Selecting Cost-Effective Systems for Deep Foundations

Atlas Tube

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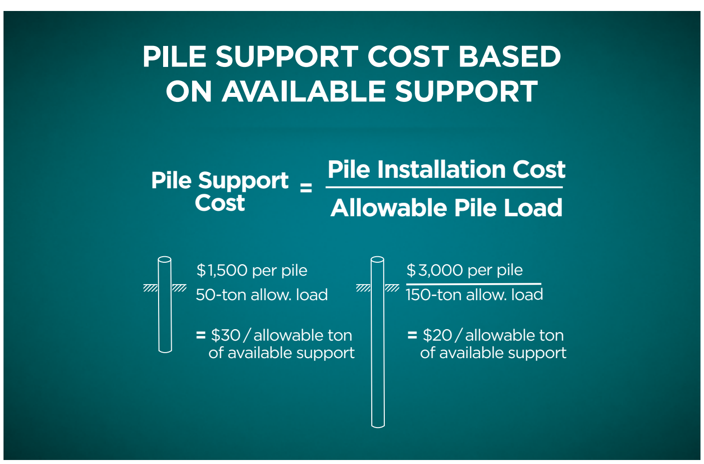
Deep-foundation systems are expensive. Among multiple other design and decision parameters, cost-effectiveness should be considered when selecting among multiple viable foundation options. Wagner Komurka Geotechnical Group Inc. (WKG) pioneered the concept of, and coined the term, "support cost," which is an integral component of a rigorous, quantitative approach to selecting the most cost-effective foundation system for a project. In this article, and in the article "Support Cost Based on Available Support," we will explore this valuable decision-making tool.

Sup•port' Cost (sŭ•pōrt' kŏst), n. The cost of an installed or constructed foundation element, component or system, divided either by its available, or its utilized, allowable load / factored resistance.[1] Units are dollars per allowable ton, or dollars per structure design ton.

As a normalized parameter, support cost can be easily used to compare the relative cost-effectiveness of different foundation types (e.g., shallow vs. deep), different deep foundation types (e.g., drilled piers vs. driven piles), different driven pile types (e.g., H-piles vs. pipe piles), different pile sections (e.g., 10.75-inch vs. 12.75-inch diameter pipe piles), different construction-control methods (e.g., wave equation analysis vs. load testing), different allowable pile loads and their associated depths (e.g., 75-ton piles vs. 150-ton piles), etc. The concept of support cost based on available allowable load is illustrated in the following figure:



A review of the figure indicates that the pile on the right has the lower pile support cost. This conclusion may be counterintuitive to some industry practitioners. It is often erroneously assumed that a pile that costs less per foot and is installed shallower, is more cost-effective than a pile that costs more per foot and is installed deeper. It is often also erroneously concluded that installing piles of the type on the right adversely affects productivity because fewer deeper, higher-capacity piles get installed in a day. However, productivity is properly determined based not on the number or piles installed, but instead on the number of tons of support installed.

WKG's cost studies have shown that piles with higher allowable loads tend to have lower pile support costs based on available support. Potential reasons for this include:

Since piles are generally installed to transfer load through weak surficial soils to the more competent material below, a certain pile length is "invested" to penetrate the weak soils. The more available support that is provided relative to this invested pile length (and cost), the more cost-effective the design becomes.

Installed pile cost can be generalized as increasing linearly with depth; allowable load often increases at a faster-than-linear rate with respect to embedded length. So a given percent increase in embedded length may result in a greater percentage increase in allowable load, resulting in a more cost-effective installation.

However, the concept of support cost based on available support is only half the story. Without an understanding of how support cost based on utilized support differs, the concepts presented above can be misapplied and lead to overly conservative and unnecessarily costly designs.

[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).

Support Cost Based on Utilized Support

As discussed in the first article of our Support Cost series, support cost can be based on available allowable load, which can provide insights into the cost of installing allowable resistance to load (i.e., into the cost of supplying available support). However, the concept of support cost based on available support is only half the story. Without an understanding of how support cost based on utilized support differs, the concept can be misapplied and lead to overly conservative, and unnecessarily costly, designs. This article will discuss support cost based on utilized allowable load, which can provide insights into how efficiently installed resistance is utilized (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:

PILE SUPPORT COST BASED ON UTILIZED SUPPORT =

$$\frac{\text{Pile Installation Cost}}{\text{Structure Design Load Assigned to Pile}}$$

Pile support cost based on utilized support has units of dollars per structure design ton, and indicates how much the owner pays to use each ton of allowable support to resist load. When compared to pile support cost based on available support (how much the owner pays to install each ton of allowable support), it is an indication of how well allowable pile loads match actual assigned pile design loads (i.e., design efficiency). This concept is illustrated in Figure 1:

Pile Support Cost: Design Efficiency

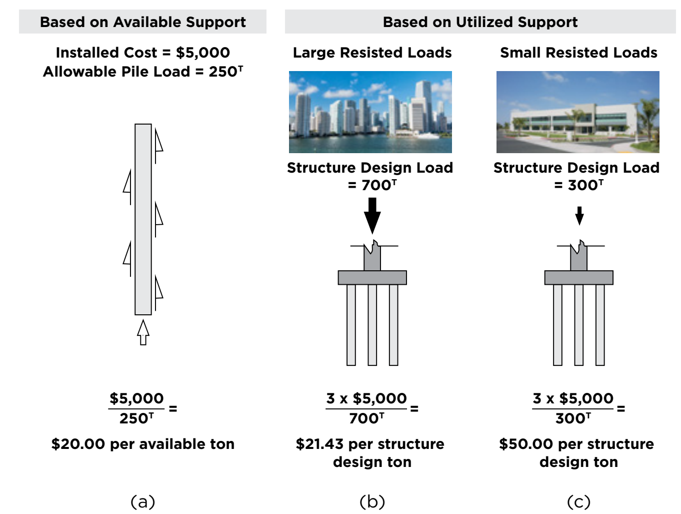


Figure 1. Illustration of Design Efficiency Using Support Cost

Figure 1a illustrates a pile with a relatively high allowable load, and an installed support cost of $20.00 per available ton; the available resistance to support structure loads was installed, was put "in the bank," so to speak, and is ready and waiting to be loaded, at a cost of $20.00 per ton.

Figures 1b and 1c illustrate two potential design scenarios (each of which requires a minimum of three piles to satisfy structural stability). In Figure 1b, three of the 250-ton piles are installed to support a column with a design load of 700 tons, resulting in a utilized pile support cost of $21.43 per structure design ton (a relatively cost-efficient design). In Figure 1c, the same three piles are installed to support a column with a design load of only 300 tons, resulting in a utilized pile support cost of $50.00 per structure design ton (a relatively cost-inefficient design).

This example demonstrates that installing high-allowable-load piles, and then inefficiently loading them, is false economy. This conclusion may be counterintuitive to some industry practitioners, who subscribe to a "more allowable load is better" philosophy without appropriate economic assessment. The large disparity between the pile support costs based on utilized support presented in Figures 1b and 1c highlights the potentially significant effect on costs.

Improved Pile Design: Load-Matching Evaluation (Part 1)

The other articles in this brochure presented the concept of foundation support cost as it applies to driven piles. One of the concepts stressed was that, in general, piles with higher allowable loads are likely to be more cost-effective than piles with lower allowable loads. An important caveat to using higher-allowable-load piles on a project is that structure loads warrant their use (i.e., unutilized capacity is not installed).

The allowable pile load(s) used on a project can have a significant impact on foundation cost, schedule, and risk. Driven-pile design often involves a "one-size-fits-all" approach, using a favorite pile section and/or a common allowable pile load for every project, including projects with a wide range of structural loads. This approach routinely produces an inefficient design. A load-matching evaluation is the first step to improved pile design, providing a rigorous, quantitative approach to judicious allowable pile load selection, with cost considered.

Pile design should start with an understanding of the structure loads to be resisted, as resistance to structure loads is why piles are installed. Piles are below-grade extensions of the above-grade structure they support, and their design should be integrated with the above-grade structure. Too often, pile design recommendations (pile type, section, and capacity and/or allowable load) are provided without detailed knowledge of structure-support requirements. Pile design will benefit from better communication between geotechnical and structural engineers, with each gaining a better understanding of how one's design requirements and recommendations affects the other.

For example: On a driven-pile project, the geotechnical engineer requested structure load information from the structural engineer. The structural engineer was reluctant to provide loading information, replying that to design the piles, the geotechnical engineer only needed to determine how much load the soil could support. The geotechnical engineer replied that recommendations could be provided for piles having allowable loads ranging from 30 to 300 tons, and that a load-matching evaluation would determine the most-appropriate allowable pile load(s) for the project.

Beneath columns, structure support requirements consist of two basic components: the design load to be resisted, and the minimum number of piles required to satisfy structural stability (Figure 1). At each column location, the column design load is divided by the minimum required number of piles, which determines the optimum allowable pile load for that column (Figure 2). For a given column, use of the optimum allowable pile load results in no additional piles installed, and no wasted pile capacity, saving cost.

Design Load to be Resisted and Minimum Required Number of Piles

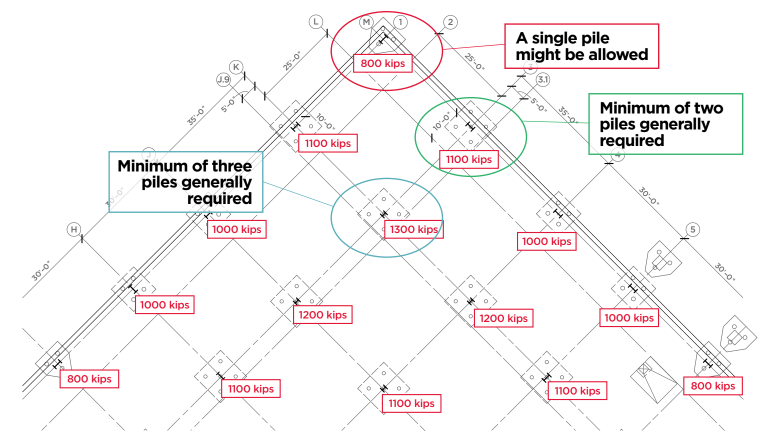
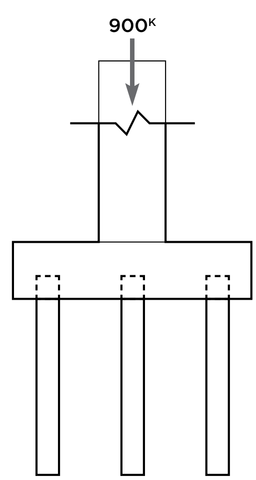


Figure 1

Optimum Allowable Pile Load



Optimum Allowable Pile Load =

$$\frac{\textbf{Column Design Load}}{\textbf{Minimum Req'd No. of Piles}}$$

- Column Design Load = 900 kips
- Minimum Req'd No. of Piles = 3
- Optimum Allowable Pile Load =

$$\frac{900 \text{ kips}}{3 \text{ piles}}$$

= 300 kips/pile = 150 tons/pile

Figure 2

Obviously, it is impractical to install optimum allowable load piles beneath each column; such design would result in an inordinate number of different allowable pile loads on a project. The determination of which allowable load(s) is/are best-suited for a project will be illustrated in Part Two of the Load-Matching Evaluation series.

Improved Pile Design: Load-Matching Evaluation (Part 2)

In Part One of the Load-Matching Evaluation series, we introduced the concept of load-matching evaluation, and defined optimum allowable pile load—the column design load divided by the minimum required number of piles at each column location.

However, it is impractical to install optimum allowable load piles beneath each column. Such a design would result in an excessive number of different allowable pile loads on a given project. In this article, we will illustrate the quantitative determination of which allowable load(s) is/are best-suited for a project, including an economic evaluation.

The information required for a load-matching evaluation includes the design compression load at each column location, and the minimum number of piles required to satisfy structural stability. For load-bearing walls and grade beams, or pile-supported floors, loading and minimum pile spacing information is required. From this information, a histogram is produced, indicating the frequencies of occurrence of specific optimum allowable pile loads, from which the number and magnitudes of potential allowable pile loads for the project are selected (see Figure 1). Structural engineers can perform this evaluation without geotechnical input.

Once the potential number and magnitudes of allowable pile loads are selected, a geotechnical engineer will determine the most-appropriate pile type(s) and section(s) based on the target allowable loads and subsurface profile, in addition to estimating depth vs. ultimate capacity profiles. For the potential allowable loads, requisite ultimate capacities must be established. These capacities are a function of the safety factor for design, usually associated with the construction-control method used to develop the driving criteria. Lastly, installed pile costs per foot must be estimated for each candidate pile section.

This information can be assembled and evaluated as presented in Figure 2. Note that such a load-matching evaluation can be used to quantitatively assess the design and economic effects (i.e., the pile count and installed footage) of using various pile sections installed to various allowable loads. The process can be iterated by modeling different combinations of allowable loads and/or pile sections to optimize design and minimize cost.

Available Pile Load Histogram

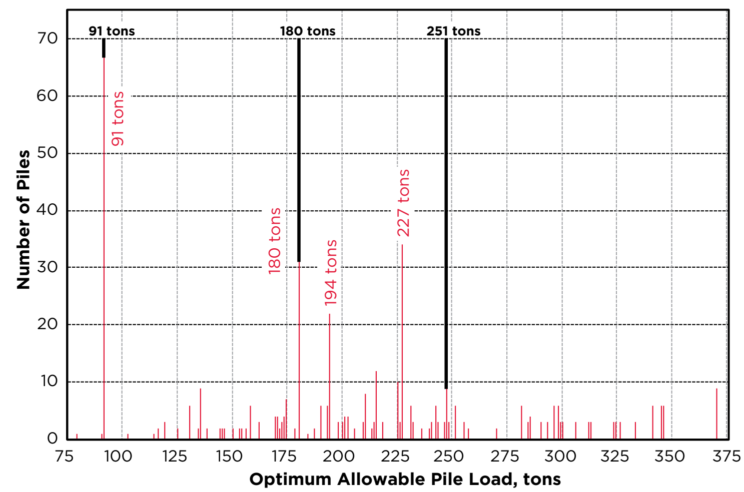


Figure 1

Column Line Designation	Min. No. of Piles	Column Load, kips	Optimum Allowable Pile Load, tons	Maximum Required "Ultimate" Pile Capacity, tons	3 Capacities (91, 180, and 251 tons): No. of Piles	Est. Pile Length, feet	Est. Pile(s) Footage, feet	Est. Pile(s) Cost, dollars	
0.A-8.5	1	158	79	158	1	62	62	1,340	
0.A-0.5	1	180	90	180	1	62	62	1,340	**$21.61 / ft**
P-3.3	1	181	91	181	1	62	62	1,340	91-ton max.
P-3.7	1	181	91	181	1	62	62	1,340	allow. load:
P-4.5	1	181	91	181	1	62	62	1,340	71
P-5	1	181	91	181	1	62	62	1,340	10.75x0.365
P-5.5	1	181	91	181	1	62	62	1,340	feet:
P-6	1	181	91	181	1	62	62	1,340	4,402
0.A-8	1	203	102	203	1	86	86	2,405	
M.5-8	1	228	114	228	1	86	86	2,405	**$27.97 / ft**
N-8.5	1	360	180	360	1	86	86	2,405	180-ton max.
P.7-8.5	1	360	180	360	1	86	86	2,405	allow. load:
P-0.5	1	360	180	360	1	86	86	2,405	108
P-8.5	1	360	180	360	1	86	86	2,405	13-3/8" 0.480
Q.8-3	1	360	180	360	1	86	86	2,405	feet:
Q-0.5	1	360	180	360	1	86	86	2,405	9,288
M.5-4	1	368	184	368	1	95	95	2,657	
J-5	2	748	187	374	2	95	190	5,314	
G-7	3	1479	247	493	3	95	285	7,971	251-ton max.
H-7	3	1479	247	493	3	95	285	7,971	allow. load:
K-6	3	1484	247	495	3	95	285	7,971	177
B-7	3	1487	248	496	3	95	285	7,971	13-3/8" 0.480
B-6	3	1507	251	502	3	95	285	7,971	feet:
C-8	3	1508	251	503	3	95	285	7,971	16,815
R1-5.9	3	1510	252	503	4	95	380	10,629	
K-7	3	1529	255	510	4	95	380	10,629	
C-4	3	1874	312	625	4	95	380	10,629	251-ton max.
F-6	3	1879	313	626	4	95	380	10,629	allow. load:
J-6	3	1942	324	647	4	95	380	10,629	125
J-4	3	1995	333	665	4	95	380	10,629	13-3/8" 0.480
Q-9	3	2003	334	668	4	95	380	10,629	feet:
R-9	3	2003	334	668	4	95	380	10,629	11,875
	448				481		42,380	$1,157,416	

Figure 2

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Atlas Tube, a division of Zekelman Industries, produces a wide range of steel tubular products and is the leading provider of hollow structural sections (HSS) in North America. Other offerings include HSS Design Tools and straight-seam electric resistance weld (ERW) pipe piling.

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