Factors Affecting the Selection and Use of Drilled Shafts for Transportation Infrastructure Projects

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ABSTRACT

This paper summarizes some of the critical components of drilled shaft design and construction that influence the selection of this foundation type for transportation structures. Recent advances in construction technology encourage the use of drilled shafts to overcome many of the challenges associated with modern infrastructure projects. Improvements in methods for performance verification measurements also impact the use of drilled shafts. Selected case histories are included.

INTRODUCTION

The rehabilitation of our nation's aging transportation infrastructure presents a significant challenge, and drilled shaft foundations play an essential role in the replacement, repair, and improvement of critical structures. The inherent advantages of drilled shafts for many types of structures, loadings, and site conditions have been enhanced by improvements in construction equipment and techniques. Foundation designers have opportunities to exploit these advantages to build structures in ever more challenging environments and demanding situations. This paper outlines some of the situations in which drilled shafts provide solutions to difficult foundation engineering problems with respect to transportation infrastructure, and presents selected case histories where drilled shafts have been utilized to meet unusual challenges.

DRILLED SHAFT FOUNDATIONS AND TRANSPORTATION INFRASTRUCTURE

Some of the features of drilled shaft foundations that are particularly well-suited to transportation infrastructure applications include the following:

- <u>Flexural strength.</u> Drilled shafts provide a reinforced concrete structural member which can provide excellent flexural strength for applications where lateral and overturning forces control design, a common situation with transportation structures. Besides bridge structures, other structures such sign foundations, noise walls, and earth retaining structures are dominated by lateral loadings. Recent developments in construction capabilities have extended the range of drilled shaft diameters that may be efficiently utilized.

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- High axial resistance. Drilled shafts are capable of developing extremely large axial resistance, particularly when constructed on or within a rock bearing formation.

- Scour resistance. Where bridges cross waterways, foundations may be affected by scour around piers. Drilled shafts provide a foundation solution which can minimize the obstruction to flow that increases scour of the streambed, and also extend the foundation support into a hard, scour-resistance bearing formation.

- Small footprint. Drilled shafts can provide a foundation of great strength within a small footprint area, often utilizing a single drilled shaft to support a column. This feature provides advantages when constructing in congested areas where available space is at a premium. The need for a pile cap may be reduced or eliminated, thus saving the need for shoring or construction of temporary cofferdams.

- Minimal impact on nearby structures. Much of today's needs for infrastructure construction consists of the replacement or widening of existing structures, and new foundations may be constructed in close proximity to existing structures that may be old and in poor condition. Drilled shafts can often be constructed to minimize vibrations and impact on surrounding structures. In some cases, drilled shafts may be constructed in such a way as to minimize the impact on existing infrastructure so that time for closures and disruption to the traveling public is reduced.

- Earth Retention. Drilled shafts can be utilized as earth retention structures, utilizing the aforementioned features of flexural strength and minimal impact on nearby structures. Secant or tangent pile walls can be constructed from the top down, often as cantilever walls without anchors, so that useable space for roadways is expanded without the need for additional right-of-way.

The following sections provide several examples in which the features of drilled shafts described above have been used to advantage in the construction of transportation structures.

I-15 BECK ST. BRIDGE, SALT LAKE CITY

This structure included a new 6-lane interstate bridge crossing surface streets and numerous railroad lines with an extensive network of underground utilities. The piers for the new bridge had to be constructed within the, but without disruption to, active rail traffic, as these lines served nearby industrial facilities. Utilities included high pressure gas lines, petroleum pipelines, and water mains. In addition, the foundations had to be designed for seismic-induced liquefaction, which could result in large lateral forces on the foundations due to lateral spreading of soils to depths as great as 40 ft (13m). These conditions constitute a perfect storm of large demand, limited space, and the necessity to achieve axial and lateral resistance at great depth below the surface.

The foundation solution was to construct a single large diameter drilled shaft to support each individual column, thus minimizing the footprint to a size only slightly larger than the column. The 9.2ft (2.8m) diameter drilled shafts were constructed to depths of around 120ft (36m) using temporary casing installed and extracted with oscillator equipment, as shown in Figure 1. This technique minimized the amount of vibrations and potential soil movements around the foundation. Foundations were installed to within a few feet of existing utilities and railroad lines, and measurements determined that the vibrations from the drilled shaft construction were less than those imposed by the railroad traffic.

Figure 1 Oscillator Constructing Drilled Shaft in Tight Quarters, I-15 Beck St. Crossing

Besides the typical lateral forces from the bridge structure resulting from wind, traffic, and seismic loadings, the analysis of lateral loads for this project included the evaluation of liquefaction-induced lateral spreading. The soils at the approach embankments and abutments were treated using deep soil mixing in order to mitigate the potential for liquefaction, but this approach was neither practical nor cost-effective for the intermediate piers. Instead, the flexural strength of the drilled shaft foundations was utilized to resist lateral spreading forces.

The effect of lateral spreading is illustrated in Figure 2, in which the unstable soil mass slides laterally and imposes earth pressure forces against the foundation; a slender pile foundation would be dragged along with potentially several feet of resulting lateral displacements. The results of lateral analyses are presented graphically in Figure 3 for a typical case of lateral spreading acting on one of the Beck St. drilled shaft foundations. In this analysis, p-y curves are used to represent the nonlinear relationship between soil resistance and relative shaft/soil displacement; in order to model the effect of lateral spreading, the p-y curves within and above the zone of liquefaction are offset so as to induce lateral forces applied to the foundation. The drilled shaft transfers this loading through flexure to the p-y curves below the zone of liquefaction.

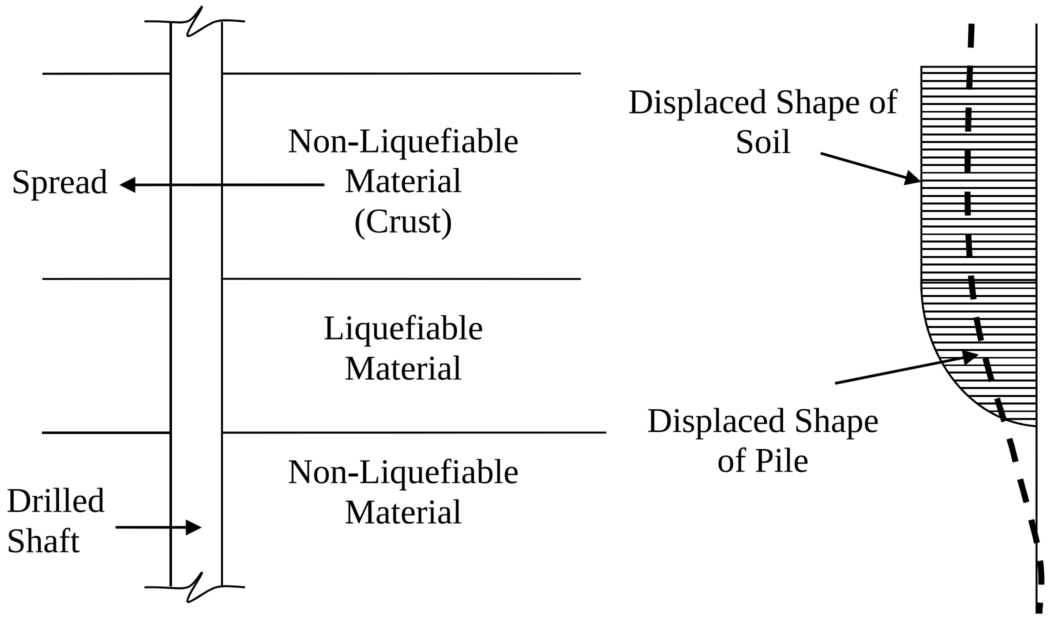

Figure 2 Schematic Diagram of Lateral Spreading

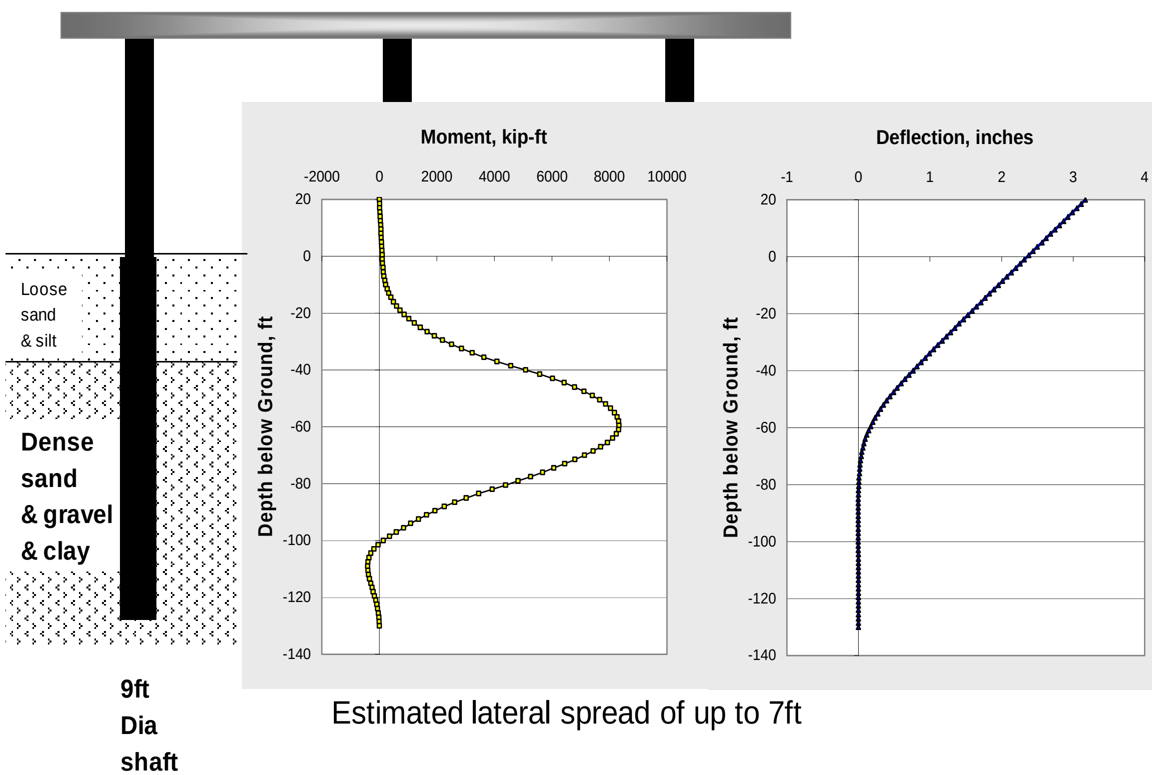

Figure 3 Computed Lateral Bending Moments and Deflections for Lateral Spreading

In order to facilitate the connection between the column and the drilled shaft, the design utilized a “type II” non-contact lap splice whereby the column reinforcement is placed within the drilled shaft reinforcement for some depth below grade to form the splice. This connection can present a challenge for construction in a wet environment, as was the case for this project. The solution was to install a short permanent “slip-in” casing within the oscillator casing so that the permanent casing would allow the formation of a cold joint below the splice. After the drilled shaft concrete hardened, the splice zone within the permanent casing could then be dewatered, the column reinforcement placed, and the splice zone concrete placed in a dry environment. Column formwork was erected and the column construction completed after the splice zone concrete had set. A key feature allowing this approach was that the drilled shaft reinforcement was designed with sufficient cover to allow room for the temporary casing and the slip-in permanent casing.

The I-15 Beck St. Bridge was a component of a design-build project for the Utah Department of Transportation. The foundation type selection was made by the design-build team as the most cost-effective and constructible solution which could satisfy the many competing demands for this challenging situation. Parsons Transportation Group led the design effort for the design-build joint venture of Kiewit and W.W. Clyde. Malcolm Drilling was the drilled shaft subcontractor.

MISSISSIPPI RIVER BRIDGE, ST. LOUIS

This new cable-stayed bridge crossing the Mississippi River at St. Louis will carry I-70 traffic over the river at a location a short distance upstream of the historic Eads Bridge, the first major crossing of the river which was completed in 1874. From his work as a salvage diver, James Eads understood the tremendous scour potential of the currents in the great river. He pioneered the use of pneumatic caissons in North America (Washington Roebling studied this bridge in designing the Brooklyn Bridge), and demanded that the caissons be sunk to bear on the limestone bedrock below the sandy bottom.

The pylon foundations supporting the 1500ft (450m) span for the new Mississippi River Bridge (MRB) shown in Figure 4 are designed for the modern demands of a wide multilane, long span bridge with consideration of vessel collision and seismic loadings, as well as the deep scour that was well understood by Mr. Eads. The limestone bedrock was at a depth of over 110ft (33m) below the normal river surface elevation. The more than 70ft (21m) of overburden was but an impediment to construction, and, because of scour, provided no value in resisting the loads.

Caissons extending to rock would need to be much larger than those supporting the smaller Eads Bridge, but could be constructed as modern open well dredged caissons. However, caisson construction is extremely time consuming and expensive, and modern drilled shaft construction techniques afforded the construction team an opportunity to complete the foundations more quickly and economically.

The base design put out for bid by the Missouri Department of Transportation included alternates for both caisson and drilled shaft foundations, but also included a provision allowing the contractor to propose alternate technical concepts (ATC). The approach selected for the project by the winning construction team included a redesign of the foundation through the ATC process, with foundations comprised of 11.5ft (3.5m) diameter drilled shafts. A key component of the ATC design was the use of load testing to verify the performance and justify the high axial resistance of the rock sockets used in the ATC foundation design. The ATC foundation design targeted a nominal axial resistance of 43,000 kips (200MN) for each of the six drilled shafts supporting each of the pylons. A single drilled shaft was used to support each of the columns at the anchor piers.

Figure 4 The Mississippi River Bridge (rendering from Missouri Dept. of Transportation); Eads Bridge is in the Background

By using a few very high capacity drilled shafts, the size of the cofferdam was minimized, saving construction costs and time for sheet piling, seal concrete, footing size, etc. Seismic demands are reduced by reducing the mass of the footing, so efficiencies in the foundation design provided extra dividends in this regard.

Construction of the load test shaft demonstrated the ability of modern construction equipment to form drilled shaft foundations into hard rock, and the testing demonstrated the incredible load carrying capacity of drilled shafts socketed into the hard limestone at this site. The rock coring tools provided efficient means of drilling, and the rock was removed as a series of intact cores using a Haines hydraulic core extractor (Figure 5). The load testing was performed using a cloverleaf arrangement of Osterberg load cells at the base of the 22ft (7m) deep rock socket, and loaded the test shaft to a world record test load of 72,000 kips (320MN) without fully mobilizing the available side and base resistance. The upward movement of the shaft was around 0.05 inches at an average unit side resistance of over 40 ksf, and the downward movement of the shaft was just under ¼ inch at a base resistance of around 450 ksf.

The load test demonstrated that the minimum length of the rock socket was controlled by the lateral load demands, and that the axial resistance of the rock socket exceeded the structural capacity of the reinforced concrete.

Figure 5 Limestone Rock Extracted During Construction of Load Test Shaft

A boring was drilled at each production foundation location, with coring and downhole acoustic televiewer profiling to verify the integrity of the bedrock at each drilled shaft location. Although solution cavities are known to exist at some locations within the limestone in this area, no significant cavities were found during construction. A secondary benefit of the boring program was that the televiewer profiles at each shaft location provided information on weak seams in the rock so that the construction team could plan the locations to extract cores without exceeding the lifting capacity of the crane. The foundations were completed successfully by Massman Construction Co., and the superstructure is under construction as of the time of this writing.

MOSES WHEELER BRIDGE, CONNECTICUT

The Moses Wheeler Bridge represents a foundation engineering challenge that is typical of many situations involving the replacement of our aging infrastructure. The existing bridge carries 135,000 vehicles per day on Interstate 95 over the Housatonic River in Connecticut, and was badly in need of replacement (Figure 6). There was very limited right of way in this congested area between a railroad and marina, and the replacement bridge had to be constructed in phases to both maintain traffic and minimize impacts on the traveling public (who are the owners, by the way). Construction involved shifting traffic to portions of the existing bridge while other portions were demolished and replaced, then shifting again to portions of the new structure to complete construction.

Figure 6 Existing Moses Wheeler Bridge during Construction

Foundations for the new structure consist of a single 9.8ft (3m) diameter drilled shaft supporting each column, supporting the loads with a rock socket into the underlying mica-schist bedrock. The overlying alluvial strata included boulders and cobbles in the river, as well as abandoned timber piles and other detritus of the many years of human existence in this riverfront area. In addition, the new foundations were constructed in close proximity to existing foundations, with limited overhead in which to construct the foundations for the new structure beneath the existing bridge. This approach to foundation construction was used to both minimize disruption to traffic and yet maintain the footprint of the existing bridge for the new structure.

Foundation construction utilized a host of modern drilled shaft equipment that was especially suited to the challenges of this project. Rotator equipment was used to install permanent casing into the bedrock through the overburden materials and obstructions. Overburden was removed using a short hydraulic grab that was specifically designed for the limited headroom; overhead clearance was as small as 23ft (7m) in some locations (Figure 7a). The rock socket excavation was completed using a reverse circulation drill (Figure 7b) with a closed system to collect spoils and avoid spillage in the very sensitive area around the adjacent waterway and marina.

a) Rotator and Hydraulic Grab b) Reverse Circulation Drill

Figure 7 Construction Equipment Working in Limited Overhead Clearance

The existing bridge was founded on footings with large groups of driven steel piles, including outwardly battered piles that extended the footprint of the existing structure into areas needed for the construction of the new foundations. For this reason, construction of some of the foundations for the new bridge were planned to occur after demolition so that the piles could be extracted and the new drilled shafts installed. The time required for demolition, extraction, and construction of new foundations was a critical path item that had a major impact on the construction schedule and the duration of time that traffic would be affected by construction.

The drilled shaft subcontractor, Raito, Inc., offered a value engineering proposal to expedite this portion of the project by using the rotator to construct the new drilled shafts by cutting through any conflicting piles, thereby completing the foundation construction prior to demolition, thus saving many months on the schedule. Engineering analyses of the existing foundations confirmed that the safety and functional performance requirements of the existing bridge could be maintained even with a few piles lost.

The excavation of new drilled shafts through conflicts with existing battered steel piling was accomplished without incident, and the drilled shaft foundations were completed with savings of many months over the original schedule. Steel pipe and H piling were encountered and cut by the rotator; some of the recovered pieces are illustrated in Figure 8. The steel pipe had been driven as closed end piles, and the pile bottom plate on the left photo in Figure 8 is seen to have bent inward to a concave shape caused by the pile driving process.

The successful completion of the new drilled shaft foundations at the Moses Wheeler Bridge demonstrates the capabilities of modern drilled shaft technology to meet the challenges associated with congested and difficult site conditions.

Figure 8 Portions of Steel Piling Removed from Drilled Shaft Excavations

SUMMARY AND CONCLUSIONS

The replacement and improvement of our transportation infrastructure presents unique challenges for foundation design and construction, and the capabilities of drilled shaft foundations provide designers with a powerful tool for developing solutions that meet the demands of high capacity within a small footprint with minimal impact on existing structures. The capabilities of the contractors employing modern construction equipment can offer innovative solutions to utilize these capabilities, and three examples were presented in which such solutions are demonstrated.

Not surprisingly, each of these examples included solutions developed through either design-build project delivery or a proposal developed through collaboration between contractors and engineers. The complexity of such projects presents opportunities for those equipped to innovate and to exploit the advantages of drilled shaft foundations.

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