Comparison of static and high strain dynamic tests on driven steel piles at several industrial sites in Alberta

Robin Tweedie
Thurber Engineering Ltd., Edmonton, Alberta, Canada
Renato Clementino & Donald Law
Thurber Engineering Ltd., Edmonton, Alberta, Canada

ABSTRACT
This paper describes three case histories where static load tests (SLT) and high strain dynamic tests (HSDT) were conducted on driven steel piles at industrial plant sites in Northern Alberta. The sites involved H-section and pipe piles up to 610 mm diameter driven to depths ranging from 10 m to 40 m, with design loads up to 2200 kN. A combination of SLT and HSDT provided information on capacity, distribution of shaft and end bearing resistance, and "set-up". HSDT were an economical method of providing quality assurance and confirmation of pile capacities during construction.

RÉSUMÉ
Cet article décrit trois études de cas, où des essais de chargement statiques (SLT) et des essais de grande déformations dynamiques (HSDT) ont été entrepis sur des pieux battus en acier, sur des sites industriels situés dans le nord de l'Alberta. Des pieux de types H, et à section tubulaires ayant des diamtères allant jusqu'à 600 mm, ont été battus à des profondeurs variant de 10 m à 40 m, avec des charges de conception allant jusqu'à 2200 kN. La combinaison des méthodes SLT et HSDT a permit de recuelllir des données sur la capacité, la distribution de la résistance le long du fût et à la pointe ainsi qu'au niveau de la mise en place des pieux. De plus, l'utilisation de la méthode HSDT s'est averé une méthode économique afin de vérifier l'assurance de qualité au niveau des installations tout en confirmant les capacities des pieux lors du battage

1 INTRODUCTION

Driven steel piles are commonly used for support of industrial plant foundations in Northern Alberta and offer relatively high capacities with ease of installation. Common pile sizes include 250 mm to 360 mm H-section piles and steel pipe piles ranging from 219 mm to 610 mm diameter supporting working loads up to about 2500 kN.

The piles are frequently installed through thick glacial clay and sand deposits where "set-up" due to excess pore pressure dissipation following driving results in significant strength gain with time (e.g. Yang and Liang, 2009). Economical pile design requires consideration of the "set-up" in determining long-term capacity.

Pile load test programs are an integral part of design and construction and may include Static Load Tests –SLT (ASTM 1994) and High Strain Dynamic Tests – HSDT (ASTM 2000), also frequently referred to as PDA (Pile Driving Analysis) tests. By careful combination of static and dynamic tests, including HSDT tests at End of Initial Drive (EOID) and restrike (RST) valuable information can be obtained on the distribution of shaft friction and end bearing resistance, and also pile "set-up" with time. HSDT also provides an efficient and economical method of confirming capacities of representative piles during construction.

With the introduction of Limit States Design in the National Building Code of Canada (2005) the geotechnical resistance factor also increases with the application of representative pile load tests, from 0.4 to a maximum of 0.6, thereby providing an increase in factored ULS pile capacity of 25% based on dynamic tests to 50% for static load tests.

The pile load tests should be carried out during the design phase to gain most benefit in terms of optimizing pile designs and applying the higher geotechnical resistance factors.

This paper describes three case histories where a combination of SLT and HSDT were performed on driven steel piles at industrial plant sites in Northern Alberta.

2 SITE CONDITIONS

Table 1 presents a summary of the soil conditions and typical pile sizes used at the three sites.

Typical ranges of Standard Penetration Test N values (uncorrected) and Cone Penetration Test tip resistance is provided for the main soil units.

Piles included 310 mm H-section piles and pipe piles ranging from 219 to 610 mm, driven to embedment depths ranging from 10 m to 40 m.

3 SITE 1 – SAGD OILSAND PLANT SITE

Site 1 involved a SAGD (Steam Assisted Gravity Drainage) Central Processing Facility used for bitumen production from oilsand. The plant will be built in several phases ultimately requiring about 10,000 piles having design loads ranging from about 400 kN to 1000 kN.

Table 1. Typical site conditions and pile designs.

Site	General Stratigraphy	Typical Soil Properties* SPT N (CPT Q_t -Bars)	Pile Sizes	Typical Pile Embedment Depths	Typical Pile Design Loads (kN)
1	Glacial Clay Till with Sand and Gravel Layers	10-60 (20-60) 20-100 (100-350)	219 mm to 610 mm pipe	10 m to 20 m	400-1000
2	0 m - 5 m Fine Sand; 5 m - 15 m Stiff Clay; 15 m - 22 m Clay Till; 22 m - 40 m Sand and Gravel	5-15 (40-80) 5-20 (10-30) 15-50 (40-300) 50-100 (>400)	HP310 x 79, 310 x 94 & 310 x 110 273 mm to 610 mm dia. pipe	14 m to 24 m	200-900
3	0 m - 20 m Clay and Silt; 20 m - 40 m Silt and Sand; 40 m - 60 m Clay Till;	8-20 (10-20) 10-30 (20-150) 10-50 (20-100)	HP310 x 79 HP310 x 110 610 mm pipe	30 m to 40 m	1200-2200

*SPT N (Uncorrected) Blows per 300 mm; CPT – Cone Penetration Test

Three Static Load Tests (SLT) were conducted on 324 mm dia. pipe piles (P3, P6 and C&E 1) at three different sites. In addition, HSDT were performed on a companion 324 mm pipe pile (P2), and also on two HP 310 x 100 piles and one 610 mm pipe pile. The HSDT were conducted at end of initial drive (EOID) and also at RST after 25 days.

All piles were driven to embedment depths of 16 m. The pipe piles were driven open ended and the soil plugs were left inside the piles after driving.

The piles were founded in a heterogeneous deposit of very stiff sandy clay till interbedded with compact to very dense sand with occasional very dense gravel layers. The groundwater table is typically about 2 m to 4 m below ground surface.

Details and results of the pile load tests are summarized in Table 2. Average mobilized skin friction and end bearing resistance during restrike as interpreted from the HSDT results are presented in Table 3.

Following are the main conclusions of the SLT and HSDT results:

1. The capacities of 324 mm dia. pipe piles, as determined by SLT using the Davisson (1972) method, ranged from 2620 kN to 3090 kN (Figure1). Piles P3 and P6 had comparable capacities of 3090 kN and 2970 kN, however P6 had a softer response than P3.
2. As a comparison, pile P3 yielded a SLT capacity of 3090 kN whereas the companion (adjacent) pile P2 pile yielded a lower capacity of 2500 kN by the HSDT method.
3. The capacities of the HP 310 x 110 piles (P1 and P4) as determined by HSDT were about 65% of the equivalent 324 mm dia. pipe pile capacities. The average mobilized shaft friction of the H-section piles was about 50% of the average mobilized shaft friction for the 324 mm pipe pile (P2). The higher shaft friction of the pipe piles is attributed to the greater soil displacement during pile driving resulting in higher normal effective stresses on the pipe (Meyerhof 1976).
4. The HSDT capacity of the 610 mm x 9.5 mm pipe pile (P5) was 3200 kN at restrike after 25 days. The average mobilized shaft friction of 74 kPa was lower than that of the adjacent 324 mm pipe pile (P2) and the end bearing resistance was also about one third of the 324 mm pipe pile. This suggests that the soil plug in the larger 610 mm dia. pile was not as effective as that in the smaller 324 mm pipe pile.
5. All piles indicated a significant increase in capacity between EOID and RST after 25 days. The greatest increase of about 78% was noted for the 324 mm pipe pile (P2). The H-section pile capacities (P1 and P4) increased by about 15% to 20%, and the 610 mm pipe pile capacity increased by 14%.

Based on the results of the pile load test program, the 324 mm pipe piles were selected as the main pile type. A maximum allowable (working stress) load of 870 kN was specified for a 16 m deep pipe pile, based on a maximum permissible pile top settlement of 6 mm at design load (Figure 1). This provided a factor of safety of greater than 3 based on the SLT results.

During construction, HSDT were conducted on about 100 pipe piles to confirm the pile capacities and determine the relationship between End of Initial Drive (EOID) capacity and Long Term Capacity after “set-up”.

Figure 2 presents a summary of the capacities versus time after initial drive for the 324 mm dia. x 16 m long pipe piles. It is noted that the pile capacities derived from SLT were significantly higher than the majority of the HSDT interpreted capacities. Furthermore, the trend of increase in capacity with time is also noted.

Comparison of HSDT results on three 324 mm pipe piles at the adjacent well pad site indicated increases in capacity ranging from 44% to 110% between EOID and RST after a “set-up” period of 9 to 12 days (Figure 2).

Figure 3 shows a summary of the pile capacities at RST for pile embedment lengths ranging from 10 m to 17 m. The

Table 2. Site 1 Summary of SLT and HSDT results.

Pile[1]	Test Method[2]	Testing Condition[3]	Mobilized Static Resistance Shaft (kN)	Toe (kN)	Total (kN)
P1 - HP310 x 110	HSDT	EOID	700	600	1,300
		RST	900	650	1,550
P2 – 324 mm dia x 9.5 mm pipe	HSDT	EOID	900	500	1,400
		RST	1,600	900	2,500
P3 – 324 mm dia. x 9.5 mm pipe	HSDT	EOID	950	900	1,850
		RST	-	-	-
	SLT[4]		-	-	3,090
P4 - HP310 x 110	HSDT	EOID	600	800	1,400
		RST	750	850	1,600
P5 – 610 mm dia. x 9.5 mm pipe	HSDT	EOID	1,900	900	2,800
		RST	2,260	940	3,200
P6 – 324 mm dia. x 9.5mm pipe	HSDT	EOID	900	1,200	2,100
		RST	-	-	-
	SLT		-	-	2,970
C&E – 324 mm diax 9.5mm pipe	SLT		-	-	2,620

[1]All Pile Embedment Lengths 16 m / [2]SLT – Static Load Test; HSDT – High Strain Dynamic Test
[3]Restrike taken 25 days after Initial Drive, [4]SLT Interpretation by Davisson (1972) Method

Table 3. Site 1 Mobilized skin friction and end bearing resistance at restrike after 25 days.

Pile No.	Type	Average Mobilized Skin Friction (kPa)	Mobilized End Bearing Resistance (kPa)
P1	HP 310 x 110	47	6,750
P2	324 mm pipe	98	10,900
P4	HP 310 x110	39	8,850
P5	610 mm pipe	74	3,200

"set up" period at the time of RST of these piles was not constant but ranged from about 20 to 100 days. Also shown for comparison is the specified pile design envelope based on a minimum factor of safety of 2.

Several of the HSDT capacities fell below the design envelope with a FOS of 2; however, these HSDT tests were typically taken at about 20 to 30 days after initial drive, and the capacities are expected to increase further with time. Furthermore, the capacities derived from the SLT were consistently higher than those derived from the HSDT.

Based on the results of the HSDT, the capacity for 324 mm pipe piles at EOID was conservatively estimated to be about 67% of the Long Term Capacity (i.e. an increase of 50% of the EOID capacity was considered appropriate for Long Term Design) to establish set criteria at EOID and RST.

4 SITE 2 – PETROCHEMICAL PLANT

Site 2 involved the installation of approximately 18,000 H-section and pipe piles with typical design (working stress) loads ranging from about 200 kN to 900 kN. The majority of the heavier loaded piles were HP310 x 110 sections driven to practical refusal in very dense sand or hard till at depths ranging from about 20 m to 25 m.

A pile load test program was completed at the start of construction to confirm the pile design capacities, and included five SLT's on HP310 x 110 piles and over 100 HSDT tests conducted on HP 310 piles and 508 mm diameter pipe piles.

The maximum applied load during SLT ranged from 3500 kN to 4500 kN on the 310 HP piles driven to practical

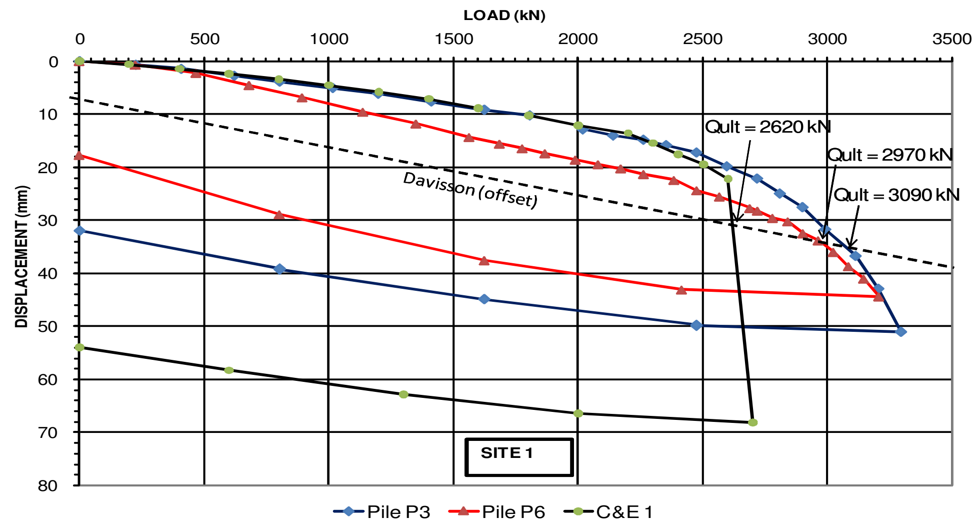

Figure 1. Static Load Test Results for 324 mm dia x 16 m long pipe piles

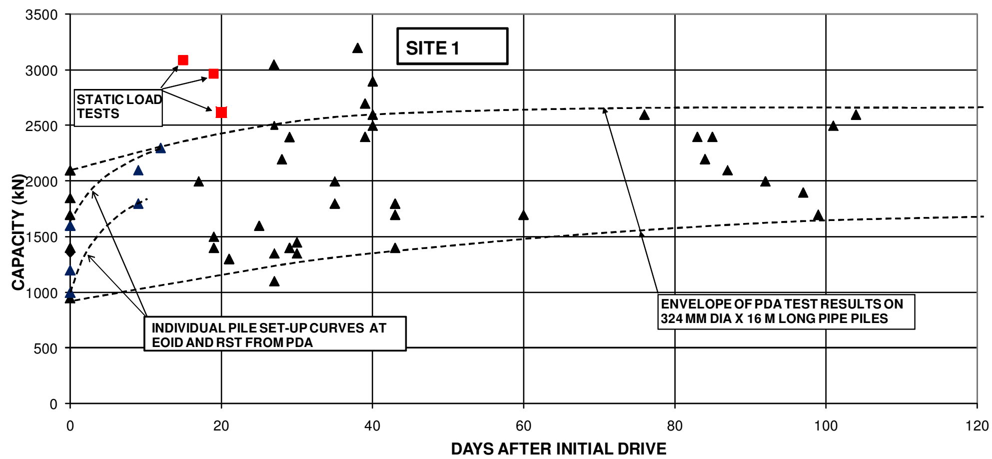

Figure 2. Capacity versus days after initial drive for 324 mm x 16 m long pipe piles

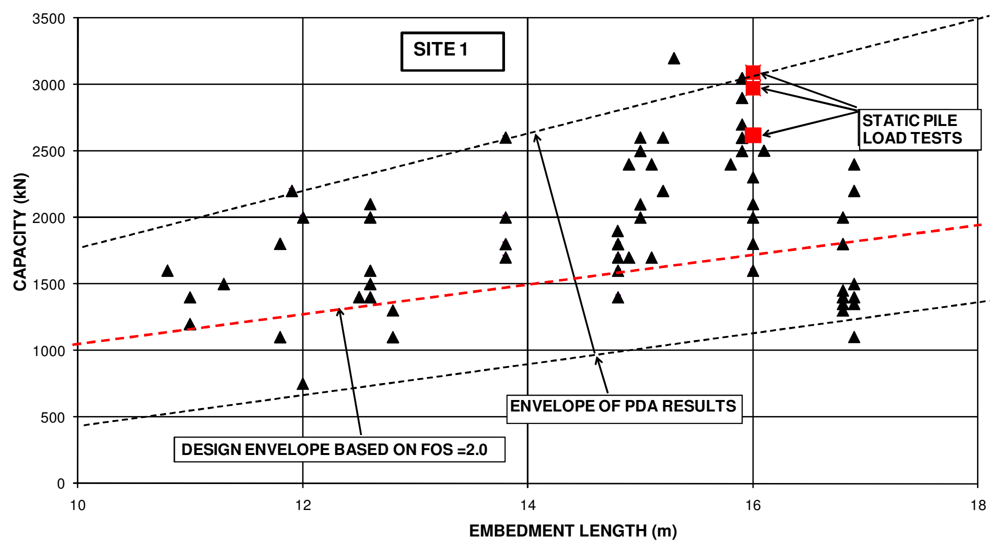

Figure 3. Capacity versus Length for 324 mm pipe piles

refusal at depths of 20 m to 24 m, and 3500 kN on the 508 mm diameter pipe pile driven open ended to refusal at a depth of 16 m, as shown on Figure 4. However, the maximum applied loads from the SLT were limited by the load test frame capacity and also the structural pile capacity and none of the piles experienced plunging failure. The maximum applied loads are therefore considered as lower bound values, whereas pile capacities of greater than 5000 kN were estimated based on load test interpretation methods in most cases.

The allowable pile loads were also dictated by serviceability criteria. Allowable static loads on the H-section piles corresponding to a limiting vertical displacement of 6 mm varied from about 1100 kN to 1300 kN, and 1650 kN for the pipe pile (Figure 4). This provided a factor of safety ranging from about 2.8 to 3.6 for the H-section piles and 2.1 for the pipe pile.

The pile designs had already been completed based on theoretical analysis prior to the load testing and were in the order of 840 kN to 900 kN; hence the piles had even higher factors of safety at the working design loads. This emphasizes the value of undertaking the pile load tests during the design phase, when the potential benefits of obtaining higher capacities can be effectively applied to the pile designs.

The interpreted pile capacities based on HSDT are plotted versus pile embedment depth in Figure 5 and show an increasing trend of pile capacity with depth. The data set was limited to piles tested at least 2 days after the initial drive. A trend of increasing capacity with time due to set-up is also evident in Figure 6. The SLT results are also plotted on these figures for comparison, and are in all cases higher than the HSDT capacities.

The HSDT results confirm a pile capacity of at least 2500 for piles tested at RST after 40 days. Part of the reason for the significant range in capacities determined by PDA is that the pile lengths are not constant and hence the basing conditions may vary.

A comparison of pile capacities determined by SLT and HSDT on the HP310 and 508 mm diameter pipe piles is provided in Table 4. The pipe piles were driven open ended to practical refusal at depths ranging from 16 m to 24 m. The average mobilized skin friction and end bearing resistance calculated using the results of the HSDT and SLT are also shown in Table 4. The end bearing resistance of the SLT was calculated by subtraction of the shaft resistance obtained from static tension load testing (ASTM 1990) undertaken on the same piles.

It is noted that the average mobilized skin friction of the pipe piles was higher than the H-section piles, which is similar to the observations at Site 1, and was attributed to greater soil displacement of the pipe section during driving. The difference in capacities obtained between the HP310 x 94 and HP310 x 110 piles is due to the significant increase in the strength of the founding clay till below 18 m, in which the latter piles were founded. The difference between the skin friction mobilized during the SLT on the pipe pile and that calculated from results of the HSDT on the pipe piles is also likely attributable to higher soil strengths with depth.

The end bearing resistance determined from SLT is significantly greater than obtained from HSDT, which is believed to be a result of the larger magnitude of displacement, generated during SLT. However, the end bearing resistance developed for the pipe pile is only about one half of that determined for the H-piles using both HSDT and SLT methods. It is suspected that the open ended pile provided a lower resistance than would be the case for a closed end pipe pile.

5 SITE 3 – POWER PLANT

Site 3 involved a coal fired power plant housing heavy boilers and turbine generators. The boilers and turbines were founded on large mats supported by groups of 610 mm pipe piles driven to depths of up to 40 m, while the building structure was supported on smaller groups of H-section piles driven to depths of up to 35 m. Typical soil strata and properties are shown in Table 1 and consisted of thick clay overlying sand and silt deposits.

HSDT were performed on two H-section piles (one 310 x 79 and one 310 x 110) and two pipe piles (610 mm dia. x 12.5 mm pipe) prior to construction (Table 5). Results of the HSDT indicated increases in capacity of 85% for the H-section pile (P3) and 140% for the pipe piles (P2 and P4) between initial drive and RST after 19 days.

Results of HSDT on H-section piles during construction are presented in Figure 7. The results indicate a considerable range of capacities, but generally follow a trend of increasing capacity with time similar to the previous two sites and also reported by others (Stevens 2004 and Fellenus 2002).

The average trend line provides a capacity of about 2200 kN after 60 days. The trend line was skewed downwards due to a series of lower HSDT results performed on piles located in the Boilerhouse area.

Two SLT's were subsequently carried out on production piles in the Boilerhouse area and confirmed a lower pile capacity (1500 kN and 2000 kN for piles P760 and P328, respectively) in this area. The results of the two SLT are included in Figure 7 for comparison.

As a result of the SLT, it was decided to downgrade the capacity of the H-section piles in the Boilerhouse and piles were added to achieve a FOS of at least 2. It is believed that the low capacities obtained for both the HSDT and the SLT were affected by the magnitude of pore pressure generation caused by the driving in the large groups of piles, such that the piles had not fully "set-up" at the time of the SLT. Nevertheless, it was considered prudent to downgrade these piles, as it was not feasible to wait longer and check if additional "set up" would occur.

6 CONCLUSIONS

The case histories demonstrate the importance of combining SLT and HSDT to optimize pile designs. It is most beneficial to undertake the pile load tests during the design phase,

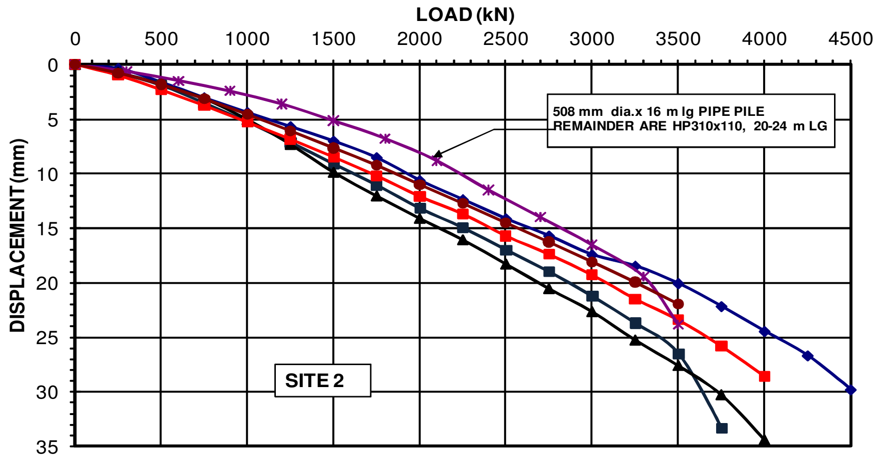

Figure 4. Summary of static load tests for Site 2

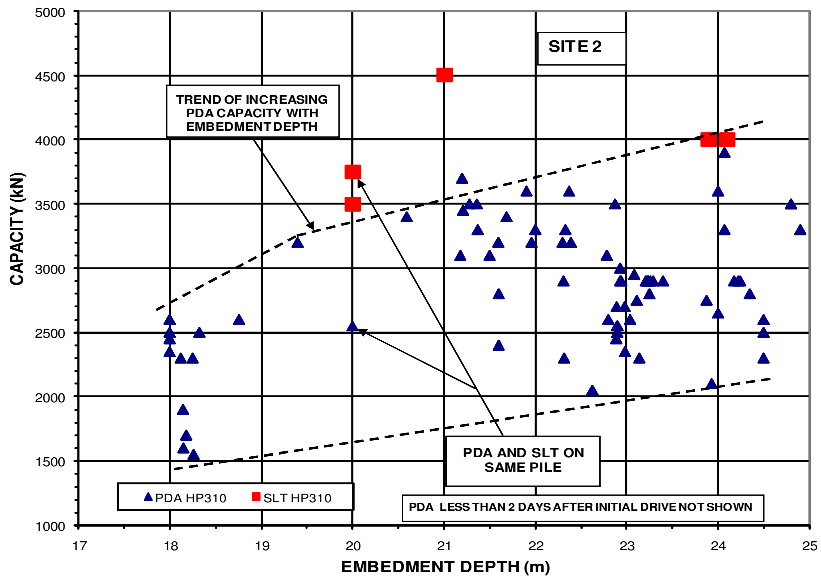

Figure 5. Capacity versus embedment depth

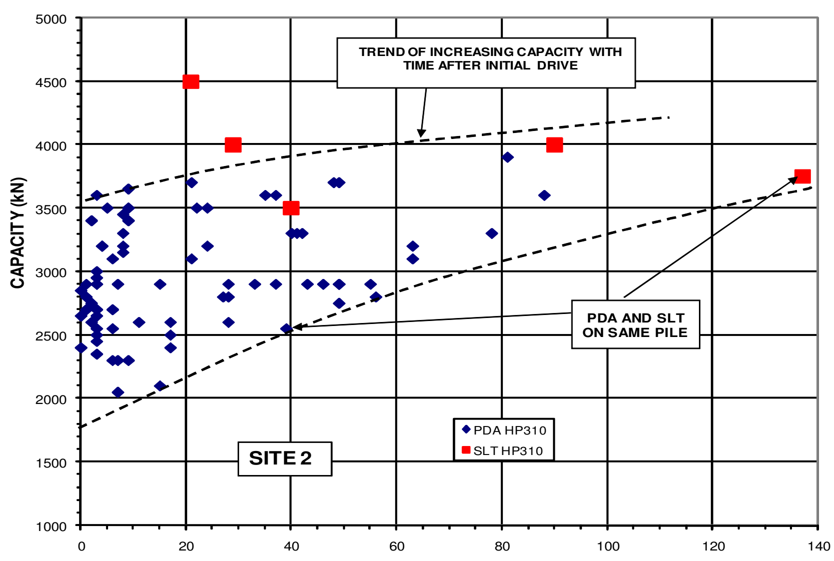

Figure 6. Capacity versus days after initial drive

Table 4. Site 2 Summary of HSDT and SLT Results

Pile Type (tip depth, m)	Test Method[1]	Number of Tests	Average Mobilized Static Resistance				
			Shaft (kN)	Toe (kN)	Total (kN)	Skin Friction (kPa)	End Bearing (MPa)
HP310 x 110 (20 to 25)	HSDT[2]	73	2055	935	2990	73	9.7
	SLT[3,4]	5	1950	2000	3950	69	20.6
HP310 x 94 (18 to 19)	HSDT	14	955	1340	2295	59	9.9
508 mm dia. x 9.5 mm (16 to 24)	HSDT	9	2795	950	3745	87	4.7
	SLT[3,5]	1	1325	2175	3500	52	10.9

[1]SLT – Static Load Test; HSDT – High Strain Dynamic Test
[2]Restrike at least 2 days after Initial Drive. [3]SLT taken as maximum load applied (see text)
[4]Estimated from SLT in tension undertaken on two of the piles and pro-rated to the average total load for the five tests
[5]Estimated from SLT in tension undertaken on the pile (16 m depth)

Table 5. Site 3 Results of HSDT tests at end of initial drive and restrike.

Pile No.	Test Condition*	Embedment Length (m)	Mobilized Capacity (kN)	Shaft Resistance (kN)	Toe Resistance (kN)
P1 - HP 310 x 79	RST (19)	35.0	2400	2150	250
P3 - HP 310 x 110	EOID	35.2	1500		
	RST (1)	35.2	2100		
	RST (19)	35.2	2800	2500	300
P2 - 610 mm dia. x 12.5 mm pipe	EOID	40.0	1800	1500	300
	RST (18)	40.1	4300	3800	500
P4 - 610 mm dia. x 12.5 mm pipe	EOID	40.0	1850	1450	400
	RST (1)	40.0	3100	2800	300
	RST (19)	40.1	4400	3900	500

*EOID – End of Initial Drive; RST – Restrike (19) 19 days after Initial Drive

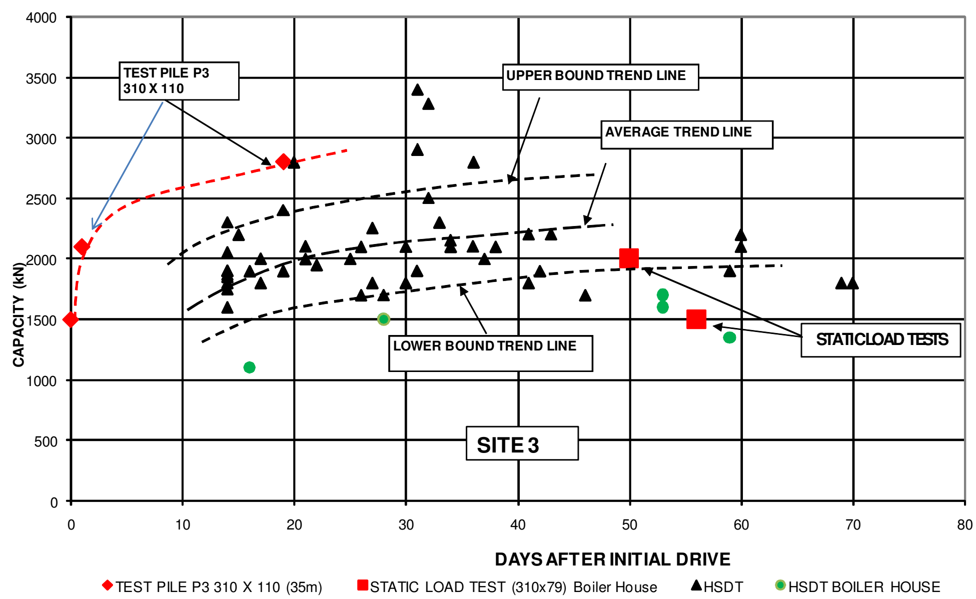

Figure 7. Capacity versus days after end of initial drive (HP310 x 79 and HP310 x 110)

when the potential benefits of obtaining higher capacities can be effectively applied to the pile designs.

Pile design based on Limit States Design (LSD) in accordance with NBC 2005 must satisfy the Ultimate Limit States (ULS) to prevent plunging failure and also Serviceability Limit States (SLS) to maintain tolerable settlement. In the first two case histories, the SLS criteria of limiting individual pile settlements to 6 mm was the governing criteria, and these results were obtained primarily from the Static Load Tests. In fact, no information was obtained on settlement criteria from the Case 3 prior to construction.

Pile “set-up” resulted in significant gain in capacity for all the three cases and was relied upon to achieve the design capacities. Using End of Initial Drive capacities would have been overly conservative and would have required significantly longer piles with commensurate increases in costs.

Fellenius (2002) and others have stressed the importance of “set-up” and this needs to be taken into account when organizing and conducting pile load test programs. It is important, when comparing results, that the SLT and HSDT are in “temporal agreement” and that the pile dimensions, basing conditions, etc, are consistent between the different piles analysed.

Furthermore, when the SLT and HSDT are conducted on the same pile, it is preferable to undertake the SLT first as this generally results in less disturbance (and loss of “set-up”) to the pile, than would be the case if the HSDT were conducted first.

Sufficient wait time is required between tests to allow for adequate “set-up” and resulting strength gain. Methods are presented in the literature for evaluating the required set-up time (e.g. Skov and Denver 1988) Comparison of pipe pile and H-section pile capacities at the first two sites indicated higher capacities were obtained on the pipe piles for similar sized pipe piles. This is considered to be a result of the greater soil displacement caused from plugging of pipe piles, thereby resulting in higher confining stresses and friction on the sides of the pile (Meyerhof 1976).

7 ACKNOWLEDGEMENTS

The authors wish to acknowledge the assistance provided by the staff of Thurber Engineering Ltd during the SLT and HSDT tests. The SLT were conducted by Agra Foundations Ltd, and the HSDT were conducted by Urkkada Technology Ltd.

REFERENCES

ASTM 1981. D1143 Standard Test Method for Pile Under Static Axial Compressive Load. Annual Book of ASTM Standards, vol. 04.08, pp.93-103

ASTM 1990. D3689 Standard Test Method for Individual Piles Under Static Axial Tensile Load. Annual Book of ASTM Standards, vol. 04.08, pp.413-423

ASTM 2000. D4945 Standard Test Method for High Strain Dynamic Testing of Piles. Annual Book of ASTM Standards, vol. 04.08, pp.981-987

Davisson, M. T. 1972. High capacity piles. Proceeding, Lecture Series, Innovations in Foundation Construction, ASCE, Illinois Section, 52 pp.

Fellenius, B.H. 2002. *Basics of Foundation Design. Production of eLib*, geoforum.com.

Meyerhof, G.G. 1976. Bearing Capacity and Settlement of Pile Foundation. JGED, ASCE, vol. 102, GT3, March, pp. 195-228 (Terzaghi Lecture).

National Building Code of Canada 2005. National Research Council Canada, Canada Commission of Building and Fire Codes.

Skov, R., and Denver, H. 1988. Time dependence of bearing capacity of piles. In Proceedings of the 3rd International Conference on the Application of Stress-Wave Theory to Piles, Ottawa BiTech Publishers Ltd.

Stevens, R. F. 2004. The use of dynamic pile testing to interpret soil set-up. Current Practices and Future Trends in Deep Foundations. ASCE Geo. Spec. Pub. No. 125, pp 96-109.

Yang, L., and Liang, R. 2009. Incorporating setup into load and resistance factor design in sand. Canadian Geotechnical Journal 46; pp 296-305.