DRIVEN PILE COST COMPARISON FOR TWO LARGE WISCONSIN DOT BRIDGE PROJECTS

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This paper presents a cost comparison of the driven pile foundations for two large Wisconsin Department of Transportation ("WisDOT") projects in Milwaukee, Wisconsin: the Marquette Interchange South Leg, and the Canal Street Viaduct. The projects' geology is fairly similar, but their methods/approaches to pile foundation design and installation differ. Although the Marquette Interchange South Leg had deeper poor soils, its pile design was more-cost-effective than the Canal Street Viaduct's. Potential reasons for cost differences between the projects are identified, and the effect of the different design and construction approaches on economics is discussed.

INTRODUCTION

The Marquette Interchange project is an $810-million interchange replacement. The South Leg portion of the project spans Milwaukee's Menomonee Valley area, and contains project-wide deep organic deposits underlain by a layered profile of granular and cohesive soils. Driven closed-end steel pipe piles, representing a number of design departures from WisDOT's traditional approach, were installed to support numerous high bridges. Outside pile diameters ranged from 13.375 to 16 inches, and allowable axial compression loads ranged from 200 to 250 tons.

Located nearby, and also in the Menomonee Valley area, is the $18.6-million Canal Street Viaduct project. At this site, subsurface conditions were similar to those at the South Leg project, but with a more-limited organic layer which was not present across the entire site. Using a more-traditional approach, WisDOT used driven steel HP14x73 H-piles, with an allowable load of 75 tons, to support two relatively low bridges.

Although there were some significant design/construction differences between the two projects, an economic comparison of the driven pile foundations was performed using the concept of support cost. Support cost is the cost of a deep foundation element or system divided by its allowable load, which is expressed in units of dollars per allowable ton (i.e., the cost to support 1 ton of allowable load). An all-inclusive support cost comparison accounts for all deep-foundation-related costs (e.g., pile caps, design-phase testing, pile installation, production control/testing, criteria development, etc.), and thus provides a comprehensive normalized cost determination.

PROJECT DESCRIPTIONS

Pertinent project details are presented in Table 1, and shown in Figure 1.

Marquette Interchange South Leg

General

Construction of the Marquette Interchange project was performed by a joint venture comprised of three contractors. The South Leg portion consisted of widening four existing multi-span, high-level, steel-girder bridge structures. The widening involved increasing deck widths, and constructing new hammerhead piers and foundations adjacent to existing substructure footings. Both the northbound and southbound sides were widened. Span lengths range from 153 to 256 feet, and the majority of piers are approximately 100 feet tall. The South Leg included a total of 29 new substructure footings.

TABLE 1

Project Details

Project	Project Construction Cost	Span Lengths, feet	Pier Type	Pile Driving Time Frame	Embedded Pile Lengths, feet
Marquette Interchange South Leg	$46 Million	153 to 256	Single-Shaft Hammer-Head	Apr. ’05 to Nov. ‘05	62 to 168, Avg. = 127
Canal Street Viaduct	$18.6 Million	80 to 153	Multi-Shaft Hammer-Head	Oct. ’05 to June ‘06	80 to 153, Avg. = 92

Project	Pile Testing		Set-Up Incorporated	Pile Material Stresses, ksi	
	Design Phase	During Construction		AASHTO Maximum Allowable, ksi	Used in Design, ksi
Marquette Interchange South Leg	Yes	Yes	Yes	0.25 f_y plus 0.40 f'_c	0.25 f_y plus 0.40 f'_c
Canal Street Viaduct	No	No	No	12.5	7

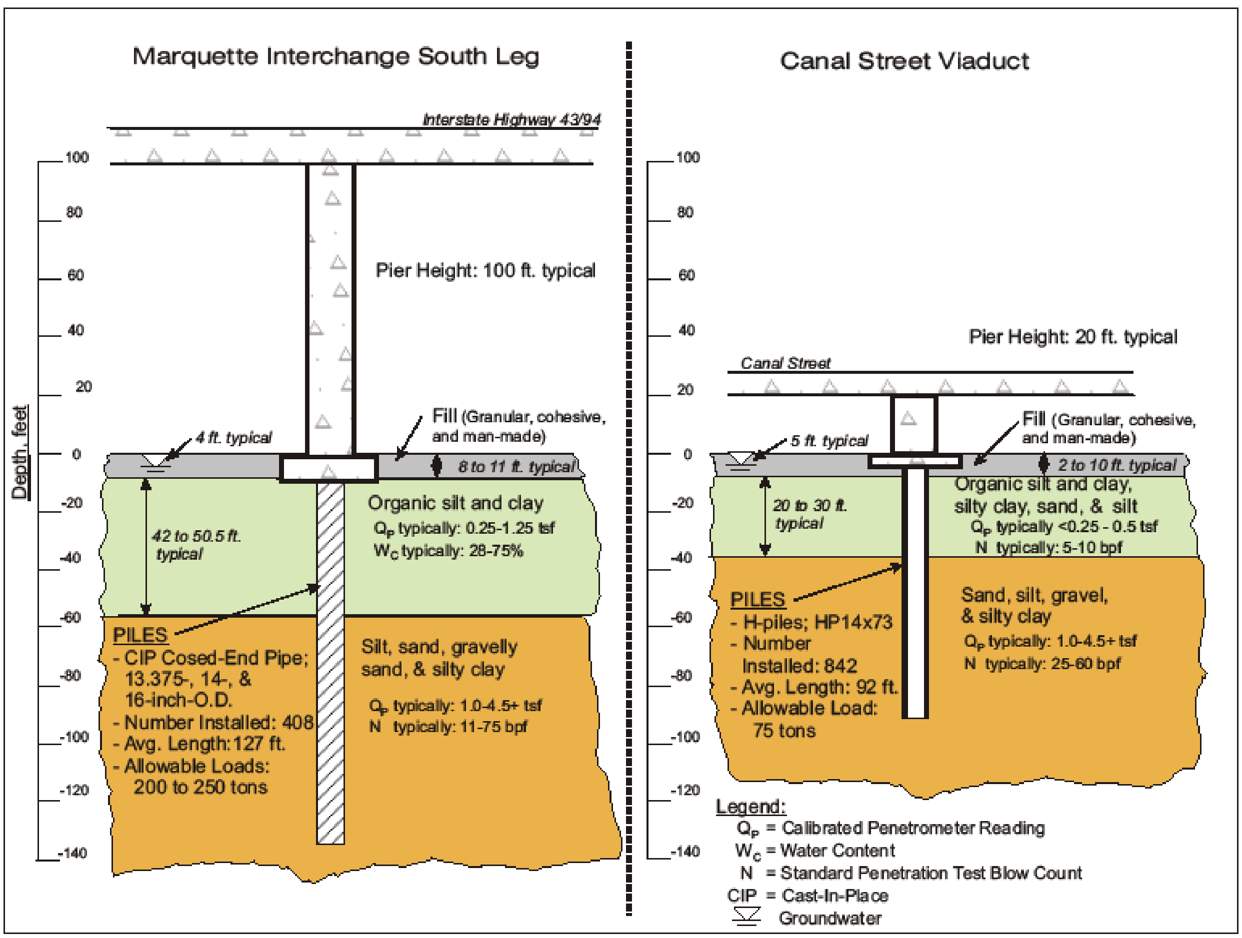

Figure 1. Projects’ Comparison

Subsurface Conditions

Generalized subsurface conditions for both projects are presented in Figure 1. For the South Leg, 8 to 11 feet of miscellaneous fill is underlain by soft to stiff organic deposits to 42 to 50 feet. Beneath the estuarine deposits is a varied and layered inorganic soil profile comprised of medium dense to very dense granular deposits, and stiff to hard silty clay. Relative densities and/or consistencies generally increase with depth. Bedrock is inconsistently encountered below 186 feet.

Driven Pile Foundations

Design-Phase Test Program – To benefit the entire Marquette Interchange project, a significant design-phase pile test program was performed in the summer of 2003. This program's main purpose was to characterize capacity (axial and lateral) and soil/pile set-up[1]. A total of 89 design-phase test piles of three different outside diameters ("O.D.s"), were installed at 43 indicator pile sites and six static load test sites. The lateral load test sites included both compression and lateral tests, which were both internally instrumented full depth. Five of the indicator pile sites, and two of the static load test sites, were germane to the South Leg project area. To determine both magnitude and rate of soil/pile set-up, the design-phase test piles received a minimum of three restrikes: at between 2.5 and 24 hours, at approximately 10 days, and at a minimum of 28 days after driving. Dynamic monitoring using a Pile Driving Analyzer® ("PDA") (Hussein and Likins, 1995; Likins et al., 2000; Rausche et al., 1985) was performed during all installations and restrikes. For all test piles, CAse Pile Wave Analysis Program ("CAPWAP®") analyses (Hussein et al., 2002; Likins et al., 1996; Rausche et al., 1972, 1994, 1996, 2000) were performed on representative end-of-initial-drive ("EOID") and beginning-of-restrike ("BOR") blows. The design-phase test piles were not incorporated into the finished structures. The estimated South Leg portion of the design-phase test program cost was $245,000.

Because of the design-phase test program's scope and the complexity associated with its intended purposes (characterization of set-up magnitude, rate, and distribution, full-depth instrumentation of axial compression and lateral load test piles, evaluation of multiple pile diameters, validation of high allowable loads, etc.), its cost should not be considered representative for more-conventional projects, which would typically require lesser test programs.

Production-Phase Dynamic Test Piles – At each South Leg substructure footing, one or two dynamic test piles were installed (and monitored with the PDA), and restruck between 42 and 96 hours after installation, after which driving criteria were developed for the remaining production piles in the substructure footing.

Driving Criteria Development – At each South Leg substructure footing, soil/pile set-up magnitude, rate, and shaft distribution of the production-phase dynamic test pile(s) were compared to proximate design-phase pile test program results. Based on this comparison, a design pile-shaft set-up profile (shaft set-up as a function of depth) was established for each footing (Komurka et al., 2004). Footing-specific design shaft set-up profiles were deemed necessary because of the variability in set-up evidenced during the design-phase test program. Based on this design pile-shaft set-up profile, depth-variable driving criteria were developed for each footing, which decreased the required penetration resistance with increasing embedment depth (i.e., increasing embedment depth results in more shaft set-up, requiring less initial capacity at the end of driving). The depth-variable ultimate capacity[2] criteria were developed using the GRLWEAP™ wave equation program (Hussein et al., 1988; Thendean, 1996), using input parameters refined by comparison with production-phase dynamic test piles' dynamic measurements (Hannigan et al., 2006). Allowable loads were determined using a safety factor of 2.25. The approximate cost of contractor, dynamic testing, and engineering services for the production-phase dynamic testing and driving criteria development for the South Leg was $192,000.

Installations – South Leg allowable pile loads were optimized to structural support and footing

[1] Set-up is time-dependant capacity increase.

[2] "Ultimate" pile capacity is a misnomer, as capacity is ultimate resistance. It is commonly used, however, and so is used herein. Allowable pile load is ultimate pile capacity divided by a safety factor. Design load is the calculated load which will be applied to the pile. Accordingly, a pile's allowable load must be equal to, or greater than, its design load.

geometry requirements, and selected on a footing-by-footing basis, after which the pile O.D. was selected which best-suited the allowable load. A total of 408 cast-in-place ("CIP") closed-end steel pipe piles were installed between October 2005 and June 2006. O.D.s ranged from 13.375 to 16 inches; wall thicknesses were most-commonly ½ inch; and allowable axial compression loads ranged from 200 to 250 tons. Embedded lengths ranged from 62 to 168 feet, averaging 127 feet. Contract pricing for the 13.375-, 14-, and 16-inch-O.D. piles was $38.45, $42, and $48 per linear foot installed (driven and concrete-filled), respectively. The total cost of the pile installations, including linear footage and splices, was $2,200,212.

Canal Street Viaduct

General

The Canal Street Viaduct project is located approximately 1.3 miles west of the South Leg project, and is composed of two new multi-span bridge structures carrying four lanes of traffic and a multi-use lane. One bridge is a prestressed concrete girder structure; the other bridge is a steel girder structure. Both bridges are founded on hammerhead piers, incorporating multi-shaft (2 to 4 shaft/hammerhead combinations per pier) supports. Span lengths range from 80 to 153 feet, and maximum pier heights are approximately 20 feet. The Canal Street Viaduct includes a total of 24 substructure footings, and was constructed by one of the three Marquette Interchange joint venture contractors.

Subsurface Conditions

For the Canal Street Viaduct, 2 to 10 feet of miscellaneous fill is generally underlain by loose to medium dense granular deposits to 20 to 30 feet. Over portions of the site, very soft to soft organic and inorganic silty clay is present to these depths. Underlying soils consist of stiff to hard silty clay, and medium dense to very dense granular soils. Relative densities and/or consistencies generally increase with depth. Bedrock was not encountered up to 120 feet.

Driven Pile Foundations

Driving Criteria – The Canal Street Viaduct piles were installed to their required allowable load according to the WisDOT-modified version of the Engineering News dynamic formula (Wisconsin Department of Transportation, 2003):

$$P = \frac{2E}{S + 0.5} \qquad \text{\{Eq. 1\}}$$

where: P = safe bearing value, pounds
E = energy per blow, foot-pounds
S = average penetration rate for the last 10 to 20 blows, inches per blow

For this dynamic formula, WisDOT generally assumes a safety factor between 3 and 5.

Installations – An allowable pile load of 75 tons was used for the entire Canal Street Viaduct project. A total of 842 HP14x73 steel H-piles were installed between April 2005 and November 2005. Embedded lengths ranged from 80 to 153 feet. Contract pricing for the HP14x73 pile was $32 per installed foot. The total cost of the pile installations, including linear footage and splices, was $2,675,000.

SUPPORT COSTS

Support cost is the cost of a deep foundation element or system divided by its allowable load, which is expressed in units of dollars per allowable ton (i.e., the cost to support 1 ton of allowable load) (Komurka, 2004). An all-inclusive support cost computation accounts for all deep-foundation-related costs (e.g., design-phase testing, criteria development, pile installation, construction control/testing, substructure footings, etc.), and thus provides a comprehensive normalized deep foundation system cost.

For these projects, substructure footing (i.e., pile cap) costs were evaluated, but comparison proved inappropriate. The two projects' differing pier heights and span lengths resulted in significantly different footing loads and moments. The South Leg footings support tall, single columns, and therefore are resisting large overturning moments, requiring large footings. The Canal Street Viaduct utilized low-level piers in a multi-column frame configuration, resulting in significantly reduced moments and associated footing size. Since these geometric and structural differences (which controlled footing size and cost) are unrelated to pile design, substructure footing support costs were excluded from this comparison. More appropriately, cost components of the two projects' deep foundation elements including piling, design pile testing, and construction control were compared.

Project costs are presented in Table 2. This table presents the total allowable tons of support installed, and the respective costs for the piles, and design testing/construction control components, as well as these components' sum. Accordingly, support costs for each component, and a total support cost, were determined for each project and compared (Hannigan, 2006). The support cost determinations summarized in Table 2 are presented in Figure 2, and are discussed below.

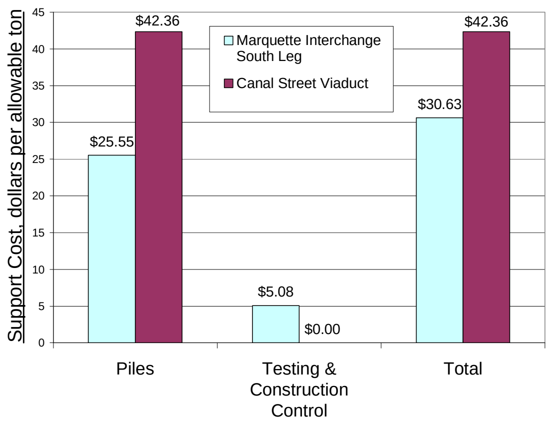

Figure 2. Support Cost Summary

Pile Support Cost

A review of Figure 2 indicates that the South Leg's pile support cost was $16.81 per allowable ton lower than for the Canal Street Viaduct. The South Leg achieved a much lower pile support cost, despite having the poorer soil conditions (in particular, much deeper project-wide organic deposits). There are a number of potential factors contributing to this difference. Although assigning relative contributions among the factors is difficult because they tend to work in conjunction with one another, the factors are presented below in a subjective order of decreasing impact on cost:

Soil/Pile Set-Up
Unlike the Canal Street Viaduct, the South Leg incorporated soil/pile set-up into design and installation. Accounting for set-up may reduce pile lengths, reduce pile sections (use smaller-diameter or thinner-walled pipe piles), or reduce the size of driving equipment (use smaller hammers and/or cranes). Any one, or a combination, of these reductions could result in cost savings (Komurka et al., 2003). For the South Leg pile test program, measured shaft set-up generally ranged from 200 to 500 percent (100 percent set-up indicates that the shaft resistance doubled; 200 percent indicates it tripled, etc.).

Allowable Pile Load – Magnitude
The South Leg used higher allowable pile loads than the Canal Street Viaduct. In general, higher allowable pile loads tend to result in lower pile support costs for several related reasons. First, if poor soils must be penetrated, a certain length of pile must be installed, or "invested," just to reach more-competent soils below. The higher the allowable load, the greater the return on each pile's "investment". Second, while installed pile cost increases linearly with depth, soil strength/pile resistance often increases at a greater rate (e.g., driving a pile 25 percent deeper often results in greater than a 25 percent capacity increase). Hence, pile support cost generally decreases with increasing depth and associated higher allowable load.

TABLE 2

Cost Summary

Project	Piles				Design Testing and Construction Control		Totals	
	Total Allowable Tons of Support Installed	Total Footage Installed, linear feet	Total Cost, dollars	Support Cost, dollars per allowable ton	Total Cost, dollars	Support Cost, dollars per allowable ton	Cost, dollars	Support Cost, dollars per allowable ton
Marquette Interchange South Leg	86,100	51,989	2,200,212	25.55	437,000	5.08	2,637,212	30.63
Canal Street Viaduct	63,150	77,108	2,675,000	42.36	0.00	0.00	2,675,000	42.36

Pile Type – Geotechnical Capacity

H-piles are well-suited as predominately end-bearing piles, driven to a bearing layer. Closed-end pipe piles are well-suited as predominately shaft-resistance piles. The project stratigraphies appear to favor closed-end, friction pipe piles (it should be noted that WisDOT does not typically use H-piles as predominately shaft-resistance piles).

Driving Criteria

The South Leg used wave equation analysis, while the Canal Street Viaduct used a dynamic formula, to develop driving criteria. The wave equation may have provided less-conservative driving criteria (i.e., resulted in a lower safety factor).

Pile Section – Design Stresses

Based on desired allowable load, the South Leg design selected from multiple candidate pile sections and concrete strengths, and used composite pile design, to maximize design stresses within code-permitted limits. The Canal Street Viaduct piles have a design stress of 7 kips per square inch ("ksi"), compared with a maximum of 12.5 ksi permitted by the AASHTO code (American Association of State Highway and Transportation Officials, 2002).

Pile Type – Structural Capacity

The South Leg concrete-filled pipe piles derive structural capacity from both the steel shell (expensive) and concrete fill (inexpensive). The Canal Street Viaduct H-piles piles derive structural capacity from only steel (expensive).

Allowable Pile Load – Selection

The South Leg used multiple allowable loads, with selection at each substructure footing based on matching allowable loads to structure support requirements. In this way, installing excess (wasted) capacity is minimized. The Canal Street Viaduct used one allowable load at all substructure footing locations.

Unit Prices

Since the two projects did not use the same pile type, direct unit price comparison is difficult. Differences in pile type, installed footage, construction dates, physical site constraints, contract documents, bidding strategies, etc., may account for indiscernible differences between the projects' unit prices.

Testing and Construction Control Support Cost

A review of Figure 2 indicates that the South Leg's testing and construction control support cost was $5.08 per allowable ton higher than for the Canal Street Viaduct. This is attributable to the South Leg performing a design-phase test program, and production-phase dynamic testing and engineering services to develop footing-specific driving criteria, while the Canal Street Viaduct performed no design- or production-phase testing.

Total Support Cost

A review of Table 2 indicates that the South Leg's total support cost was $11.73 per allowable ton lower than for the Canal Street Viaduct. Although the Canal Street Viaduct had lower testing and construction control support cost, the South Leg's much-lower pile support cost resulted in its lower total support cost. This total support cost difference, applied to the Canal Street Viaduct's total allowable tons supported, amounts to approximately $741,000.

CONCLUSIONS

There were some fundamental differences between these two projects. Some differences were related to pile design (design testing and construction control, set-up incorporation, allowable loads, pile type, design stresses, driving criteria, safety factor, etc.), others were not (subsurface conditions, applied loads, structure design, etc.). Although the South Leg project exhibited poorer soil conditions, and had a significant design testing and construction control program, its total support cost was slightly lower than for the Canal Street Viaduct. The reason for this is its much-lower pile support cost, to which a number of potential factors contributed.

A review of the factors potentially contributing to lower pile support cost (presented previously in the "Pile Support Cost" section) indicates that if design policies permit, the majority of factors can be incorporated in a relatively straightforward and inexpensive manner. If design policies require field testing to incorporate any of these factors, it may still be cost-effective to do so.

The least-straightforward and most-expensive factor is characterizing soil/pile set-up, determining how to apply it in design, and construction monitoring/confirmation during pile installation. Although assigning relative value to the contributing factors is difficult, and the factors tend to be interrelated, characterization and application of set-up appears to have had the greatest effect on reducing the South Leg pile support costs.

A major objective of the South Leg's design testing and construction control programs was to characterize set-up. However, if a project size warrants, such programs may yield other beneficial economic results. These benefits may include lower permissible safety factors, higher permissible resistance factors, higher allowable loads, improved driving criteria, higher allowable material stresses, more-economical selection among potential pile type/section candidates, reduced contingencies in bid prices, etc.

During a project's design phase, support-cost comparisons among viable pile foundation systems are affected only by differences in the pile designs under consideration. The designer can assume that all factors not related to pile design, but which may influence support costs (span length, pier height, footing size, etc.), remain constant among the various foundation system options. Since these and other influencing factors likely vary between projects, accurate post-construction economic comparisons between different projects require more-detailed investigations, and have inherent accuracy limitations. For this reason, the results of such comparisons must be used judiciously when drawing conclusions related to the relative cost-effectiveness of different projects' deep foundation systems.

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