SAVINGS FROM TESTING THE DRIVEN-PILE FOUNDATION FOR A HIGH-RISE BUILDING

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ABSTRACT

The project consists of a high-rise building supported on driven piles. Design objectives included determining the highest maximum long-term capacity which could be reasonably obtained from a drivability perspective, using readily available equipment. A pre-production test program was performed on 16-inch-diameter (406-mm-diameter) ASTM 252, Grade 3 (45 ksi, 310 MPa) steel pipe piles, having a wall thickness of 0.50 inch (13 mm). Based on evidenced capacities, including long-term set-up, a maximum allowable pile load of 600 kips (2,670 kN) was used on the project. The cost-effectiveness of the test program was evaluated by comparing the cost of a design using 600-kip allowable load piles to alternative designs using the same pile section, but assuming that various lesser testing scenarios had been performed, warranting higher safety factors. Six complete alternative foundation designs were performed for these lower allowable pile loads. Costs associated with the piles (based on production-pile driving behavior), concrete caps and mat, and construction-control methods were estimated for the redesigns. Foundation costs were evaluated for piles designed both with and without the benefit of capacity contribution from set-up. Cost differences among the various construction-control methods were determined in terms of total cost, and support cost. Pile-driving schedule impacts associated with the six alternative allowable loads were also estimated. Additional savings that resulted from applying test-program results to production piles which were damaged or terminated short were quantified.

INTRODUCTION

Column service loads for the high-rise building range from 1,400 to 4,200 kips (6,230 to 18,700 kN). The generalized soil conditions are presented in Figure 1. Site grades were relatively level, with a ground-surface elevation of approximately +53 feet (16 m). Fill material from previous construction was encountered to approximate Elev. +33 feet (10 m). Below the fill, medium dense silty sand, to silt with sand, was encountered to approximate Elev. +23 feet (7 m). Underlying deposits consisted of lean clay, with undrained shear strengths ranging from approximately 1,000 to 3,000 pounds per square foot ("psf") (48 to 144 kPa), and extended to Elev. -5 feet (-2 m). Silty sand, to silt with sand, exhibiting increasing relative density with depth, was found below the lean clay to approximate Elev. -92 feet (-28 m), where hard lean clay (glacial till) with undrained shear strengths in excess of 5,000 psf (239 kPa) was encountered. Borings did not extend below Elev. -103 feet (-31 m).

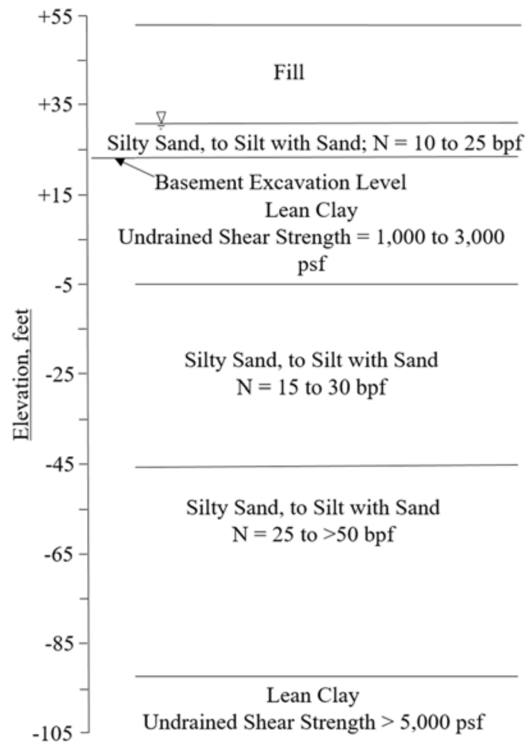

Figure 1. Generalized soil profile

Based on a review of the project service loads, it was determined that the project would benefit from a program to maximize allowable pile loads while maintaining reasonable installation methods, including readily available pile sections, and hammer types and sizes. The project design team reviewed the option of using 16-inch-diameter (406-mm-diameter) closed-end pipe piles, having a nominal wall thickness of 0.50 inches (13 mm), and a steel cross-sectional area of 24.3 square inches (157 cm^2). It was estimated that piles with an allowable geotechnical load on the order of 500 to 600 kips (2,220 to 2,670 kN) could reasonably be obtained utilizing a carefully planned and executed test program which included both dynamic and static load testing. A 600-kip (2,670 kN) allowable load on an unfilled pipe pile results in a steel stress of 24.7 kips per square inch (170 MPa), necessitating that the pipe be filled with concrete after driving, and that the concrete be credited with contributing to the pile's structural resistance.

This project's foundation piles were designed using allowable stress design ("ASD"). In ASD, allowable geotechnical load is equal to ultimate geotechnical capacity[1] divided by a safety factor. This range of potential allowable pile loads was predicated on the ability to install the 16-inch (406-mm) piles to long-term ultimate capacities on the order of 1,000 to 1,200 kips (4,448 to 5,338 kN), and a test program scope which justified using a safety factor of 2.0.

[1] "Ultimate capacity" is a misnomer, as an element's capacity (e.g., "compression/bearing capacity," "tension/uplift capacity," "shaft capacity," and "toe capacity") is the element's ultimate geotechnical resistance. It cannot be misunderstood, however, and so is used here.

Initial Capacity, Set-Up, Long-Term Capacity, Safety Factor, and Allowable Load

The as-built building foundation design utilized two allowable pile loads: 500 kips (2,220 kN), and 600 kips (2,670 kN). For comparison purposes of this paper, the baseline foundation design herein used only an allowable load of 600 kips (2,670 kN). This allowable load is a function of both the long-term geotechnical capacity to which the piles could be installed, and the safety factor applied to that long-term capacity. The long-term capacity to which the piles could be installed included two components: end-of-initial drive capacity, and soil set-up (time-dependent capacity increase after driving).

Initial Capacity – End-of-initial-drive capacity is a function of a site-specific specific hammer/pile/soil combination, and is generally limited by an established maximum driving stress, and by a terminal equivalent blow count (equivalent blow counts are measurements of blows per driving distance converted to units of blows per foot ("bpf")). Target maximum driving stress was limited to 90 percent of the pile's yield strength ($0.9f_y$). The piles were fabricated to ASTM A252 Grade 3 requirements, which specify a minimum yield strength of 45 kips per square inch ("ksi"; 310 MPa), accordingly limiting driving stresses to 40.5 ksi (279 MPa). The target maximum terminal equivalent blow count was 120 bpf (blows per foot are roughly equivalent to blows per 0.3 meter). For this project, the hammer/pile/soil combination afforded the pile installations to approach their driving stress and blow count limits more or less simultaneously.

Based on test program results, and later corroborated by production-pile driving, a reasonable maximum end-of-initial-drive ("EOID") capacity to which the piles could be driven was 800 kips (3,560 kN).

Set-Up – One of the test program results provided by dynamic load testing during pile installation and long-term restrikes was to develop cumulative shaft set-up profiles for each of the restruck test piles. A cumulative shaft set-up profile presents the estimated shaft set-up at any pile toe elevation above the test pile's terminal toe elevation, and is a function of pile embedded shaft area. The greater a pile's embedment length, the more set-up occurs, and therefore the less EOID capacity is required. Since required EOID capacity decreases with increasing embedment depth, so does required penetration resistance. Therefore, a design shaft set-up profile can be used to develop depth-variable production-pile driving criteria which reflect decreasing required EOID capacity with increasing embedment depth [Komurka 2004]. Resulting production pile installations will be driven only as deep as necessary to achieve (after set-up) their required long-term capacity, reducing unnecessary driven length. These depth-variable driving criteria were generated using refined wave equation analyses [Hannigan 2016].

A pre-production test program was performed which included five indicator piles, four reaction piles, one axial compression static load test pile with embedded strain gages, restrike testing, dynamic load testing, and CAPWAP® analyses. A major objective of the test program was to establish the highest long-term axial compression capacity to which the 16-inch (406-mm) piles could reasonably be installed from a drivability perspective using readily available equipment. Ten test piles were installed, driven to near-maximum attainable end-of-drive capacities. The piles were driven using a Delmag D46-32 single-acting diesel hammer. According to the manufacture's literature, the Delmag D46-32 has a 10.1-kip (45.1-kN) ram, a rated maximum stroke of 12.0 feet (3.67 m), and a maximum rated energy of 122 foot-kips (165 kJ).

To aid in demonstrating even higher capacities, soil set-up was characterized utilizing relatively long-term restrikes (36 to 54 days after EOID). Set-up characterization included determining both total set-up magnitude and distribution along the shaft, allowing set-up to be incorporated into production-pile driving criteria. Dynamic monitoring using a Pile Driving Analyzer® ("PDA"), and subsequent CAPWAP analyses, were performed on dynamic test records from all the test piles' installations and restrikes. Based on test-program results, it was anticipated that production piles could be driven to depths at which they would experience a minimum set-up of 400 kips (1,780 kN), so that their long-term capacity would equal or exceed 1,200 kips (5,340 kN). Design and construction proceeded using 600-kip (2,670-kN) allowable load piles.

COST COMPARISON

Alternate Construction-Control Methods and Safety Factors

A basic constraint in evaluating the relative cost-effectiveness of various foundation designs is that projects virtually never get constructed more than once, using a different design each time. Such was the case for this building foundation. However, for this study, multiple foundation designs were performed using the same pile section, but using different allowable pile loads.

The various allowable loads used for the multiple foundation designs resulted from using four (different) safety factors (associated with different construction-control methods), applied to two ultimate capacities. These values are presented in Tables 1a and 1b.

For a large project, it is important to consider the structure loads, the target pile capacity, the number of piles required, the installed footage, and the site's subsurface variability. It is appropriate to study certain combinations of construction-control methods ("CCMs"), while excluding certain "stand alone" CCMs. For example, either a dynamic formula, or a wave equation analysis, alone could be used to control driving. However, dynamic testing would likely be accompanied by wave equation analysis. Similarly, static load testing would likely be performed in conjunction with dynamic testing. For example, performing only a static load test would not have allowed assessment of site variability with respect to drivability or set-up behavior. Site variability was evidenced by the embedded lengths of production piles with a long-term ultimate capacity of 1,200 kips (5,340 kN) ranging from 52 to 150 feet (15.8 to 45.7 m).

The four construction-control methods presented in Tables 1a and 1b are considered representative of options often considered for projects. The four safety factors associated with the various CCMs are sometimes discretionary, sometimes code-mandated. For a given CCM, differences between ASD and Load and Resistance Factor Design ("LRFD") platforms complicate determining equivalent ASD safety factors from LRFD code-mandated resistance factors. Rather than associating safety factors with specific CCMs, this study's intent was to investigate the effect of various CCMs and a range of realistic safety factors on foundation costs and schedule.

To evaluate the effect of characterizing set-up and incorporating it into design and installation, the four safety factors associated with the various construction-control methods were applied to two

Table 1a. Design Scenarios Summary – With Set-Up

Construction-Control Method ("CCM")	Safety Factor	Allowable Load, kips[1]	Piles					Pile Caps and Core Mat Concrete		
			Count	Total Length, feet	Pile Cost, dollars			Total Volume, yd^3	Concrete Cost, dollars	
					Total	Difference			Total	Difference
WE, DLT, & SLT	2.0	600	456	30,313	1,548,702	---		1,548	728,800	---
WE & DLT	2.5	480	572	38,024	1,942,669	393,968		1,810	852,680	123,880
WE	3.0	400	684	45,470	2,323,052	774,351		2,091	982,235	253,435
DF[2]	3.5	343	806	53,580	2,737,398	1,188,696		2,355	1,097,125	368,325

Construction-Control Method ("CCM")	Safety Factor	Allowable Load, kips	Construction-Control Method Cost, dollars		Total Foundation Cost, dollars	
			Total	Difference	Total	Difference
WE, DLT, & SLT	2.0	600	236,260	---	2,513,762	---
WE & DLT	2.5	480	187,959	-48,301	2,983,308	469,547
WE	3.0	400	2,000	-234,260	3,307,287	793,526
DF	3.5	343	500	-235,760	3,835,023	1,321,261

DF = Dynamic Formula; DLT = Dynamic Load Test; SLT = Static Load Test; WE = Wave Equation.
[1]Long-term geotechnical capacity with set-up = 800 kips EOID + 400 kips set-up = 1,200 kips.
[2]The dynamic formula and its associated safety factor is representative of dynamic formulas which estimate ultimate capacity (e.g., Gates).
1 kip = 448 kN; 1 foot = 0.3048 m; 1 yd^3 = 0.765 m^3.

long-term capacities: one including set-up, and one not including set-up. The first long-term capacity is the maximum reasonably achievable EOID capacity of 800 kips (3,560 kN), plus 400 kips (1,780 kN) set-up, resulting in a long-term capacity of 1,200 kips (5,340 kN). For comparison purposes, it was assumed that use of these two CCMs included an accurately estimated design set-up profile. The second long-term capacity is 800 kips (3,560 kN) EOID, without contribution from set-up.

Using test program results and as-built information, the cost impacts of alternate designs using the allowable loads listed in Tables 1a and 1b were estimated. Cost estimates were divided into piles, concrete (pile caps and core mat), construction-control method, and total foundation cost.

Table 1b. Design Scenarios Summary – Without Set-Up

Construction-Control Method ("CCM")	Safety Factor	Allowable Load, kips[1]	Piles				Pile Caps and Core Mat Concrete		
			Count	Total Length, feet	Pile Cost, dollars		Total Volume, yd^3	Concrete Cost, dollars	
					Total	Difference[2]		Total	Difference
WE, DLT, & SLT	2.0	400	684	45,470	2,323,052	774,351	2,091	982,235	253,435
WE & DLT	2.5	320	885	58,832	3,005,704	1,457,002	2,631	1,225,465	496,665
WE	3.0	267	1,050	69,800	3,566,089	2,017,388	3,065	1,424,675	695,675
DF	3.5	229	1,222	81,234	4,150,248	2,601,547	3,543	1,663,925	935,125

Construction-Control Method ("CCM")	Safety Factor	Allowable Load, kips	Construction-Control Method Cost, dollars		Total Foundation Cost, dollars	
			Total	Difference	Total	Difference
WE, DLT, & SLT	2.0	400	172,640	-63,620	3,477,927	964,166
WE & DLT	2.5	320	130,339	-105,921	4,361,508	1,847,746
WE	3.0	267	2,000	-234,260	4,992,764	2,479,003
DF	3.5	229	500	-235,760	5,814,673	3,300,912

[1]Long-term geotechnical capacity without set-up = 800 kips EOID.
[2]Compared to same construction-control method with set-up.
1 kip = 448 kN; 1 foot = 0.3048 m; 1 yd^3 = 0.765 m^3.

Pile Costs

The same 16-inch-diameter (402-mm-diameter) 0.5-inch-wall (12.7-mm-wall) pipe pile section was evaluated for all the allowable loads presented in Tables 1a and 1b. Although this section may be structurally excessive to support the lower allowable loads, its steel area is required to withstand the driving stresses associated with a required EOID capacity of 800 kips (3,560 kN).

The average as-built embedded length of the project's 600-kip (2,670 kN) allowable load piles, 66.5 feet (20.3 m), was used in the evaluation. To achieve a minimum long-term capacity of 1,200 kips (5,340 kN) including set-up, the as-built 600-kip (2,670 kN) allowable load piles were driven to EOID capacities on the order of 800 kips (3,560 kN) or less. The as-built piles would have been driven to EOID capacities of less than 800 kips (3,560 kN) if they terminated at toe elevations where the design set-up exceeded 400 kips (1,780 kN). Accordingly, the average as-built embedded length is conservative (underpredicts) with respect to estimated pile lengths, costs, and schedule impacts for the designs which do not include set-up.

A representative unit pile installation cost of approximately $51 dollars per foot (0.31 m) was used, which includes both the pile and its concrete fill. A summary of pile cap, core mat, and total pile count, total embedded pile length, and pile cost for the various designs is presented in Tables 1a and 1b.

As would be expected, pile count and total embedded length increased with decreasing allowable loads. A review of Tables 1a and 1b indicates that the difference between the design scenarios using the highest allowable load with set-up and the lowest allowable load without set-up amounted to 766 piles, and a total embedded length of 50,921 feet (15,521 m). This results in an *extra* pile cost of $2,601,547 ($4,150,248 versus $1,548,702).

Concrete Costs

The building design resulted in concentrated structure loads in the area of a building core. These concentrated loads were supported on a mat. Elsewhere, building loads were supported on pile caps.

Decreased allowable loads routinely required more piles per pile cap at given columns, which resulted in increased cap volumes because of increased plan areas. Any typically small reductions in cap thickness associated with decreased allowable pile load (controlled by punching shear) was swamped by a substantial increase in footprint to accommodate more piles.

For the core mat, punching shear did not control design, so mat thickness was not reduced with decreasing allowable loads. Mat stiffness was required to deliver load to the piles farther out from the core walls via mat flexure.

Representative unit concrete placement costs of $565 and $335 dollars per cubic yard (0.76 m^3) was used for pile cap concrete, and core mat concrete, respectively. These costs included excavation, shoring, reinforcing steel, concrete placement, and stripping. A summary of pile cap and core mat concrete volume, total concrete volume, and concrete cost for the various designs is presented in Tables 1a and 1b.

As would be expected, total concrete volume and cost increased with decreasing allowable loads. A review of Tables 1a and 1b indicates that the difference between the design scenarios using the highest allowable load with set-up and the lowest allowable load without set-up amounted to 1,995 cubic yards (1,525 m^3) of concrete. This results in an *extra* concrete cost of $935,125 ($1,663,925 versus $728,800).

Construction-Control Method Costs

Based on actual costs incurred for the test program, costs associated with the various construction-control methods and components were estimated. Costs incurred by the contractor, the dynamic testing agency, and the geotechnical engineer were included. Distinction was made between dynamic load testing during installation (performed for designs both with and without set-up), and during restrike testing (performed only for designs with set-up). Distinction was also made between a static load test instrumented to provide load-transfer behavior (performed for designs with set-up), and a non-instrumented static load test (performed for designs without set-up). A summary of CCM costs for the various designs is presented in Tables 1a and 1b.

As would be expected, construction-control method costs increased with increasing allowable loads, and CCMs which included field characterization of set-up were more expensive than those that did not characterize set-up. A review of Tables 1a and 1b indicates that the CCM cost difference between the design scenarios using the highest allowable load with set-up and the lowest allowable load without set-up was $235,760.

Nine of the 10 test piles were installed in production-pile locations. Based on the production piles' average embedded length and unit installation cost, installing nine test piles in production-pile locations reduced the project's net test program cost by approximately $28,000.

Total Foundation Costs

For each of the design scenarios and their associated allowable pile loads, total foundation cost was determined by adding the pile, concrete, and construction-control method costs. The resulting total foundations costs are presented in Tables 1a and 1b. A review of Tables 1a and 1b indicates that the *total cost difference* between the design scenarios using the highest allowable load with set-up and the lowest allowable load without set-up results in a total foundation cost *savings* of $3,300,912 ($2,513,762 versus $5,814,673, a factor of 2.3).

Despite increased construction-control method costs associated with higher allowable loads, whether incorporating set-up or not, total foundation costs decreased with increasing allowable loads. Similarly, despite increased CCM costs associated with characterizing set-up, for a given safety factor total foundation costs decreased when set-up was incorporated in design. In other words, whether testing resulted in using a lower safety factor or in incorporating set-up, the savings resulting from increased testing far exceeded the cost of the testing.

The relationships between pile cost, concrete cost, and the sum of the two versus allowable load are presented in Figure 2. A review of Figure 2 indicates that the piles account for approximately 65 to 70 percent of the constructed foundation cost. A review of Figure 2 also indicates that a given increase in allowable pile load from a lower value results in greater cost savings than a given increase in allowable load from a higher value. For example, greater savings are realized by increasing the allowable load from 250 to 350 kips (1,110 to 1,560 kN) than from 500 to 600 kips (2,220 to 2,670 kN), an allowable load increase of 100 kips (445 kN) in both cases. This is because at higher allowable loads, a reduction in pile count at a given cap is less-sensitive to an increase in allowable load. Additionally, at higher allowable loads more pile caps are more-likely to already contain the minimum required number of piles (from a structural design standpoint), and still-higher allowable loads do not result in fewer piles in those caps.

Benefit Cost Ratios

The cost-effectiveness of the testing was evaluated in terms of benefit/cost ratios. For design scenarios with and without set-up, differential costs and resulting savings were compared to those associated with dynamic formula without set-up. Benefit/cost ratios were only considered appropriate for the construction-control methods that included field testing. For the various allowable loads, the calculated benefit/cost ratios represent how many construction dollars would be saved for each dollar spent on testing. A summary of the results of this evaluation are presented in Table 2.

Table 2. Benefit/Cost Ratios Summary

			Total CCM Cost, dollars		Total Foundation Cost, dollars		
Construction-Control Method ("CCM")	S.F.	Allow-able Load, kips	Cost	Differential Cost[1]	Cost	Resulting Savings[1]	Benefit/ Cost Ratio
With Set-Up							
WE, DLT, & SLT	2.0	600	236,260	235,760	2,513,762	1,321,261	14.0
WE & DLT	2.5	480	187,959	187,459	2,983,308	851,715	15.1
Without Set-Up							
WE, DLT, & SLT	2.0	400	172,640	172,140	3,477,927	2,336,746	13.6
WE & DLT	2.5	320	130,339	129,839	4,361,508	1,453,165	11.2

[1]Compared to construction-control method of dynamic formula without set-up.

A review of Table 2 indicates that the benefit/cost ratios for designs which incorporate set-up are greater than for those designs which do not incorporate set-up. This indicates that for this site, the savings resulting from characterizing set-up exceeded the cost of charactering set-up. This is more-directly apparent by comparing total foundation costs in Table 2 for designs with and without set-up.

SCHEDULE COMPARISON

Evaluation of potential construction-control method scenarios needs to include not only economic aspects, but also construction schedule impacts, because time is money. Projects often have a direct correlation between economics and construction schedule, such as facilities that generate daily revenue when brought into service. Less-apparent economic aspects related to construction schedule might include interest on construction loans, penalties or fines for regulatory non-compliance, construction productivity adversely affected by a change of season, out-of-service delays to the public (as with roads and bridges), etc.

At the startup of production driving, a limited number of piles were driven in the northwest corner of the project, after which driving operations were suspended for a time before resuming. As driving operations neared conclusion, the pile-driving production rate was significantly reduced by staged removal of the excavation's access ramp. Staged access ramp removal necessitated that the crane vacate the excavation multiple times, precluding driving operations during each time that the ramp was reconfigured. The initial suspension of driving, and the staged ramp removal time frame, were omitted from the production rate determination.

Using as-built information, the schedule impacts of alternate designs, both with and without set-up, using the allowable loads listed in Tables 1a and 1b were estimated. Dividing production-driving duration (determined as described above) by the number of piles installed yielded an overall average production rate of 5.37 piles per calendar day. A summary of schedule impacts for the various designs is presented in Table 3, and in Figure 3.

Table 3. Construction Schedule Impacts Summary

Construction-Control Method ("CCM")	Safety Factor	Allowable Load, kips	Piles			
			Count	Total Length, feet	Driving Duration, calendar days	
					Total	Difference
With Set-Up						
WE, DLT, & SLT	2.0	600	456	30,313	85	---
WE & DLT	2.5	480	572	38,024	107	22
WE	3.0	400	684	45,470	127	42
DF	3.5	343	806	53,580	150	65
Without Set-Up						
WE, DLT, & SLT	2.0	400	684	45,470	127	42
WE & DLT	2.5	320	885	58,832	165	80
WE	3.0	267	1,050	69,800	196	111
DF	3.5	229	1,222	81,234	228	143

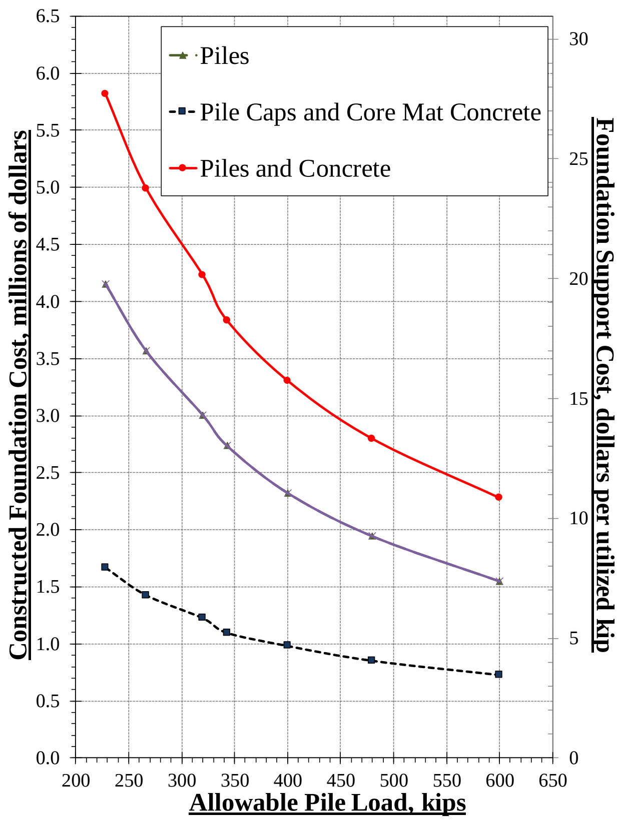

Figure 2. Constructed Foundation Cost, and Foundation Support Cost, vs. Allowable Pile Load.

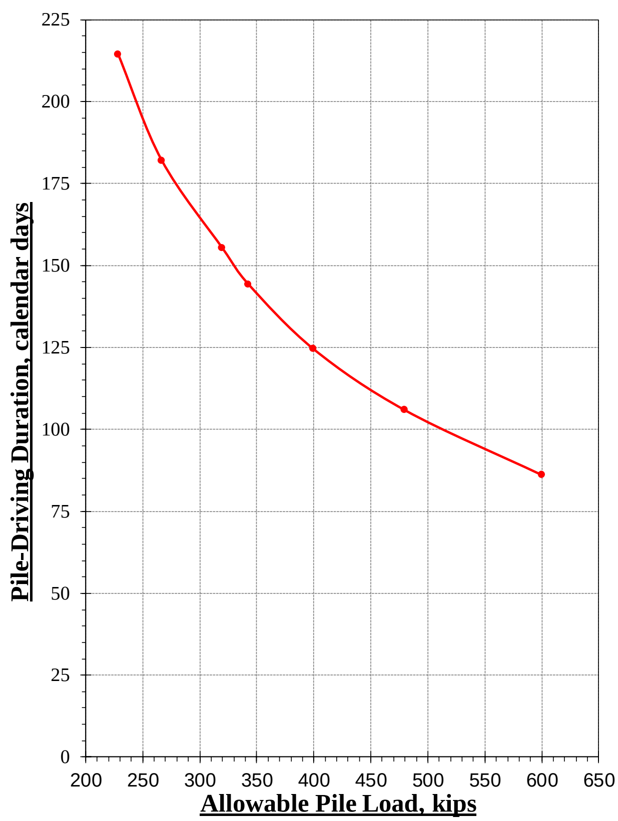

Figure 3. Driving Duration vs. Allowable Pile Load.

Often, an impediment to performing increased deep-foundation testing is that it ostensibly adds time to the construction schedule. Depending on the construction-control method (and particularly the time after EOID at which restrike testing is performed to characterize set-up), increased testing can clearly save more time than it takes to perform the testing. A review of Table 3 indicates that the design scenarios using the highest allowable load with set-up and the lowest allowable load without set-up results in a *savings* of 143 fewer calendar days to install production piles.

Similar to the constructed foundation cost relationships presented in Figure 2, a review of Figure 3 indicates that a given increase in allowable pile load from a lower value results in greater driving duration savings than a given increase in allowable load from a higher value. This is result of the same reasons discussed for the constructed foundation cost relationships.

SAVINGS FROM SET-UP

Quantifying set-up's contribution to long-term geotechnical capacity permits foundation designs using piles designed both with and without the benefit of set-up to be evaluated. For each safety factor evaluated, the parameters presented in Tables 1a and 1b for designs with and without the benefit of set-up were compared. This comparison indicates differences in the corresponding designs attributable to testing for set-up, and to incorporating it into design and installation. The resulting differences attributable to set-up are presented in Table 4, and in Figure 4.

A review of Table 4 indicates that the for the range of safety factors evaluated, incorporating set-up into pile design resulted in total foundation cost savings ranging from $964,166 to $1,979,651, and driving duration savings ranging from 42 to 78 calendar days. A review of Figure 4 indicates

that for the range of safety factors evaluated, the relationships between total foundation cost savings, and driving duration savings, and safety factor were reasonably linear.

FOUNDATION SUPPORT COSTS

Foundation support cost is a normalized parameter that permits the relative cost-effectiveness of viable foundation design options to be evaluated, thereby allowing designers to include cost among other decision parameters [Komurka 2015]. Support cost related to driven-pile design has several components: piles, pile caps and mats, and construction-control methods, the sum of which is total support cost. Pile support cost has two bases: available support, and utilized support. Pile caps and mats and CCM support cost is based on utilized support.

Pile support cost based on available support is a measure of the cost to install allowable resistance to load. That is, how much it costs to install allowable pile load, and is defined as the pile installation cost divided by the allowable pile load. It has units of dollars per available kip (or available kN), and indicates how much the owner pays to install each kip (or kN) of allowable support available to resist load. Pile support cost based on available support can provide insights into the cost of installing allowable resistance to load (i.e., into the cost of supplying available support). However, once available support is installed, how efficiently it is utilized also contributes to overall cost-effectiveness (i.e., what the demand is for the installed available support).

Table 4. Savings Attributable to Set-Up Summary

Construction-Control Method ("CCM")	Safety Factor	Allowable Load With Set-Up/Without Set-Up, kips	Piles			Pile Caps and Core Mat Concrete		CCM Savings, dollars	Total Foundation Cost Savings, Dollars	Driving Duration Saved, calendar days
			No. Saved	Length Saved, feet	Pile Savings, dollars	Volume Saved, yd^3	Concrete Savings, dollars			
WE, DLT, & SLT	2.0	600/400	228	15,157	774,351	543	253,435	-63,620	964,166	42
WE & DLT	2.5	480/320	313	20,807	1,063,034	821	372,785	-57,620	1,378,199	58
WE	3.0	400/267	366	24,330	1,243,037	974	442,440	0	1,685,477	69
DF	3.5	343/229	416	27,654	1,412,851	1,188	566,800	0	1,979,651	78

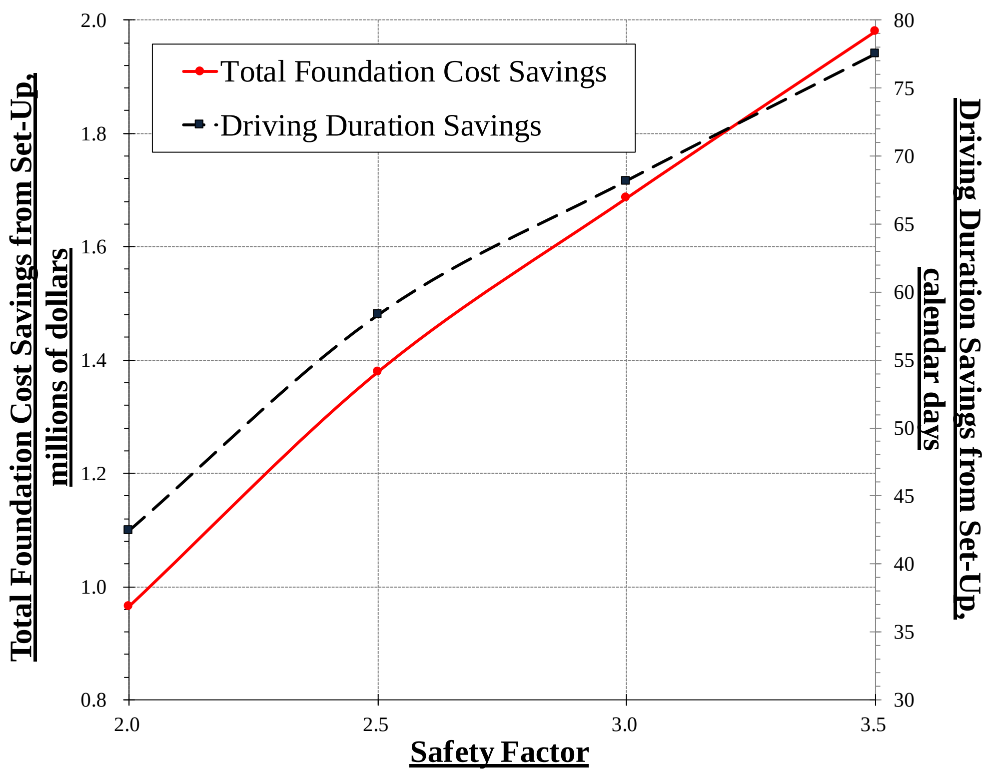

Figure 4. Savings from Set-Up.

Pile support cost based on utilized support is a measure of the cost to use installed allowable support to resist load, and is defined as a pile's installation cost divided by the structure design load assigned to that pile. It has units of dollars per structure design kip (or design kN), and indicates how much the owner pays to use each ton (or kN) of allowable support to resist load. When compared to pile support cost based on available support, it is an indication of how well allowable pile loads match actual assigned pile design loads (i.e., design efficiency).

Support costs determined from this study can aid application of results to other projects. To determine pile support costs based on available support for each design scenario, the total pile cost was divided by the number of piles required times their allowable load. To determine pile, concrete, and construction-control method support costs based on utilized support for each design scenario, each of these foundation components' total cost was divided by the total building load to be resisted by the piles (210,000 kips (934,000 kN)); these results are presented in Table 5, and in Figure 2.

A review of Table 5 indicates that the difference between the design scenarios using the highest allowable load with set-up compared to the lowest allowable load without set-up results in a total foundation support cost savings of $15.72 per design kip (per 4.45 design kN). The support costs based on utilized support presented in Figure 2 are simply the foundation costs presented in Figure 2 divided by the total building load to be resisted by the piles.

ADDITIONAL SAVINGS FROM TESTING

The number of production piles damaged during driving was approximately three percent. Test program results were used to assist both in assigning reduced capacities to the damaged piles, and in assigning individual capacities to the undamaged piles in the group. This was done in close coordination with the structural engineer who evaluated the actual load required to be resisted for each group, and for each pile within the group, where damaged piles occurred.

These combined efforts reduced the number of replacement piles which would have otherwise been required by 50 percent. Using contract prices and average driving productivity rates, the resulting savings were $70,000 in pile costs alone (not accounting for increased re-designed pile-cap costs), and three calendar days of driving.

CONCLUSIONS

The cost-effectiveness of a design-phase driven-pile test program was evaluated by comparing the project's as-built foundation cost to the estimated costs of six alternative complete foundation design scenarios. As-built unit prices for the piles, the concrete in pile caps and a core mat, and various construction-control methods ("CCMs") were applied to the alternative design scenarios. The alternative designs were based on various allowable pile loads (lower than were actually used on the project) that resulted from a range of safety factors associated with the different CCMs. Foundation costs were determined for piles designed both with and without set-up. Both costs and schedule impacts were evaluated. It was demonstrated that designing with the highest allowable pile load, which included contribution from set-up, resulted in the lowest total foundation cost, and also required the least amount of construction time. Integral to the success of the constructed

Table 5. Support Costs Summary

Construction-Control Method ("CCM")	S.F.	Allowable Load, kips	Pile Support Cost			Concrete Support Cost		CCM Support Cost		Total Foundation Support Cost, Utilized: dollars per design kip	
			Total Pile Cost, dollars	Installed: dollars per available kip	Utilized: dollars per design kip	Total Concrete Cost, dollars	Utilized: dollars per design kip	Total CCM Cost, dollars	Utilized: dollars per design kip	Cost	Differ-ence
With Set-Up											
WE, DLT, & SLT	2.0	600	1,548,702	5.66	7.37	728,800	3.47	236,260	1.13	11.97	---
WE & DLT	2.5	480	1,942,669	7.08	9.25	852,680	4.06	187,959	0.90	14.21	2.24
WE	3.0	400	2,323,052	8.49	11.06	982,235	4.68	2,000	0.01	15.75	3.78
DF	3.5	343	2,737,398	9.91	13.04	1,097,125	5.22	500	0.00	18.26	6.29
Without Set-Up											
WE, DLT, & SLT	2.0	400	2,323,052	8.49	11.06	982,235	4.68	172,640	0.82	16.56	4.59
WE & DLT	2.5	320	3,005,704	10.61	14.31	1,225,465	5.84	130,339	0.62	20.77	8.8
WE	3.0	267	3,566,089	12.74	16.98	1,424,675	6.78	2,000	0.01	23.78	11.8
DF	3.5	229	4,150,248	14.86	19.76	1,663,925	7.92	500	0.00	27.69	15.72

foundation was the design, performance, analysis, interpretation, and application to production driving of a quality design-phase test program.

It was demonstrated that for a given pile section installed to a given EOID capacity, designs using lower allowable pile loads resulted in increased pile costs, increased concrete costs for the pile caps and core mat, and therefore increased total foundation cost. This relationship remained valid when the increased testing costs associated with higher allowable loads were taken into account, and for designs both with and without the benefit of set-up. The savings resulting from increased testing were significant, exceeding $1.3

million for designs with the benefit of set-up, and exceeding $3.3 million for designs without the benefit of set-up. Accordingly, testing for and incorporating set-up into design and installation resulted in savings on the order of $2 million. It was concluded that the savings resulting from increased testing far exceeded the cost of testing with benefit/cost ratios ranging from 4.54 to 13.57. To aid application of results to other projects, costs and savings were also determined in terms of foundation support cost.

It was also demonstrated that designs using lower allowable pile loads increased pile-driving duration. The reduction in construction time resulting from increased testing were significant, equaling up to 65 calendar days for designs with the benefit of set-up, and up to 143 days for designs without the benefit of set-up. Accordingly, testing for and incorporating set-up into design and installation resulted in construction schedule savings of up to 78 calendar days. The lowest number of days of production-pile driving (i.e., the fasted construction time) was associated with performing the most testing and incorporating set-up. It was concluded that depending on the construction-control method, testing can easily save more time than it takes to perform the testing. Additional production-pile cost and time savings derived from test-program results by assigning reduced capacities to short or damaged piles was also quantified.

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