytical method for calculating the ultimate axial-compressive geotechnical capacity under static loading and coarse-grain soil conditions.

BACKGROUND

The most significant development to date with regard to calculating the axial-compressive static capacity of tapered piles occurred only relatively recently. This was the research of Kodikara ca. 1990 (Kodikara and Moore 1993) that, for the first time, conclusively demonstrated the soil mechanics mechanism by which tapered piles develop their resistance to axial-compressive loading. Kodikara's theoretically rigorous work identified what is now formally recognized as a third capacity mechanism, called *cylindrical-cavity expansion*, for deep foundations. This mechanism is in addition to the long-recognized traditional mechanisms of side friction and end bearing.

Kodikara's analytical method represents a significant, landmark improvement over existing, traditional methods used for calculating the geotechnical capacity of tapered piles under axial-compressive loading, e.g. Nordlund (1963) and Meyerhof (1976). However, Kodikara's method is rather complex mathematically and requires a computer-solved numerical solution. While this is not an impediment to its eventual use in routine practice it does present a limitation for the immediate future.

To bridge the gap in time until software containing Kodikara's analytical method is more widely available to foundation engineers in practice, the author developed an interim improved method for calculating the axial-compressive geotechnical capacity of tapered piles (Horvath 2002). At the present time, this method is limited to applications where coarse-grain soil is the sole or at least predominant bearing material. The objective of this paper is to outline this interim method, which was recently updated (Horvath 2003a), so that it can be used in practice. In addition, the results of recent research into the application of this interim method to a variety of tapered piles will be illustrated.

INTERIM IMPROVED ANALYTICAL METHOD FOR TAPERED PILES: METHODOLOGY

Overview

The analytical method developed by the author and presented here has two distinct components, a site-characterization algorithm and a pile-capacity algorithm. Note that these two algorithms are conceptually independent. In fact the site-characterization algorithm was first developed and used to solve the problem of shallow-foundation bearing capacity (Horvath 2000a, 2000b).

The method presented in this paper is considered innovative for several reasons:

- Site characterization using state-of-art correlations is used extensively to produce all stress-state, strength and stiffness parameters necessary for pile-capacity calculation. Although site characterization has always been a fundamental part of any geotechnical investigation, in this case the site-characterization process is intimately and seamlessly integrated into the capacity-calculation algorithm. This is to provide input into the capacity-calculation algorithm that is rationally developed to the greatest extent practicable.
- An important aspect of the site-characterization algorithm is that despite its using state-of-art correlations it is simple to use. It can be solved manually if desired or necessary although using a computer greatly speeds up the work. In addition, the input required for the site-characterization algorithm are data that would be developed as part of any typical site-investigation program. The primary required input data are tip resistances, q_c, from any type of cone penetrometer (CPT) sounding although Standard Penetration Test (SPT) N values can be used as an alternative if CPT data are not available. In addition, reasonably accurate information is required concerning piezometric levels and soil density/unit weight so that vertical effective overburden stresses can be calculated accurately.
- Although the capacity-calculation algorithm does not incorporate Kodikara's rigorous cavity-expansion solution for the tapered portion of a pile, it does recognize the capacity mechanism of cylindrical-cavity expansion indirectly by considering the influence of taper angle on calculated capacity.
- The capacity-calculation algorithm recognizes the fact that the resistance mobilized in any of the three capacity mechanisms (side friction, cylindrical-cavity expansion, end bearing) is different for the peak and constant-volume (critical-state) strength conditions. Also recognized is the fact that the magnitude of axial displacement of a pile relative to the ground that is necessary to mobilize each strength condition for each capacity mechanism is quite different. While this fact in and of itself is not novel and is routinely considered in current practice for drilled shafts (O'Neill and Reese 1999), it does not appear to be routinely considered for driven piles at the present time.

Site-Characterization Algorithm

As noted previously, the primary input required for site characterization are CPT q_c data. If these are unavailable, SPT field N values (N_{field}) can be used in a two-part process as follows:

- Each piece of N_{field} data is first converted, if necessary, to N_{60}, the equivalent N value at 60% driving efficiency. As is well known, N_{60} has become the de-facto reference energy level for the SPT. This conversion can be done using either the average driving efficiencies actually measured at the site (preferred) using a device such as Pile Dynamics, Inc.'s *SPT Analyzer*™ or empirical corrections based on the type of driving system used that have been published in numerous places, e.g. Skempton (1986), Kulhawy and Mayne (1990).
- Each piece of N_{60} data is empirically converted to an equivalent piece of q_c data using the following relationship given by Kulhawy and Mayne (1990):

$$q_c = N_{60} \cdot p_{atm} \cdot 5.44 \cdot \left(D_{50}\right)^{0.26} \quad \textbf{(1)}$$

where p_{atm} is the atmospheric pressure (any system of units) and D_{50} is the soil particle diameter, in millimetres, for which 50% of the soil is finer by weight. Ideally, the value of D_{50} should be obtained in a project- and site-specific laboratory testing program but, if necessary, it can be estimated based on the visual-manual soil description that is typically provided on a boring log. Note that the value of q_c calculated using Eq. 1 will have the same units as used for p_{atm}.

Whether using actual q_c data or values calculated using Eq. 1, each piece of data is systematically input into the site-characterization algorithm. This algorithm is rather lengthy and to save space in this paper interested readers are directed to Horvath (2002) where the algorithm is given in complete detail. One important change should be made to the version of the algorithm contained in this reference to take advantage of an updated empirical correlation described in Horvath (2003a). Note that the algorithm in Horvath (2002) is an expanded version of one that was first applied to the problem of shallow-foundation bearing capacity (Horvath 2000a).

Experience to date indicates that the overall results of the site-characterization algorithm are quite sensitive to the values of q_c used as input. Thus when N values as opposed to actual q_c data are used it is particularly important that both N_{60} and the soil-particle gradation be determined as accurately as practicable. This is due to both their direct influence on q_c through Eq. 1 and the fact that there are far fewer pieces of overall data that will ultimately be used in the capacity-calculation algorithm. This is because N values are typically 1500 mm (5 ft) apart whereas CPT data nowadays are typically recorded less than 25 mm (1 in) apart. However, experience to date also indicates that if appropriate care is taken the agreement between actual q_c data and values calculated using Eq. 1 for the same site can be quite good (Horvath 2002, Horvath and Trochalides 2004) and the pile capacities calculated using actual versus inferred q_c data can be acceptably close in magnitude (Horvath and Trochalides 2004).

Capacity-Calculation Algorithm

Calculation of the net ultimate axial-compressive geotechnical capacity requires that a pile be divided into several artificial segments. The number of segments is dictated by a consideration of how many pieces of actual or equivalent q_c data there are as well as whether the calculations will be performed manually or by computer. There has be so systematic study to date as to what the minimum number of segments should be. In any event, for each segment the side capacity is calculated twice, once using peak-strength parameters and once using constant-volume strength parameters. Again, the details of how to do this are too lengthy to include here but can be found in Horvath (2002) together with an example application. The tip capacity is also calculated twice using the two different shear-strength states and this is also illustrated in Horvath (2002). Effective pile weight is also calculated although for most on-land piles of typical dimensions it will be relatively small in magnitude and have little effect on the overall results.

The calculated side and tip capacities can, theoretically, be combined in different ways to provide upper- and lower-bound total capacities as well as a "best-estimate" capacity. At the present, the "best-estimate" capacity is assumed by the author to be the sum of the following:

- the constant-volume side resistance for any portions of the pile with a constant diameter,
- the peak side resistance for any tapered portions of the pile and
- the peak tip resistance.

The validity of the first assumption has been reasonably well established in the published literature (Jardine and Chow 1996, Jardine et al. 1998). The validity of the other two assumptions are certainly open to further discussion and possible modification based on future research. However, they seem to be reasonable based on presently available information and comparison with measured capacities.

INTERIM IMPROVED ANALYTICAL METHOD FOR TAPERED PILES: RESULTS

Net Ultimate Axial-Compressive Geotechnical Capacity

The integrated site-characterization and pile-capacity algorithms described above were recently used to perform a comprehensive study of a variety of tapered timber and steel-pipe (*Monotube*™ and *Tapertube*™ brands) piles that had been driven at the John F. Kennedy International Airport (JFKIA) in New York City over a period of approximately 30 years, between 1972 and 2000 (Horvath and Trochalides 2004). Tapered piles have generally been the deep foundation of choice at JFKIA since construction first began there in the late 1940s. This long history of tapered-pile usage together with the fact that there have been a number of comprehensive and well-documented studies involving deep foundations that have been performed at JFKIA over the years provided the results from a fairly large number of load tests where the piles were loaded to a geotechnical failure in axial compression. The data from these load tests provided an unusual opportunity to evaluate the predictive accuracy of the author's interim improved analytical method for tapered piles that was presented in this paper.

Details concerning the specific subsurface conditions at JFKIA (they are remarkably uniform given the almost 20 square kilometres (8 square miles) covered by the airport) can be found in York et al. (1994), Horvath (2002), and Horvath and Trochalides (2004). In simple summary, the majority of pile bearing is provided by a generally medium-dense stratum of relatively fine, clean sand of Pleistocene age that begins approximately 6 metres (20 ft) below the ground surface. The ground surface is relatively level throughout the airport property and ground water is of the order of 2 metres (7 ft) below the surface.

Fig. 1 shows the comparison between measured and calculated capacities for a total of 17 piles. In all cases, the measured capacity was determined using traditional maintained-load (ML) tests. A discussion of some of the shortcomings and limitations of this type of test as well as specific details as to how the geotechnical failure load was defined from the load-settlement curves can be found in Horvath (2002). Note that data points with arrows in Fig. 1 indicate piles that were judged not to have failed geotechnically at the maximum load applied. However, in all such cases it appeared that the pile was close to its geotechnical failure load. The agreement between calculated and measured results is generally within±15% and is considered to be quite good.

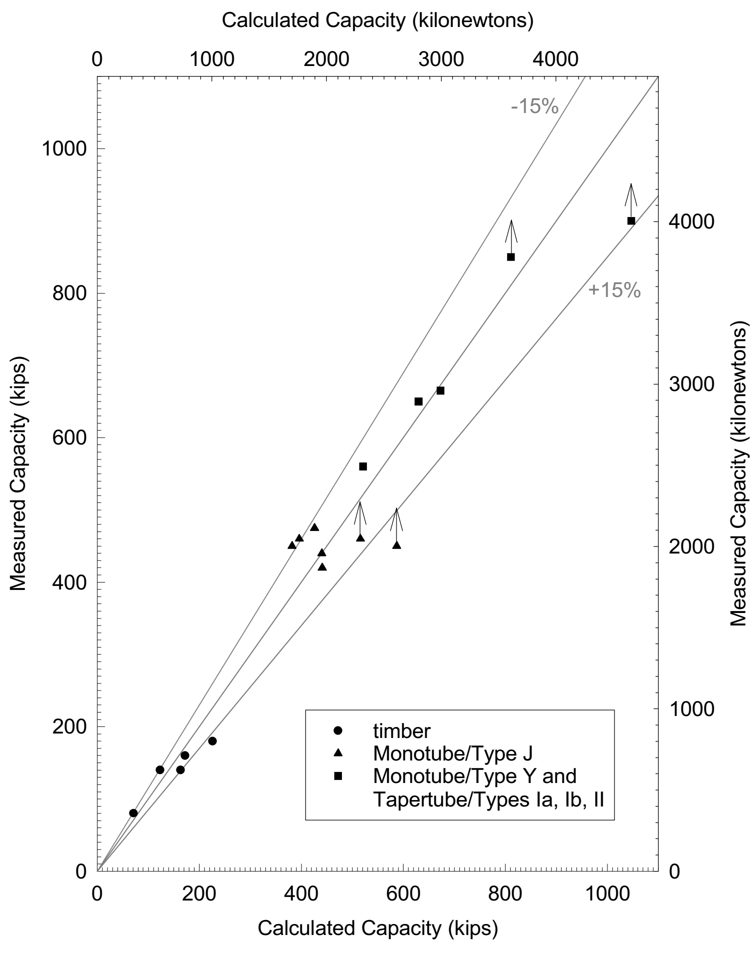

Fig. 1. Measured versus Calculated Pile Capacities

Load versus Settlement

One of the ancillary capabilities of the author's interim improved analytical method that was used to develop the results presented in Fig. 1 is the ability to generate a theoretical load-versus-settlement curve for any pile. 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 (trivial).
- 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 3 mm (0.12 in).

- The load corresponding to the constant-volume 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 (30 mm (1.2 in) for the majority of the piles shown in Fig. 1).
- When all load is removed, there is a net settlement equal to 15% of the pile tip diameter (30 mm (1.2 in) for the majority of the piles shown in Fig. 1).

Fig. 2 shows the typical results obtained using this procedure for one pile, a Type Ia*Tapertube*. As discussed in detail by Horvath et al. (2004), the *Tapertube* is a relatively new brand of tapered steel pipe pile that was developed and has been used in the U.S.A. to date but is available for use worldwide. It has a tapered lower section, in this case varying from 203 mm (8 in) to 457 mm (18 in) over a length of 4572 mm (15 ft). This equates to a taper angle, ω, = 1.6° which is quite high for a tapered steel pipe pile (Horvath 2002, 2003b). The upper section of this particular pile has a constant diameter of 457 mm (18 in).

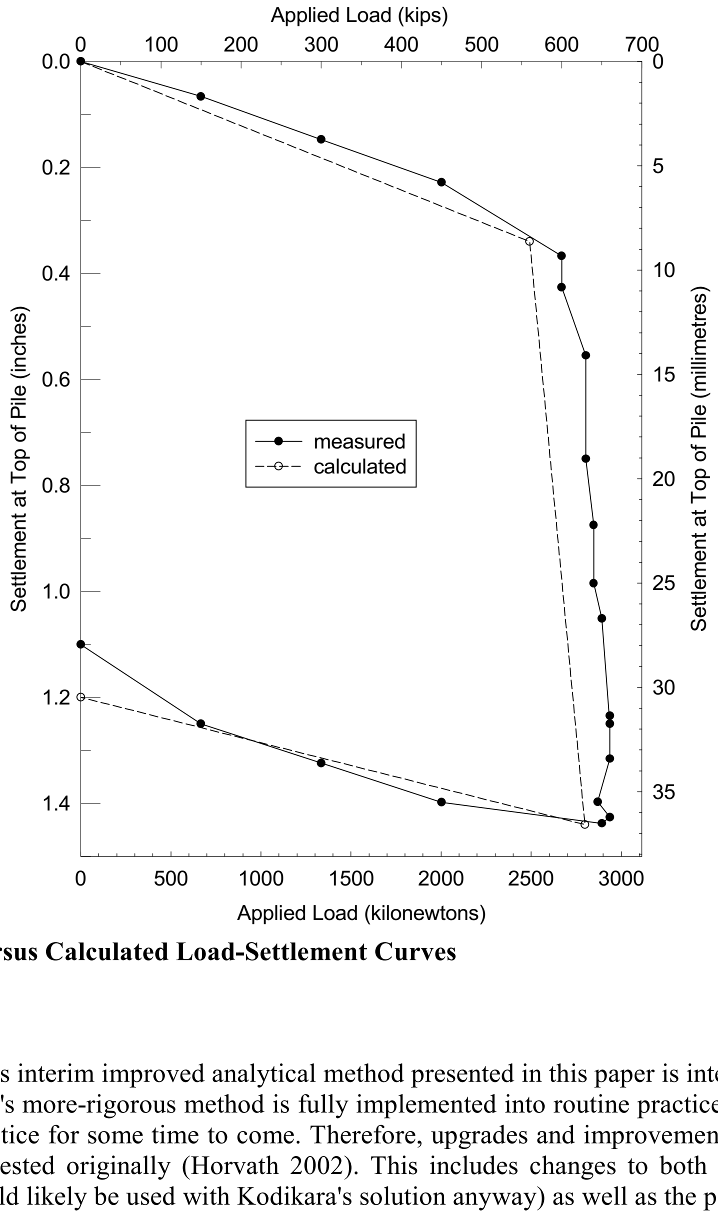

Fig. 2. Measured versus Calculated Load-Settlement Curves

FUTURE WORK

Although the author's interim improved analytical method presented in this paper is intended to serve only until such time as Kodikara's more-rigorous method is fully implemented into routine practice, it is quite possible that it will find use in practice for some time to come. Therefore, upgrades and improvements to this method should continue as was suggested originally (Horvath 2002). This includes changes to both the site-characterization algorithm (which would likely be used with Kodikara's solution anyway) as well as the pile-capacity algorithm.

Recent project experience in the New York City area suggests that some specific areas of useful research would be to extend the capacity-calculation algorithm to:

- consider time effects on capacity which are now recognized as important even for piles bearing in coarse-grain soil (York et al, 1994, Chow et al. 1997),

- include situations where fine-grain soils represent all or a significant part of the bearing material for the tapered portion of a pile, and
- consider group effects on capacity (there is some indication that this may be particularly important for tapered piles as noted by Horvath et al. (2004)).

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DISCLAIMER

Reference in this paper to tradenamed products, procedures and equipment is solely for informational purposes and does not constitute an endorsement of said products, etc. by the author, the CGT or Manhattan College. No financial compensation was made to the author, the CGT or Manhattan College by the PANYNJ, UFC or any other outside party involved in the work reported herein.

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