Influence of Taper in Selecting Pile Support System or Major Structures

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ABSTRACT

Tapered steel piles have been used predominantly at JFKIA to provide foundation support for selected structures including “International and Domestic Air Terminals” plus heavily loaded multi-level “Parking Garages”, JFK Airtrain Elevated Guideway, JFK Terminal at Jamaica, Queens, NYC and other facilities.

The historical development and comparative evaluation of tapered piles with other pile types are addressed. Results of dynamic measurements to permit evaluation of pile capacity during initial installation and at predetermined subsequent intervals to evaluate set-up (increased capacity with time) are provided. Final selected ultimate pile capacities are always confirmed by standard compression load tests illustrated by an extensive array of pile foundation case histories.

Reference has also been made to a report on “Estimating Soil / Pile Set-Up” September 2003, financed by the Wisconsin Department of Highways and the Federal Highway Administration.

INTRODUCTION

The utilization of set-up as determined during the driving and testing of tapered piles in major pile load test programs at JFKIA has resulted in a significant reduction in foundation construction costs. The apparent development of increased capacity was observed for the first time during the comparative evaluation of steel pipe piles and tapered Monotube piles for support of a new Air Traffic Control Tower included in the initial JFK2000 Redevelopment Program. Although tapered piles were not selected to support the Control Tower (explained in paper), the stage was set for a more extensive evaluation of set-up in subsequent load test programs and reliable parameters were established to ensure required ultimate capacities.

By taking advantage of capacity gain due to set-up, the cost savings in the selection of foundation support systems is estimated to be in the order of $20M. In addition, foundation construction periods for the major structures have been substantially shortened. Recent load test results on tapered piles indicate capacity increase and cost savings may have been proportionally much greater if longer tapered sections had been used. This paper presents guidelines on selection of tapered section and developed pile capacities for support of major structures.

SUBSURFACE CONDITIONS

The following general stratigraphy at JFK Airport is typical for all the case histories addressed in this paper:

Fill --- Consists primarily of 2.4 to 4.9 m (8 to 16 ft) of hydraulically placed medium to fine sand with a trace of silt and occasional layers of organic silty clay.

Organic Deposits --- Soft organic silty clay with layers of brown peat varying in thickness from 0.6 to 3.4 m (2 to 11 ft) with an average thickness of about 1.8 m (6 ft).

Glacial Outwash Sand --- Consists of medium to fine sand with varying silt content, typically in the medium dense to dense range. Depth may extend from 11.6 to 14 m (38 to 46 ft) below ground surface.

Pile support is developed in the upper region of the sand stratum for both tapered and non-tapered piles.

Groundwater level is about 2.4 m (8 ft) below the surface and bedrock is estimated at 213 m (700 ft) below the surface.

CASE HISTORIES

Air Traffic Control Tower (1989)

Initial discovery of set-up in granular soils occurred in this contract.

During installation of pipe piles (32.4 cm or 12 ¾ inch OD) and Monotube piles (3NJ 20.3 cm x 35.6 cm or 8 in x 14 in) in planned pile test program to select appropriate pile type to support a new Control Tower at JFKIA, the following series of events occurred:

Pipe piles (2) were driven to depths of 25.6 and 26.2 m (84 and 86 ft) in a dense sand and gravel layer.

Monotube piles (3) were driven to depths of 26.5, 2.0, and 2.0 m (87, 65 feet and 65 ft) respectively.

During installation of Monotube piles, it was decided to stop the driving arbitrarily at a depth of approximately 20 m (65 ft) for two of the piles. No resistance was encountered at these depths, however, it was speculated that additional resistance would be developed over time and this possibility could be evaluated in the pile test program.

Load test results demonstrated the pipe piles having capacities in excess of 2224 kN (250 Tons) for a length of 26.3 m (86 ft) and 1780 kN (200 tons) for 25.6 m (84 ft). Waiting periods ranged from16 days (high capacity) to 6 days (low capacity).

Load test data for the Monotube piles indicated that the piles had capacities in excess of 2224 kN (250 Tons) for a length of 26.5 m (87 ft) and 2003 kN (225 Tons) for 19.8 m (65 ft). Waiting periods ranged from 35 days (high capacity) to 23 days (low capacity).

It was apparent that the most economical pile type based on load test data was the Monotube pile (shortest pile meeting design requirement), however, the Contractor elected to drive the steel pipe piles to the dense granular layer since no information was available on the development of set-up and potential driving problems during installation of a large group of tapered piles (12 x12 = 144) required to support the Control Tower. Although Monotube piles were not selected to support this structure, it was apparent that significant savings could be achieved in selecting a pile type, which could develop additional capability over time.

East Parking Garage (1992)

The planned five-level garage was approximately 46,452 m^2 (500,000 sf) in size and was designed to serve as a base for a future seven-story hotel.

Monotube piles (3NJ 20.3 cm x 35.6 cm or 3NJ 8 in x 14 in) were selected to support the East Parking Garage with design and ultimate capacities of 890 kN (100 Tons) and 1780 kN (200 Tons), respectively. During the installation of the designated Monotube piles, the following observations were recorded:

As the number of driven piles increased and densification occurred in the bearing strata, it became increasingly more difficult to attain the required minimum tip elevation. On one occasion, after attempting to drive piles in a group to required resistance, it was observed that selected piles “hung-up” and could not be advanced irrespective of number of blows. On commencement of pile driving in an adjacent group, it was decided to return to first group and redrive the isolated piles, which could not be advanced. It was observed that after the initial hammer blow application, the impacted pile dropped 10 feet before being driven to required resistance. It was apparent that vibrations had been transmitted to the initial group during installation of piles in adjacent group and resulted in a significant reduction in apparent density, subsequently, designated relaxation.

Proposed Installation Procedure. To minimize problems associated with achieving acceptable pile group installations, it was recommended that all piles in a specific large group be driven to a depth corresponding to an elevation approximately 10 feet higher than the Contract minimum tip elevation. After all piles in group were installed, the Contractor commenced redriving the piles to reach the desired minimum tip elevation and designated resistance. This procedure was used successfully to install the remaining piles with minimum “high refusal” and/or relaxation problems.

Set-up and relaxation in glacial sand was addressed by York et al. (1994)

Redeveloped Roadway Network Construction Contracts (Early 1990)

During the early 90s, a number of Roadway Contracts related to JFK Redevelopment were prepared and released for bidding. Typically the roadway structures were designed based on the assumption that either Monotube piles or steel pipe piles would be selected by the low bid Contractor. With the smaller group sizes required for bridge abutments and retaining walls, it was generally concluded that Monotube piles would be preferred since installation problems similar to the East Parking Garage were not likely to occur.

Change in Pile Type. Timber piles were also included as an option to support a retaining wall structure in the first Roadway Contract, however, when the Contractor commenced driving, it was observed that timber pile breakage was occurring due to the presence of a very dense sand layer immediately below the organics. To obviate breakage and at the request of the Contractor, the pile type was changed to Monotube at 578 kN (65 Tons) capacity.
A brief summary of pile types, capacities and minimum tip elevations are summarized for selected Roadway Contracts as defined below: [surface EL +2.1 m (7 ft)]

TABLE 1

Contract No.	Monotube Pile 3NJ 20.3 cm x 35.6 cm 3NJ 8 in x 14 in		Steel Pipe Piles 32.4 cm 12-3/4" OD	
	Min Tip EL, m (ft)	Design capacity, kN (Tons)	Min Tip EL, m (ft)	Design capacity, kN (Tons)
1	-13.7 (45)	890 (100)	-18.3 (-60)	890 (100)
3	-6.1 (20)	578 (65)		
	-13.7 (45)	890 (100)		
4	-6.1 (20)	578 (65)		
	-15.2 (-50)	890 (100)		

A pile test program and report on findings related to soil set-up with instrumented piles was addressed by Fellenius et al. (2000)

<u>JFK Redevelopment</u> (1995 to 2005)

Significant Projects requiring pile supported structures including the following:

British Airways Parking Garage – Monotube Piles
British Airways Air Terminal– Monotube Piles
International Arrivals Terminal – Monotube Piles
American Airlines – Monotube Piles/Pipe Piles
Air Train Elevated Guideway Structure –
Monotube Piles/Pipe Piles/Tapertube Piles
Jamaica Station/Office Building/Station Improvements
– Tapertube Piles/Minipiles
Green Garage – Monotube Piles

It should be noted that a new tapered pile designated "Tapertube" was developed during this period and approved by PANYNJ to provide foundation support for the British Airways Air Terminal and selectively for Air Train related structural foundations. The piles consisted of 20 cm x 46 cm x 7.6 m (8 in x 18 in x 25 ft) tapered steel section welded to an 18-inch diameter steel pipe with 1-cm (0.375-inch) wall thickness. Pile lengths at JFK Airport typically ranged from 15.2 to 19.8 m (50 to 65 ft). Piles were driven with conventional impact hammers, typically a Juntaan HHK-7 with an applied energy of 54,232 kN-m (40,000ft-lbs) Experience with the development of set-up for the Tapertube piles was addressed by Sandiford et al. (2002)

<u>Latest Developments</u> (2005 to 2007)

Incorporating set-up in pile design has resulted in extremely economical foundations for the many structures including e.g. terminals, parking garages, control tower and miscellaneous buildings, which have been constructed at JFKIA in the past 15 years. Significant trends have developed as experience with tapered piles increased. In general, it may be stated that pile lengths have decreased and pile capacities (design and ultimate) have increased.

Accurate determination of the appropriate set-up value has played a large part in establishing reduced foundation costs. For most projects it has been typically assumed that at least 1/3 of the EOID (End of Initial Drive) capacity, determined by pile dynamic measurements during initial installation can be relied on for capacity from set-up. This assumption is verified by pile load tests and BOR (Beginning of Restrike) dynamic tests, performed after a waiting period of three weeks. As an example of the above, where 1780 kN (200 Ton) design capacities were required for selected elements of the Air Train project, it was observed that if 46 cm (18 in) diameter tapertube piles (7.6-m or 25-ft taper) were driven to 2669 kN (600 kips) (dynamic measurements), the additional 1780 kN (200 kips) from set-up would be confirmed in the formalized pile test program after a typical waiting period of three weeks.

<u>Red Garage</u> (2005)

Construction of the planned five level structural garage was planned to start in June 2005. Foundation design development was based on the requirement to provide high capacity piles. Details of pile design are summarized below:

. Monotube piles with a 12.2-m (40-ft) taper (3NJ 20.3 cm x 45.7 cm or 3NJ 8 in x 18 in) were selected to provide foundation support with a required design capacity of 1601 kN (180 tons). All previous tapered piles installed at JFKIA had a 7.6-m (25-ft) taper, however, intuitively it was considered that the increased length of taper may result in a higher set-up value after the standard waiting period of three weeks. No preliminary information was available on the potential for increased set-up.

. Two pile driving hammers (Vulcan 012 and 508) were selected by the piling Contractor (Falco Construction) to install the piles with the capability of delivering a minimum transferred energy of 29,828 kN-m (22,000 foot-lbs).

Details of the proposed Indicator Pile Program are summarized on Figure 1. During pile installation EOID capacities of 1891 to 2291 kN (425 to 515 kips) were recorded over a pile depth range of 16.8 to 24.4 m (55 to 80 ft). The following piles were selected for testing:

- Compression - #359, 387 and #235
- Uplift - #219
- Lateral - #235

Compression load tests indicated that the following increase in capacity had occurred over waiting periods ranging from 27 to 54 days

- #359 – 2153 to 3737 kN (484 to 840 kips)
- #387 – 2291 to 4003 kN (515 to 900 kips)
- #235 – 1895 to 3559 kN (426 to 800 kips)

Uplift load test on pile #219 indicated a maximum resistance of 712 kN (80 tons) for a movement of 0.36 cm (0.14 in). Lateral load test on pile #165 demonstrated 267 kN (30 tons) resistance for a horizontal movement of 1.52 cm (0.6 in).

It is apparent from the test data that the original hypothesis predicting reduced EOID capacities with longer taper and increased set-up over the standard minimum three-week waiting period was confirmed. It is estimated that the 33% increase for the 7.6-m (25-ft) taper may be upgraded to at least 66% and perhaps 75% in determining the appropriate ultimate capacity. As noted previously, all estimates of ultimate capacity developed from EOID readings must be confirmed by load test.

Comparative Analysis. To evaluate the relative merits of the 7.6-m (25-ft) and 12.2-m (40-ft) tapers, a test program was conducted using two Monotube piles (3NY 20.3 cm x 45.7 cm or 3NY 8 in x18 inch) and (3NJ 20.3 cm x 45.7 cm or 3NJ 8 in x18 inch) driven to a depth of 18.3 m (60 ft) and approximately 6.1 m (20 ft) apart. Dynamic measurements were taken during driving and initial capacities of 1891and 1470 kN (425 and 332 Kips) were recorded at the final driven depth of 60 feet. After waiting periods of 5.5 hours and 4.0 hours respectively, drop weight tests were performed using a 133.4 kN (15 Ton) standard weight and selected drop heights. Capacities of 2878 and 3003 kN (647 and 675 Kips) were recorded representing set-up values of 988 and 1526 kN (222 and 343 Kips). After three weeks, drop weight tests were again conducted, however, due to apparent movement of concrete at top of pile, the data recorded was considered suspect and no final capacity after three weeks was developed. It was concluded however, that the additional set-up after three weeks would confirm ultimate pile capacities of at least 3781 kN (850 kips). Comparative test data obtained in the Drop Weight program are illustrated in Figure 2. In reviewing the results, it is concluded that the longer tapered pile would be the preferred pile to attain design and ultimate capacities of 1892 and 3781 kN (425 and 850 kips) respectively.

Jet Blue Terminal (2006)

Monotube piles (3NJ 20.3 cm x 35.6 cm or 3NJ 8 in x 14 in) were selected to provide structural support for the Jet Blue Terminal with design and ultimate capacities of 712 and 1601 kN (80 and 180 Tons), respectively. The most interesting development on this project was the selection of the pile length (approximately 10.7 m or 35 ft) to attain required capacities. The pile test program was developed and conducted by the following entities:
Turner Construction Company/Heller and Johnsen/Jet Drive/Loftus. Heller and Johnson were the Geotechnical Consultants on the project.

The following significant events occurred in design development:

Two Junttan Hammers were selected to drive the Indicator piles with rated capacities of 35,251 kN-m (26,000 ft-lbs) for HHK5SL and 271,116 kN-m (20,000 ft-lbs) for HHK4, respectively.

A total of 32 piles were driven covering the planned foundation area for the structures.

Ground surface was established at Elevation +8 and driving penetration typically extended to a maximum depth of 11.6 m (38 ft) with occasional piles being stopped at 11.3 and 9.1 m (37 and 30 ft).

Case capacities were determined for all driven piles at EOID and additional Capwap analyses were conducted on selected piles. To evaluate setup (increased resistance with time) selected piles were redriven after waiting periods ranging from 3 to 27 days. Case capacities were determined for these piles at BOR (Beginning of Restrike).

Compressive Load Tests were performed on four (4) test piles: Length of piles below grade ranged from 9.1 to 11.6 m (30 to 38 ft). Load tests were conducted to design and ultimate capacities of 712 and 1601 kN (160 and 360Kips), respectively.

Period from Driving to Testing ranged from 28 to 46 days (Set-up development). End of Initial Drive (EOID) Case capacities ranged from 1214 to 1259 kN (273 to 283Kips). Computed setup (Maximum test load – EOID capacity) ranged from 343 to 369 kN (77 to 83 Kips). Maximum Beginning of Restrike (BOR) value after 27 days was 1873 kN (421Kips).

The selected pile driving criteria are as follows:

Penetration Resistance

- HHK5SL: 20 Blows/30 cm, Min. Tip EL. –8.8m (–29')
- HHK4: 25 Blows/30 cm, Min. Tip EL. –8.8m (–29')

Pile Cut-off EL. +1.7 m (+5.5')
Minimum Pile Length: 10.5 m (34.5 ft)

In reviewing the test program results, particular emphasis was placed on the following issues:

Monotube piles tested to confirm 1601 kN (360 Kips) ultimate capacity were considerably shorter than tapered piles used previously at JFKIA to support selected structures.

The principal concern was the potential impact of the organic layer on the capacity of the tapered section.

Three of the four (4) load tests were conducted at locations where the tapered section of the pile was driven to a depth, which from the borings indicated that the organic layer appeared to be in intimate contact with the tapered section over vertical intervals ranging from 1.2 to 2 m (3.9 to 6.5 ft).

Compressive load test results for the four individual test piles were satisfactory, however, potential impact of the organic layer required evaluation particularly with respect to group capacity.

Set-up time varied from 28 to 46 days for the four load tests. It was noted that pile capacity increased significantly with the longer waiting period. It was considered that if organic soils are in contact with the tapered pile section, it may be necessary to extend the customary 21-day period for commencement of verification load tests.

It had initially been considered that it may be necessary to have the tapered section driven below the organic layer. In communication with Dr. Bengt Fellenius, it was suggested that the set-up resulting from a typical pile group would be similar to that developed for an individual pile multiplied by the number of piles in the group.

RESEARCH ON SOIL/PILE SET-UP

A report was issued by Komurka et al. (2003) on estimating Soil/Pile Set-Up". Excerpts from the "Abstracts" to the report are provided below.

Soil/Pile set-up is a time-dependent increase in pile capacity and can contribute significantly to long-term pile capacity.

Set-up is predominantly associated with an increase in shaft resistance. The complete mechanisms contributing to set-up are not well understood, but the majority of set-up is likely related primarily to dissipation of excess pore water pressures within, and subsequent remolding and reconsolidation of soil, which is displaced and disturbed during pile driving. After excess pore water pressures have dissipated, aging may account for additional set-up.

In the main body of the report, the following points were noted:

In fine- grained granular soils (silts or fine sands), driving-induced excess pore water pressure may dissipate relatively rapidly (i.e. almost while driving). The less permeable the soil and the greater volume of soil displaced by the pile, the longer the duration of the logarithmically constant rate of dissipation.

Other parameters identified as germane to set-up in non-cohesive soil include pile radius, soil stiffness (shear modulus), pile-soil dilatancy (which depends on shaft roughness and soil grain characteristics – particle size, shape and strength), moisture content (saturation), chemical composition of pore water, in-situ stress level, pile geometry, chemical processes and installation procedure.

Based on tests performed on Monotube (fluted tapered steel) piles, Fellenius et al. (2000) attributed set-up to stiffening of the soil, not to increased shaft resistance.

CONCLUSIONS

The above case histories addressing pile foundation development with tapered piles driven to generally medium dense to dense, medium to fine sand at JFK Airport in New York City have resulted in the following conclusions:

1. Time-dependent accumulation of pile set-up has contributed significantly to developments of compressive pile capacities.

2. Standard load test results for Monotube piles (3NJ 20.3 cm x 45.7 cm or 3NJ 8 in x 18 in) with 12.2-m (40-ft) tapered section installed for the Red Garage indicated that "set-up" resulted in a minimum 66% increase of compressive capacity compared with 33% on Monotube piles (3NJ 20.3cm x 35.6 cm or 3NJ 8 in x 14 in) with 7.6-m (25-ft) taper section.

3. Pile installation in two stages may be advisable when driving large groups of piles in adjacent caps. This procedure should minimize problems with densification and relaxation on individual piles. (See narrative on "East Parking Garage").

JFK Airport is just one site where outwash glacial deposits have been investigated, for reliance on set-up, to provide increased capacity with time after pile installation. Similar data from other sites will assist in developing a comprehensive repository of practical knowledge on pile capacity development, including limitations on set-up related to tapered length and subsurface profile.

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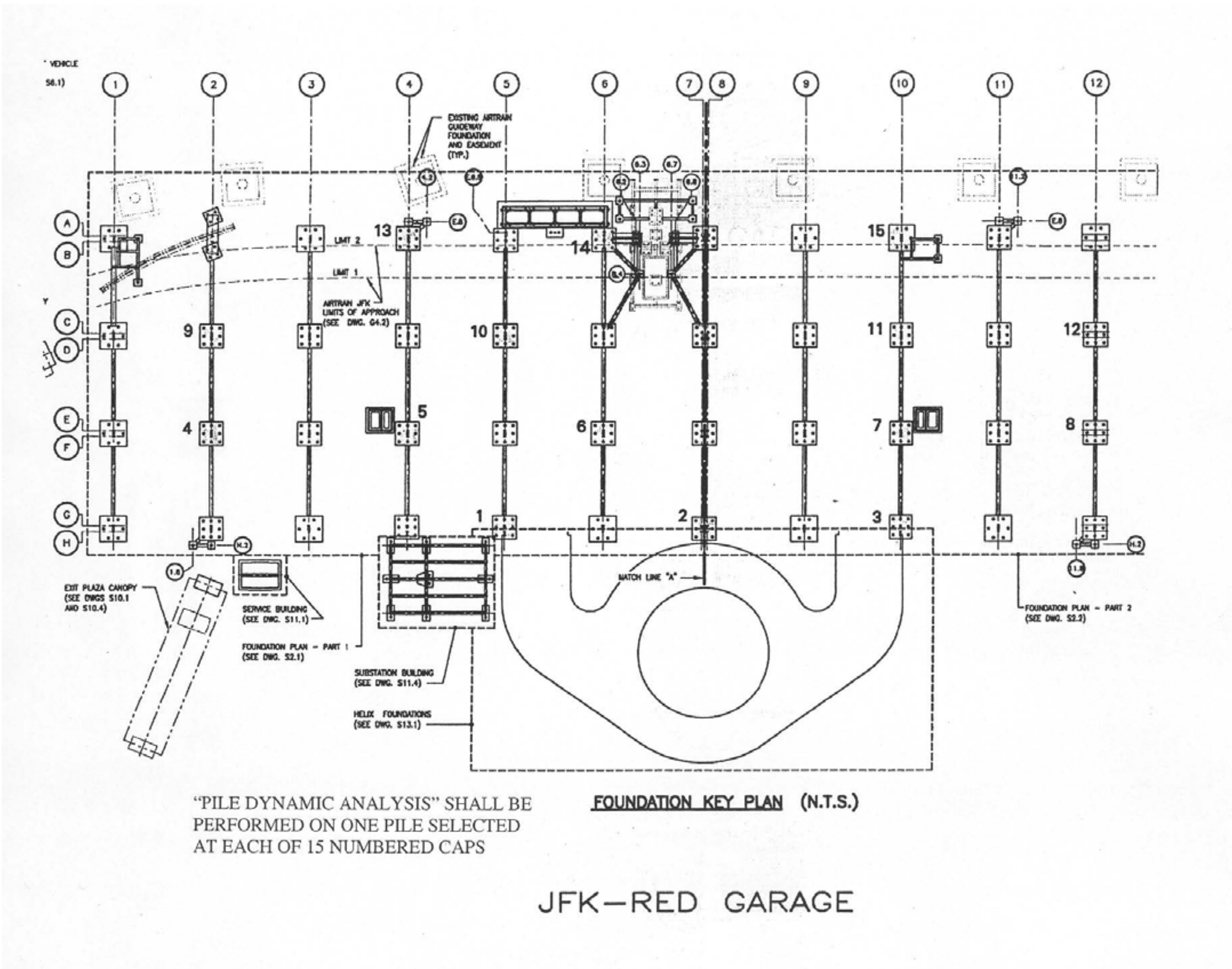

Fig. 1 Indicator Pile Program

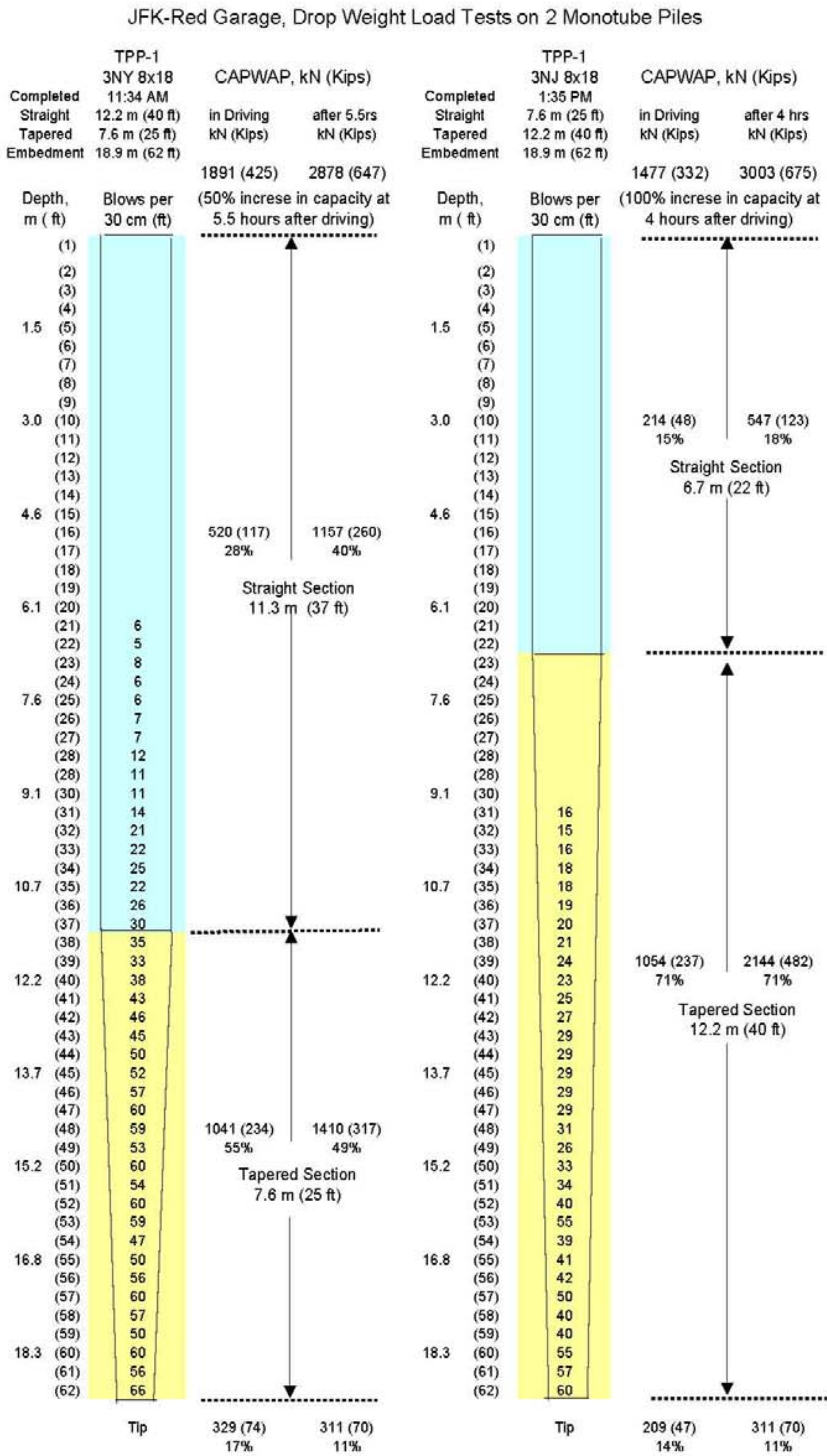

Fig. 2 Drop Weight Load Test