Foundation Support Cost – Applications to Driven-Pile Design

Van E. Komurka[1], P.E., D.GE, F.ASCE

[1]President, Wagner Komurka Geotechnical Group, Inc., W67 N222 Evergreen Boulevard, Suite 100, Cedarburg, WI 53012; komurka@wkg2.com

ABSTRACT: 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. Support costs related to driven-pile design have several components: piles, caps, and construction-control methods, the sum of which is total support cost. Two bases for pile support cost are presented and defined: available support, and utilized support. Data indicates that higher-allowable-load piles tend to have lower pile support costs based on available support; two explanations for this relationship are offered. Design efficiency and cost effectiveness should be evaluated using support cost based on utilized support, which provides an indication of how well allowable pile loads match structure design loads.

It is demonstrated that higher-allowable-load piles also result in lower pile cap support costs. The effect of allowable pile loads on pile-supported mats and foundation walls is discussed.

Construction-control methods affect design and construction in a number of ways, and their support costs alone may not indicate the most-cost-effective construction-control method. Construction-control methods' effects on other costs, such as piles and caps, should be evaluated using total foundation support cost. An example total foundation support cost determination for a number of pile design options illustrates the approach.

INTRODUCTION

There are many foundation options from which to choose for structure support. To be viable, a foundation option must (a) support required loads without overstressing the foundation itself or the geomaterial on which it bears, (b) perform within service limits, and (c) have an adequate safety factor[1]. Other factors can also contribute to a foundation's viability: construction schedule, site constraints, material availability, local contractor expertise, environmental impacts, etc. A common decision

[1] For simplicity of presentation, Allowable Stress Design ("ASD") nomenclature will be used. The principles and concepts are also applicable to Load and Resistance Factor Design ("LRFD"). However, unlike LRFD, ASD does not provide a measure of reliability (risk in terms of failure probability), so ASD cannot relate cost to reliability.

progression is to consider shallow, spread-footing or mat foundations first, and if these are found to be unsatisfactory, then intermediate-depth or deep foundations are considered.

Particularly in the case of deep foundations, there may be several viable options. When multiple foundation options are being considered, cost can become a decision parameter, and is often the deciding factor. The selection process benefits from a straight-forward evaluation by which a direct, "apples-to-apples" cost comparison among feasible options can be made without requiring multiple complete designs. Although this paper focuses on applications to driven-pile design, in doing so it also illustrates how the concept of support cost can be applied to design decisions concerning other intermediate-depth or deep foundations. In the case of driven piles, support cost can aid selection of pile type, pile section, allowable pile load, pile spacing (e.g., beneath a mat or load-bearing wall), and construction-control method.

PILE SUPPORT COST

Pile support cost is a measure of the cost-effectiveness of pile installations, and can be determined based either on available support, or on utilized support. The former relates to the cost to install support, the latter relates to the cost to use installed support. Support cost determined using either basis is a normalized parameter.

Based on Available Support

Pile support cost based on available support is a measure of the cost to install allowable resistance to load, and is defined as:

$$\textit{Pile Support Cost based on Available Support} = \frac{\textit{Pile Installation Cost}}{\textit{Allowable Pile Load}} \tag{1}$$

Pile support cost based on available support has units of dollars per available kN (ton), and indicates how much the owner pays to install each kN (ton) of allowable support available to resist load. Allowable pile load is used in the denominator (as opposed to ultimate capacity[2]) because, after all, it is allowable load for which the owner is paying. Using allowable load also permits support cost analysis to aid in making decisions about construction-control methods on which safety factors are based. The concept of pile support cost based on available support is illustrated in Fig. 1.

Fig. 1 presents two potential designs: (a) a traditional design, and (b) an alternate design capable of carrying a higher load by perhaps having a larger section and/or being driven deeper. A review of Fig. 1 indicates that the pile in Fig. 1b has the lower pile support cost. However, this conclusion may be counter-intuitive to some industry practitioners. It is often erroneously assumed that a pile which costs less per

[2] "Ultimate capacity" is a misnomer and redundant, 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 herein.

foot, and is installed shallower, is more-cost-effective than a pile which costs more per foot, and is installed deeper.

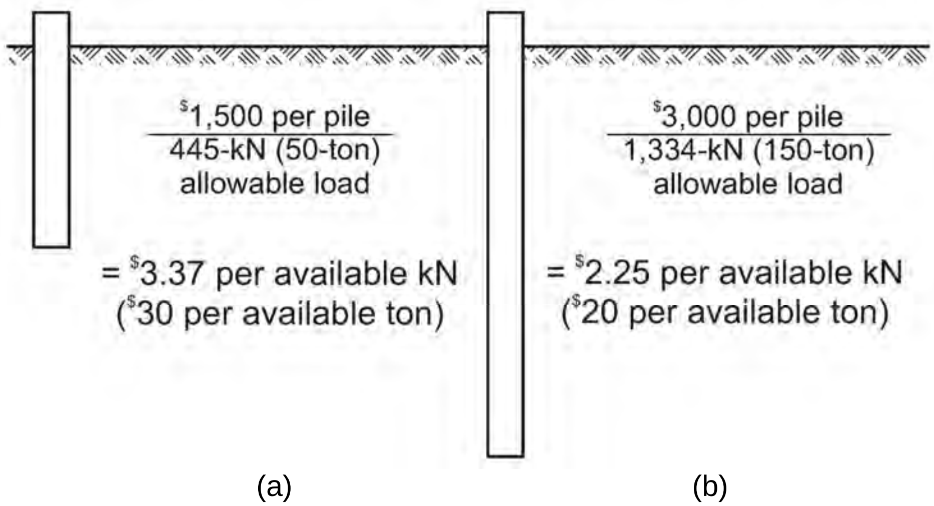


FIG. 1. Examples of Pile Support Cost Based on Available Support

Another way in which the conclusion that the pile in Fig. 1b is more-cost-effective than the pile in Fig. 1a may be counter-intuitive to some industry practitioners is related to the perceived relative productivity between the two installations. A pile-driving crew may be able to install more lower-allowable-load piles per shift than they can higher-allowable-load piles, leading to the perception that higher-allowable-load piles result in decreased productivity and therefore increased cost. Productivity based only on the number of piles installed is inappropriate; productivity is better-assessed based on the amount of allowable load installed.

Compared to Allowable Pile Loads

Pile support costs for a number of projects are presented in Table 1. The pile support costs in Table 1 are actual (not estimated), determined post-construction. All the pipe piles were driven closed-ended, and all the projects applied a safety factor of 2.0 to ultimate capacity to determine allowable load. A review of Table 1 indicates that for Project E, one pile section was used for five different allowable pile loads, and that for that project, higher-allowable-load piles tended to have lower pile support costs. Data from all the projects listed in Table 1 are presented as a plot of pile support cost based on available support vs. allowable load in Fig. 2.

A review of Fig. 2 indicates that although the data exhibit scatter resulting from a number of factors which varied among the projects, including (a) using different pile types, sizes, and sections, (b) diverse subsurface profiles, (c) fluctuating material prices, (d) varying contractor pricing strategies, (e) inflation, etc., the trend is for higher-allowable-load piles to have lower pile support costs.

This trend was also evidenced on a project for which the author was part of a design-build team for a viaduct alignment which included bascule bridges, pylon towers, a number of other substructures, as well as footings for temporary support

Table 1. Pile Support Costs Based on Available Support (courtesy Wagner Komurka Geotechnical Group, Inc.)

Project	Pile Type, mm (inches)	Allowable Pile Load, kN (tons)	Pile Support Cost, dollars per available kN (dollars per available ton)
A	273.0 x 9.27 (10.75 x 0.365)	890 (100)	1.36 (12.12)
	323.8 x 9.27 (12.75 x 0.365)	1,334 (150)	1.52 (11.52)
B	406-mm (16-inch) Monotube	1,779 (200)	1.37 (12.20)
C	323.8 x 7.92 (12.75 x 0.312)	1,317 (148)	1.51 (13.48)
D	273.0 x 6.35 (10.75 x 0.250)	712 (80)	---
	273.0 x 6.35 (10.75 x 0.250)	738 (83)	---
	Overall Project Average		*1.75 (15.55)*
E	273.0 x 7.80 (10.75 x 0.307)	356 (40)	2.31 (20.59)
		578 (65)	1.91 (16.97)
		667 (75)	1.70 (15.12)
		712 (80)	1.72 (15.34)
		756 (85)	1.66 (14.81)
	Overall Project Average		*1.76 (15.64)*
F	273.0 x 6.35 (10.75 x 0.250)	578 (65)	2.30 (20.47)
	323.8 x 9.52 (12.75 x 0.375)	1,370 (154)	1.18 (10.50)
	323.8 x 9.52 (12.75 x 0.375)	1,619 (182)	0.97 (8.62)
	323.8 x 9.52 (12.75 x 0.375)	1,690 (190)	1.56 (13.92)
	Overall Project Average		*1.72 (15.28)*
G	244.5 x 13.8 (9.625 x 0.545)	1,779 (200)	1.06 (9.40)
H	273.0 x 9.27 (10.75 x 0.365)	810 (91)	1.86 (16.57)
	339.72 x 12.2 (13.375 x 0.480)	1,601 (180)	1.35 (12.30)
	339.72 x 12.2 (13.375 x 0.480)	2,233 (251)	1.11 (9.92)
I	273.0 x 6.35 (10.75 x 0.250)	356 (40)	4.74 (42.19)
		534 (60)	3.13 (27.82)
		712 (80)	2.72 (24.21)
		890 (100)	2.36 (21.02)
	Overall Project Average		2.89 (25.68)

structures. To optimize the foundation design, a significant number of different allowable loads were used throughout the alignment. Even with the use of (a) different pile sections (273.0- and 323.8-mm-diameter (10.75- and 12.75-inch-diameter) pipe piles), (b) different safety factors (ranging from 2.0 to 2.5), (c) different construction-control methods (modified *Engineering News* dynamic formula, and wave-equation analyses refined with dynamic load testing measurements), and (d) across widely varying subsurface profiles, higher-allowable-load piles tended to have lower pile support costs. These data are presented in Fig. 3.

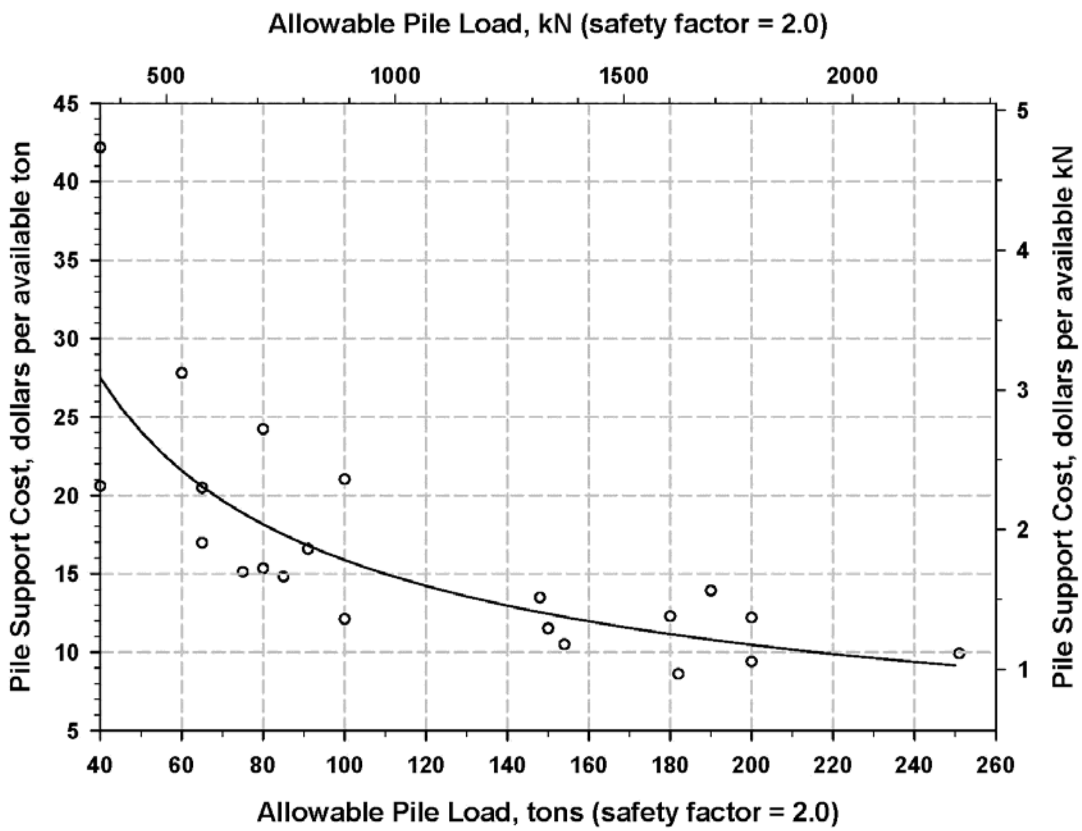


FIG. 2. Pile Support Cost Based on Available Support vs. Allowable Pile Load (courtesy Wagner Komurka Geotechnical Group, Inc.)

The following explains why higher-allowable-load piles tend to have lower pile support costs.

"Invested" Pile Length

Often when piles are used, it is to transfer loads through loose or soft ("weak") soils to deeper, more-competent soils below (this was the case for all the piles in Figs. 2 and 3). For these installations, the pile length which penetrates the weak soils provides little or no allowable pile load in return (in fact may develop negative shaft resistance), and so has to be "invested" to reach more-competent soils below. This concept is illustrated in Fig. 4. The more allowable load developed for a given invested length (and cost) per pile, the more-cost-effective the installation (Fig. 4b).

Installed Pile Cost and Allowable Pile Load vs. Embedded Length

The second potential explanation relates to the different ways in which installed pile cost and allowable pile load increase with embedded length, as illustrated in Fig. 5.

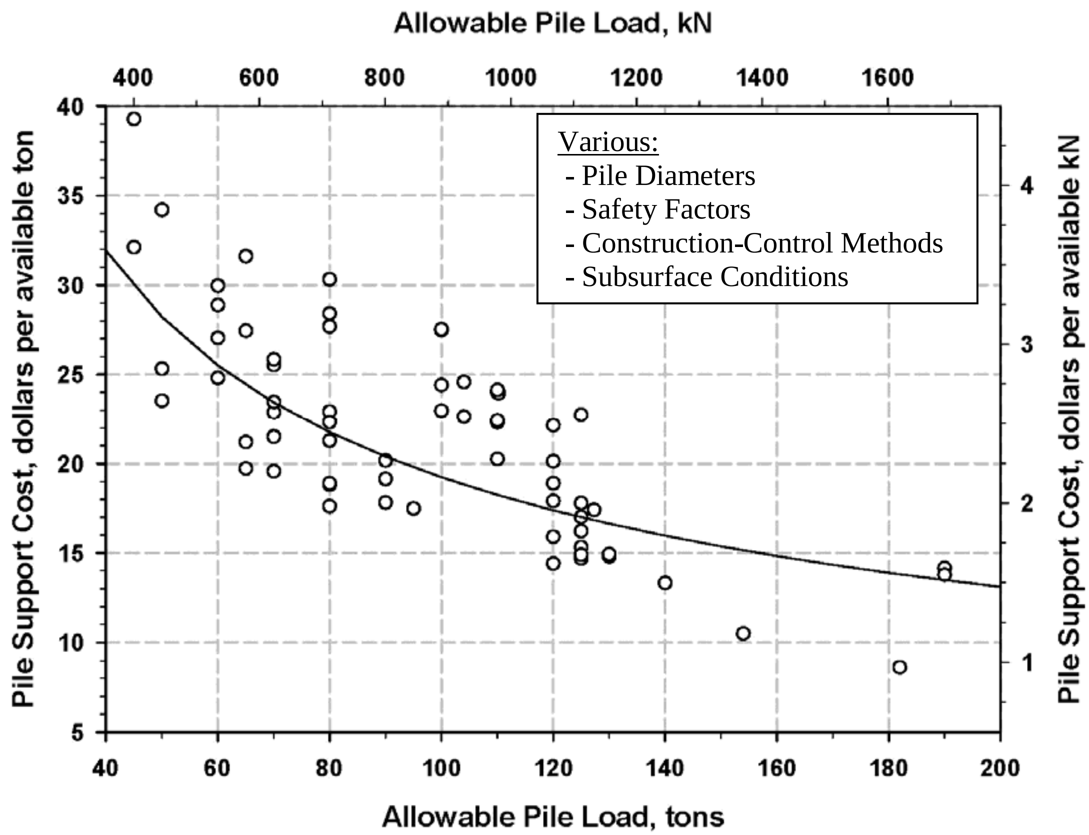


FIG. 3. Pile Support Cost Based on Available Support vs. Allowable Pile Load – Design-Build Project (courtesy Wagner Komurka Geotechnical Group, Inc.)

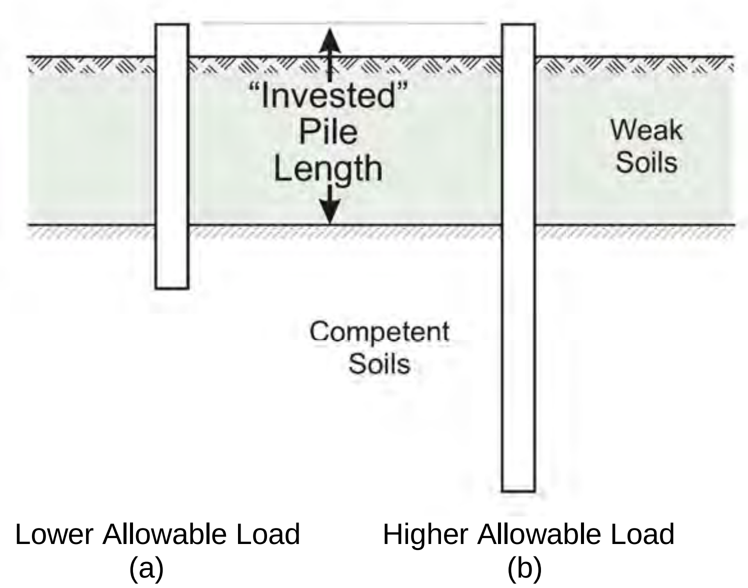


FIG. 4. Return on "Invested" Pile Length

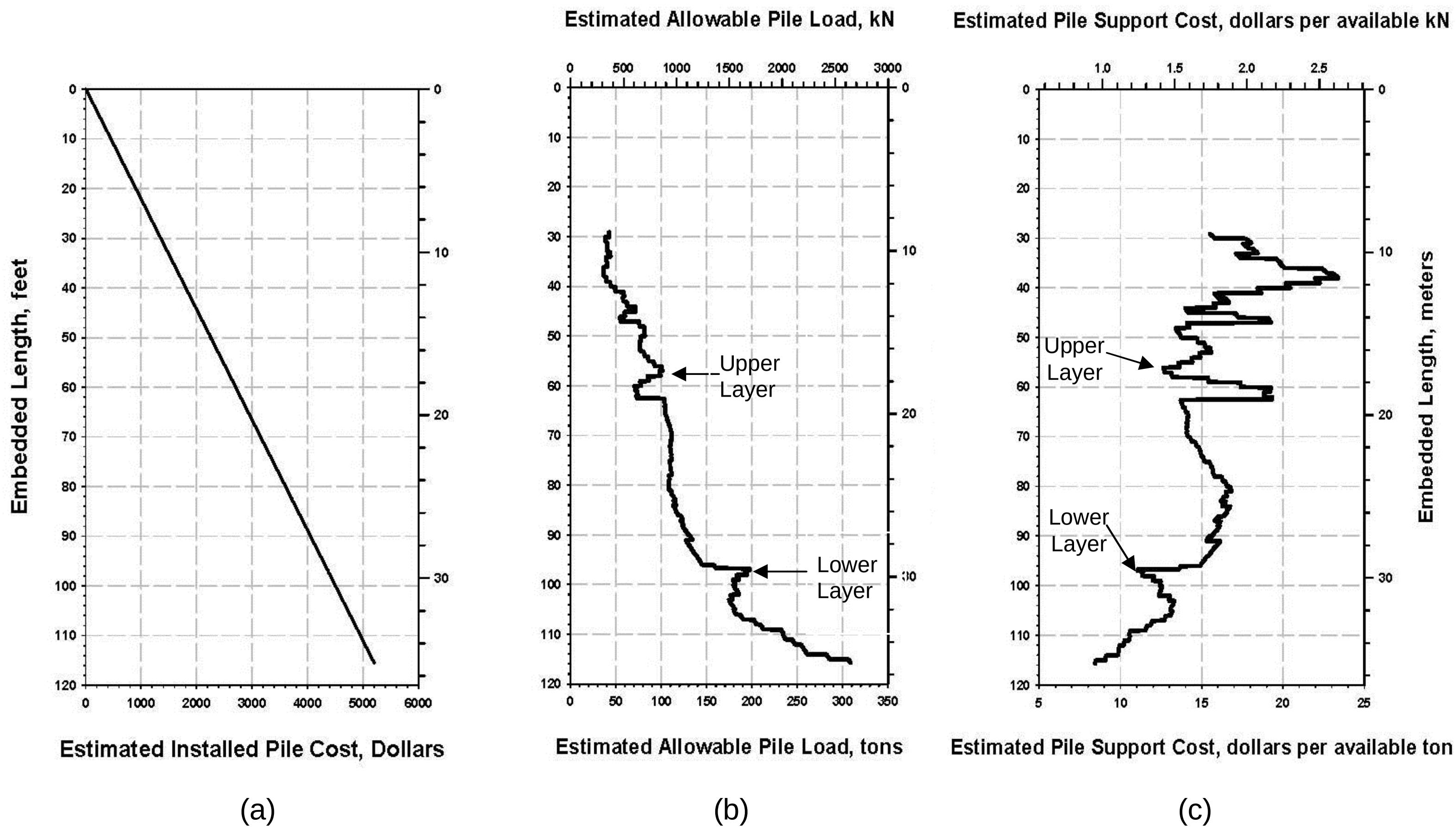


FIG. 5. Installed Pile Cost, Allowable Pile Load, and Pile Support Cost vs. Embedded Length

Pile cost can be approximated, and is in fact often bid and paid for, as a unit cost per installed foot, resulting in an installed pile cost profile[3] which is linear with respect to embedded length (Fig. 5a). As opposed to installed cost, allowable load often increases at a faster-than-linear rate with respect to embedded length. For example, a given percent increase in embedded length may result in a greater percentage increase in allowable load, resulting in a more-cost-effective installation.

Fig. 5b presents a long-term allowable load profile used for design determined from dynamic load testing and signal-matching analyses performed during installation and restrike testing [Komurka, 2004]. A review of Fig. 5b indicates that the allowable load profile exhibits (a) an upper and a lower relatively competent layer, (b) decreased allowable loads immediately below each competent layer, (c) little allowable load increase between the layers, and (d) relatively rapid allowable load increase below the lower layer.

In allowable load profiles which exhibit layering, and/or various rates of allowable load increase with increasing embedded length, it may be desirable to evaluate several options regarding cost-effective design. For example, in the allowable load profile presented in Fig. 5b, the following design/installation options might be considered (coinciding with the allowable load profile features listed previously):

1. Terminate driving at the upper layer.
2. Terminate driving somewhere between the upper and lower layers.
3. Terminate driving at the lower layer.
4. Punch through the lower layer to attain higher allowable loads deeper.

The relative cost-effectiveness of such options can be evaluated using a pile support cost profile.

Pile Support Cost Profile

Since pile support cost based on available support is installed cost divided by allowable load, the installed pile cost profile in Fig. 5a can be divided by the allowable load profile in Fig. 5b to yield the pile support cost profile presented in Fig. 5c.

Pile support cost profiles provide insight into cost-effectiveness as a function of embedded length. A review of Fig. 5c provides the following cost-effectiveness comparison of the design/installation options listed previously:

1. Terminating driving at the upper layer provides a lower pile support cost than terminating above the upper layer. Punching through into less-competent soils below results in a sharp increase in pile support cost.
2. Between the upper and lower layers, pile support costs remain higher than at the upper layer. This is indicative of a more-rapid increase in installation cost than in allowable load between the upper and lower layers. Accordingly, terminating a pile between the upper and lower layers is less-cost-effective than terminating at the upper layer.
3. Terminating driving at the lower layer, with its associated abrupt increase in allowable load, results in a lower pile support cost than at the upper layer.

[3] The term "profile" refers to the plot of a parameter vs. embedded length (or toe depth, toe elevation, etc.).

4. Punching through the lower layer into less-competent soils below results in higher pile support costs for some distance below the lower layer. However, below an embedded length of approximately 32 meters (105 feet), allowable load increases more-rapidly than installation cost, resulting in the lowest pile support costs being realized in the lowest portion of the profile.

Pile Support Cost vs. Allowable Pile Load

After pile support cost profile determination, the allowable pile loads corresponding to low pile support costs is of interest. One way to obtain this correlation is to select an embedded length with a low pile support cost from the pile support cost profile (Fig. 5c) and obtain the allowable load at that embedded length from the allowable load profile (Fig. 5b). For example, the spike to a relatively low pile support cost at an embedded length of approximately 30 meters (97 feet) in Fig. 5c corresponds to an allowable load of approximately 1,779 kN (200 tons) in Fig. 5b at the same embedded length.

Recognizing that both the allowable load profile in Fig. 5b and the pile support cost profile in Fig 5c have a mutual vertical axis of embedded length, a more-direct way of relating the two is to obtain both values over the range of their corresponding embedded lengths and plot pile support cost vs. allowable load as presented in Fig. 6.

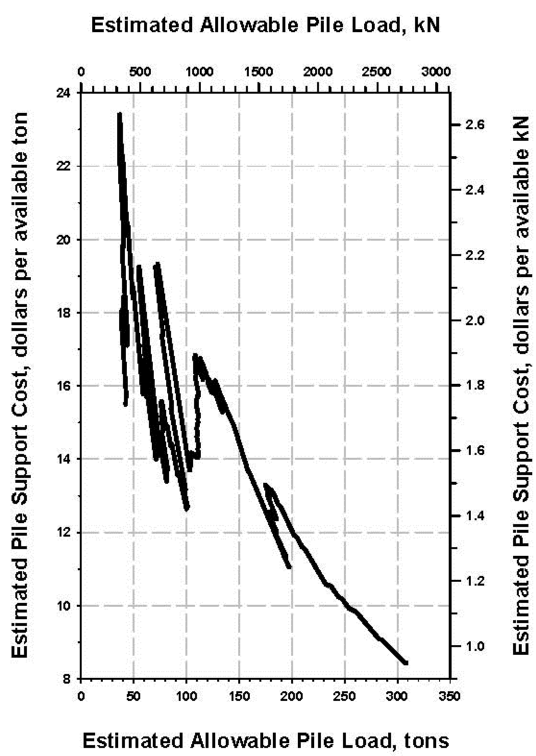


FIG. 6. Pile Support Cost vs. Allowable Pile Load

In contrast to pile support cost profiles which provide insight into cost-effectiveness as a function of embedded length, a plot of pile support cost vs. allowable load provides insight into cost-effectiveness as a function of allowable load. Fig. 6 provides correlation between the allowable pile load, and pile support cost, profiles presented in Figs. 5b and 5c, offering more-direct determination and comparison of pile support costs for different allowable pile loads (or ranges of allowable pile loads).

Based on Utilized Support

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). 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:

$$\textit{Pile Support Cost based on Utilized Support} = \frac{\textit{Pile Installation Cost}}{\textit{Structure Design Load Assigned to Pile}} \qquad (2)$$

Pile support cost based on utilized support has units of dollars per structure design kN (ton), and indicates how much the owner pays to use each kN (ton) 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). Pile support cost based on utilized support can be determined for individual piles, or for piles in groups; this concept is illustrated in Fig. 7.

Fig. 7a illustrates a pile which has an installed cost of \$5,000, an allowable load of 2,224 kN (250 tons), and a pile support cost of \$2.25 per kN (\$20.00 per ton) of available support. Figs. 7b and 7c illustrate two potential design scenarios, each of which requires a minimum of three piles to satisfy structural stability. In Fig. 7b, three of the 2,224 kN (250-ton) piles are installed to support a column with a design load of 6,228 kN (700 tons), resulting in a pile support cost of \$2.41 per structure design kN (\$21.43 per structure design ton). This illustrates a relatively cost-efficient design where the piles' utilized resistance to load closely matches their allowable load (2,073 vs. 2,224 kN (233 vs. 250 tons)), resulting in a cost efficiency of 93 percent from utilizing only a portion of their available support. In Fig. 7c, the same three piles are installed to support a column with a design load of only 2,669 kN (300 tons), resulting in a pile support cost of \$5.62 per structure design kN (\$50.00 per structure design ton) of utilized support. This illustrates a relatively inefficient design where the piles' utilized resistance to load is mismatched with their allowable load (890 vs. 2,224 kN (100 vs. 250 tons)), resulting in a cost efficiency of just 40 percent from utilizing only a portion of their available support.

This example demonstrates that installing high-allowable-load piles because they have low pile support costs based on available support, and then inefficiently loading them, is false economy; support cost based on utilized support provides a better assessment of design efficiency and cost-effectiveness. The large disparity between the pile support costs based on utilized support presented in Figs. 7b and 7c highlights

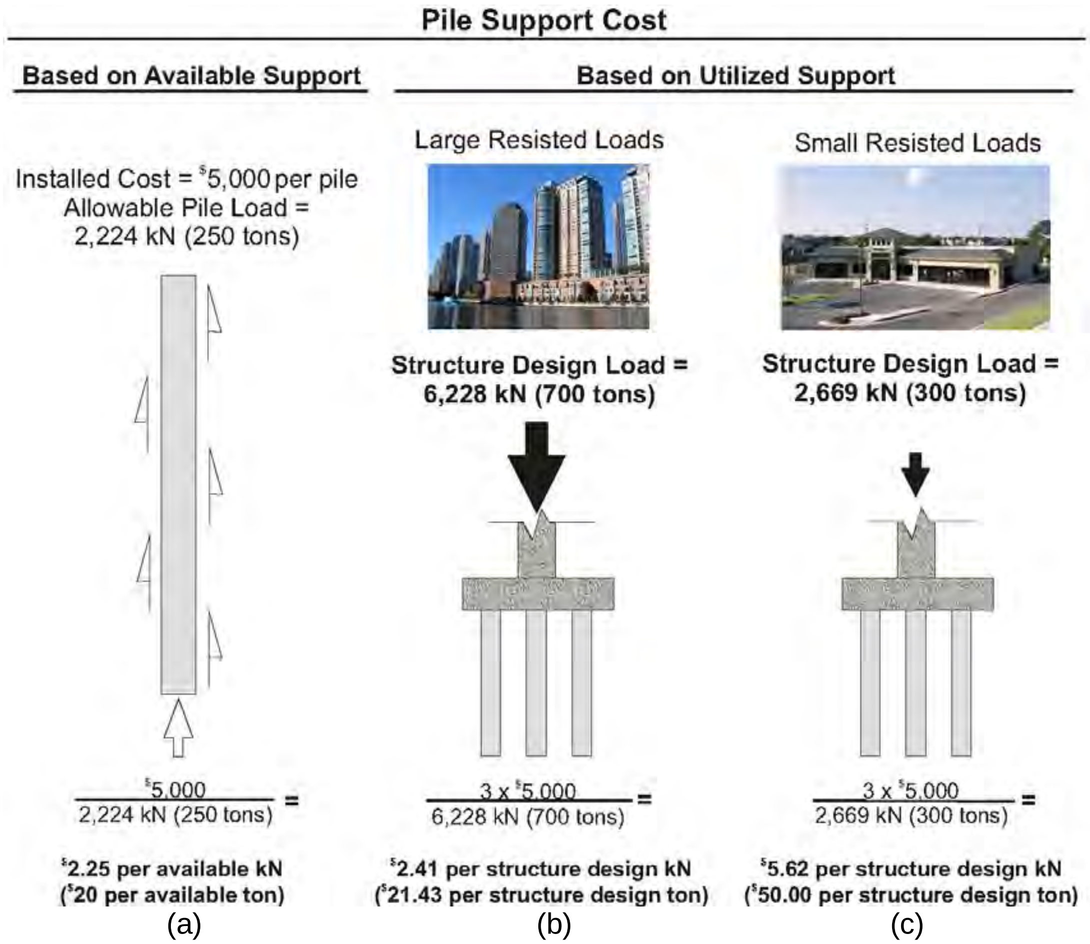


FIG. 7. Comparison between Pile Support Cost Based on Available, and Utilized, Support

the potentially significant effect design optimization decisions (e.g., judiciously matching allowable pile loads to loads to be resisted, potentially using multiple allowable pile loads on a project) can have on costs.

CAP SUPPORT COST

Pile-design decisions such as pile type, section, and allowable load affect pile-cap design, and therefore cap cost. Pile-design decisions' effects on cap costs can be evaluated using cap support cost, which is defined as:

$$Cap\ Support\ Cost = \frac{Cap\ Construction\ Cost}{Structure\ Design\ Load\ Assigned\ to\ Cap} \tag{3}$$

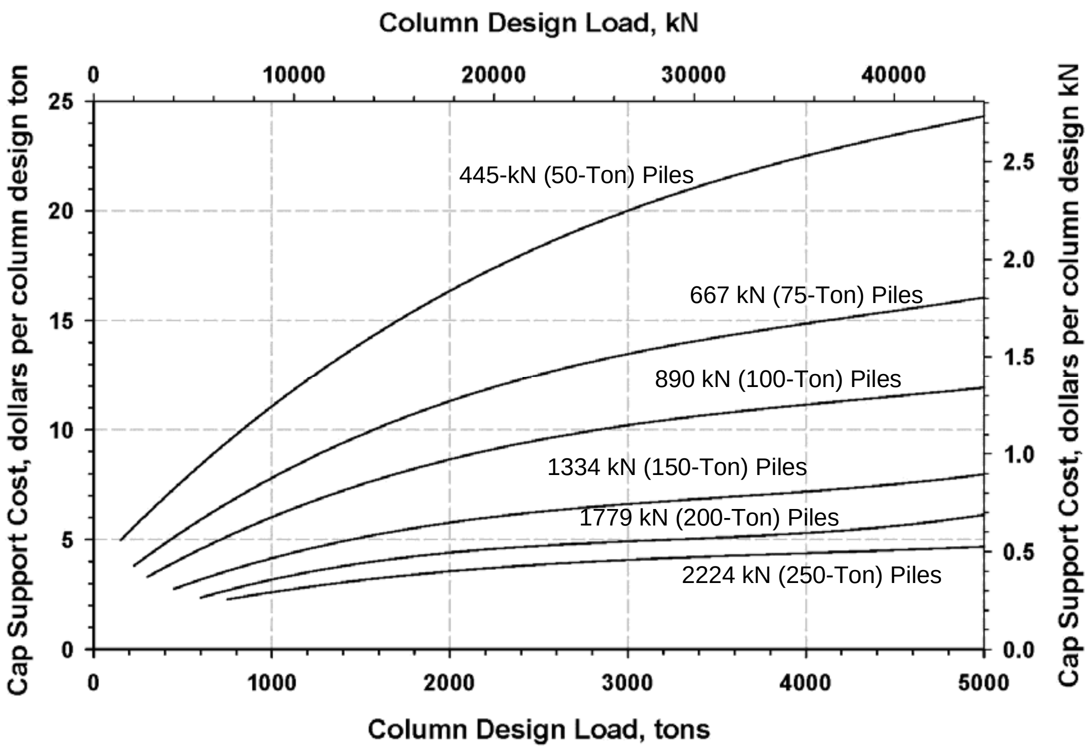
and has units of dollars per structure design kN (ton).

The number of piles in a cap and their spacing affects cap plan area, the piles' allowable load affects cap thickness, and both affect cap volume. Cap cost can be approximated, and in fact is often bid and paid for, on a unit cost per unit volumebasis. In addition to the material costs (e.g., concrete and reinforcing steel), all costs associated with cap construction such as the cost of (a) excavation, (b) excavation support, (c) permitting, (d) dewatering, (e) utility relocation, (f) spoil disposal, etc. should be included in a cap support cost determination.

Effect of Higher-Allowable-Load Piles

For a given structure design load at a cap location, use of higher-allowable-load piles will likely result in reduced cap plan area, but will require increased cap thickness (to resist greater punching shear). Of interest is whether or not cost savings associated with reduced cap plan area more than offset higher costs associated with increased cap thickness.

To evaluate this, cap support costs were determined for range of column design loads using a number of different allowable pile loads. The results are presented in Fig. 8, a review of which indicates that for any given column design load, cap support costs decrease with increasing allowable pile load.



Notes: A. *For pipe piles with center-to-center spacing of three pile diameters.*
B. *Various pile diameters were used for various allowable loads.*

27.30 cm (10.75")	*≤ 890 kN (100 tons) allowable load*
32.38 cm (12.75")	*898 to 1334 kN (101 to 150 tons) allowable load*
35.56 cm (14")	*1343 to 1779 kN (151 to 200 tons) allowable load*
40.64 cm (16")	*1788 to 2224 kN (201 to 250 tons) allowable load*

C. *Cap cost based on*
$458/m^3 ($350/yd^3) if cap thickness ≤ 0.3m (4')
$588/m^3 ($450/yd^3) if cap thickness > 0.3m (4')

FIG. 8. Pile Cap Support Cost vs. Column Design Load for a Number of Allowable Pile Loads

Pile-Supported Mats and Foundation Walls

Similar to pile caps, pile-design decisions such as pile type, section, and allowable load affect the design of pile-supported mats and foundation walls, and therefore their cost. For a given structure design load, use of higher-allowable-load piles will likely require increased foundation thickness (to resist greater punching shear). However, unlike pile caps, higher-allowable-load piles will likely have no effect on these foundation types' plan area. In addition, if use of higher-allowable-piles is associated with greater pile spacings, these foundation types will likely have to provide increased ability to structurally span between the piles, resulting in thicker foundations, more reinforcing, or both, which will increase costs. In such cases, the reduced pile costs realized with higher-allowable-load piles should be weighed against the associated increased foundation costs.

CONSTRUCTION-CONTROL METHOD SUPPORT COST

The method used to control driven-pile installations (i.e., to develop driving criteria, using dynamic formula, wave-equation analysis, dynamic load testing, or static load testing) affects pile design, and therefore cost. Generally, different safety factors are associated with the various construction-control methods. Accordingly, for a given ultimate capacity profile, the construction-control method determines the allowable load profile (e.g., Fig. 5b), and therefore the pile support cost based on available support profile.

Construction-control methods have costs associated with them. Their effects on foundation cost can be partially evaluated using construction-control method support cost, which is defined as:

$$\textit{Construction-Control Method Support Cost} = \frac{\textit{Construction-Control Method Cost}}{\begin{array}{c}\textit{Sum of Design Loads to Which}\\ \textit{Construction-Control Method Applies}\end{array}} \quad (4)$$

and has units of dollars per structure design kN (ton).

Since generally only one construction method is used on a project and applies to all the pile installations and structure loads they support, it is easy by direct comparison to determine that the least-expensive construction-control method has the lowest construction-control-method support cost. This is what leads some industry practitioners to potentially erroneously conclude that certain construction-control methods are too expensive to add value, or that they can't afford them, which is usually false economy.

Construction-control method affects safety factor, which in turn affects allowable pile load, which in turn affects pile and cap support costs. Accordingly, it is inappropriate to evaluate the cost-effectiveness of various construction-control methods using their support costs alone, without evaluating their effect on other costs, such as piles and caps. This can be accomplished using total foundation support cost [Komurka and Arndorfer, 2009].

TOTAL FOUNDATION SUPPORT COST

Total foundation support cost is a measure of how foundation design decisions interrelate and affect various cost components, and can be defined comprehensively as:

$$\textit{Total Foundation Support Cost} = \frac{\textit{Total Foundation Cost}}{\textit{Sum of Structure Design Loads}} \quad (5)$$

and has units of dollars per structure design kN (ton).

Determination, or even estimation, of total foundation cost and the sum of structure design loads can be onerous, and the required information may be unavailable when foundation design decisions are made. Alternatively, and potentially more-timely and -manageable, the sum of various support-cost components (which may be more-easily determined) can be used:

$$\textit{Total Foundation Support Cost} = \Sigma \textit{ (Pile, Cap, \& Construction-Control Support Costs)} \quad (6)$$

Pile support cost based on utilized support should be used in Eq. 6.

An example total foundation support cost determination by both approaches is presented in Table 2. A review of Table 2 indicates how, for a given pile depth and ultimate capacity, the choice of construction-control method can affect multiple design aspects and their associated costs. A comparison of construction-control method cost (Col. 11) and total foundation cost (Cols. 14 and 15) illustrates how more-expensive construction-control methods (e.g., dynamic, or static, load testing) can result in significantly lower total foundation costs, which may be counter-intuitive to some industry practitioners.

OTHER FACTORS

Obviously, other project components besides the piles, caps, and construction-control method can affect foundation cost. Some components and their associated costs may be fixed, independent of foundation design and construction decisions. The costs of other project components which are affected by foundation design and construction decisions should be appropriately included when comparing total foundation costs among viable design options.

In addition, it is recognized that other factors related to cost only indirectly, or not at all, contribute to foundation design and construction decisions.

CONCLUSIONS

When there are multiple viable deep-foundation options for structure support, cost is often the primary decision parameter. The concept of support cost provides a normalized parameter by which cost comparisons among design and construction options can be made.

Table 2. Total Foundation Support Cost Determination (adapted from Hannigan et al., 2006)

Pile Depth, feet (1)	Ultimate Pile Capacity, tons (2)	Construction-Control Method ("CCM")[1] (3)	Allowable Pile Load, tons (4)	Design Column Load, tons (5)	Approx. Pile Count per Cap (6)	Pile Cost per Cap[2] (7)	Pile Support Cost, \$/structure design ton (8)	Approx. Cost per Cap (9)	Approx. Cap Support Cost, \$/structure design ton (10)	CCM Cost (11)	No. of Caps to Which CCM Applies (12)	CCM Support Cost, \$/structure design ton (13)	Total Foundations' Cost (14)	Total Foundation Support Cost, \$/structure support ton (15)
69	124	DF	35	2,268	64	\$ 207,552	91.51	\$ 23,060	10.17	\$ 200	4	0.02	\$ 922,648	101.70
		WE	45		50	162,150	71.49	21,375	9.42	2,000		0.22	736,100	81.14
		DLT	55		41	132,963	58.63	19,125	8.43	15,000		1.65	623,352	68.71
		SLT	62		37	119,991	52.91	18,000	7.94	30,000		3.31	581,964	64.15
105	346	DF	99	2,268	23	\$ 113,505	50.05	\$ 10,460	4.61	\$ 200	4	0.02	\$ 496,060	54.68
		WE	126		18	88,830	39.17	9,900	4.37	2,000		0.22	396,920	43.75
		DLT	154		15	74,025	32.64	9,560	4.22	15,000		1.65	349,340	38.51
		SLT	173		13	64,155	28.29	9,340	4.12	35,000		3.86	328,980	36.26

Pile Depth, meters (1)	Ultimate Pile Capacity, kN (2)	Construction-Control Method ("CCM")[1] (3)	Allowable Pile Load, kN (4)	Design Column Load, kN (5)	Approx. Pile Count per Cap (6)	Pile Cost per Cap[2] (7)	Pile Support Cost, \$/structure design kN (8)	Approx. Cost per Cap (9)	Approx. Cap Support Cost, \$/structure design kN (10)	CCM Cost (11)	No. of Caps to Which CCM Applies (12)	CCM Support Cost, \$/structure design kN (13)	Total Foundations' Cost (14)	Total Foundation Support Cost, \$/structure support kN (15)
21	1,103	DF	311	20,177	64	\$ 207,552	10.29	\$ 23,060	1.14	\$ 200	4	0.00	\$ 922,648	11.43
		WE	400		50	162,150	8.04	21,375	1.06	2,000		0.02	736,100	9.12
		DLT	489		41	132,963	6.59	19,125	0.95	15,000		0.19	623,352	7.72
		SLT	552		37	119,991	5.95	18,000	0.89	30,000		0.37	581,964	7.21
32	3,078	DF	881	20,177	23	\$ 113,505	5.63	\$ 10,460	0.52	\$ 200	4	0.00	\$ 496,060	6.15
		WE	1,121		18	88,830	4.40	9,900	0.49	2,000		0.02	396,920	4.92
		DLT	1,370		15	74,025	3.67	9,560	0.47	15,000		0.19	349,340	4.33
		SLT	1,539		13	64,155	3.18	9,340	0.46	35,000		0.43	328,980	4.08

Notes: 1. *DF: Dynamic Formula, Safety Factor = 3.50*
WE: Wave Equation, Safety Factor = 2.75
DLT: Dynamic Load Testing, Safety Factor = 2.25
SLT: Static Load Testing, Saftey Factor = 2.00

2. *At \$47.00 per foot.*

Support costs related to driven-pile design have several components: pile, cap, construction-control method, and total. Pile support cost has two bases: available support, and utilized support. Piles with higher allowable pile loads tend to have lower pile support costs based on available support. This may be attributable to higher-allowable-load piles providing more available support for a given "invested" pile length, and allowable pile load increasing faster with depth than pile cost. Design efficiency and cost effectiveness should be evaluated using support cost based on utilized support, which provides an indication of how well allowable pile loads match structure design loads.

Pile cap support cost is related to allowable pile load; higher-allowable-load piles generally also result in lower cap support costs. For pile-supported mats and foundation walls, cost-effective design must consider the interrelationship between allowable pile loads, pile support cost, pile spacing, and foundation design required to span between piles, and foundation cost.

Construction-control methods affect design and construction in a number of ways, and their support costs alone may not indicate the most-cost-effective construction-control method. More-expensive construction-control methods can result in significantly lower total foundation costs, and their effects on other costs, such as piles and caps, should be evaluated using total foundation support cost. Total foundation support cost can be determined either from the total foundation cost, or from the sum of the component support costs.

REFERENCES

Hannigan, P.J., Goble, G.G., Likins, G.E., and Rausche, F. (2006). *Design and Construction of Driven Pile Foundations – Volume I*, Federal Highway Administration Report No. FHWA-NHI-05-042.

Komurka, Van E. (2004). "Incorporating Set-Up and Support Cost Distributions into Driven Pile Design," *Current Practices and Future Trends in Deep Foundations*, ASCE/Geo-Institute, Geotechnical Special Publication No. 125, 0-7844-0743-6, pp. 16-49.

Komurka, Van E. and Arndorfer, Robert P. (2009). "Driven Pile Cost Comparison for Two Large Wisconsin DOT Bridge Projects," *Proceedings of the Deep Foundations Institute 34th Annual Conference on Deep Foundations*, October 21-23 (CD Rom).