CONSTRUCTION OF LARGE DRILLED SHAFTS
The 2nd Annual Mike O'Neill Lecture

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ABSTRACT: Improvements in construction equipment and techniques in recent years have made possible the use of drilled shaft foundations in diameters and lengths not previously considered practical or feasible. Many highway bridge and other structures are now routinely founded on drilled shafts which are 8 to 12 feet in diameter and extending over 200 feet in depth below grade. There are unique challenges associated with constructing such large and deep cast-in-place foundations and engineers should be aware of the special needs associated with site investigation, construction specifications, material requirements, and quality assurance. This paper outlines a number of special considerations for these foundations, along with strategies that may be employed to improve the reliability and quality of large drilled shaft foundations.

INTRODUCTION

Large diameter drilled shafts are becoming increasingly popular on major bridge projects due to increased availability of drilling equipment and skilled contractors and inherent advantages of high capacity shafts in supporting axial and lateral loads. Shaft diameters of up to 4 m (13 ft) and lengths of up to 80 m (260 ft) are no longer unusual. These shafts pose exceptional challenges for construction because of the difficulties in excavating shafts of such size and because of the requirement for underwater placement of large volumes of concrete through dense reinforcing cages.

It is important that engineers involved in such projects be aware of the special challenges associated with construction so that designs can be developed which enhance reliability and minimize risk. In addition, engineers with responsibility for quality control and quality assurance on the project must be fully aware of the critical aspects of foundation construction. The use of design/build procurement for many large bridge projects can foster cooperative effort between design and construction professionals and typically requires engineers to proactively consider the important aspects of risk, schedule, and quality assurance in deep foundation construction.

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This paper provides an overview of some important considerations in the construction of large diameter and deep drilled shaft foundations, with an emphasis on bridge projects. These considerations include:

- Excavation techniques suited to this type of construction
- Aspects of site geotechnical investigations important for construction
- Design of reinforcement for constructability
- Concrete placement techniques
- Concrete mix design

EXCAVATION TECHNIQUES

The high load demands which drive the size and depth of drilled shaft foundations on major bridge projects also tend to drive the construction into deep and hard bearing strata. The depths associated with high capacity foundations often include the need to penetrate through layers of rock or rock-like material which may contain boulders and/or cobbles, may be difficult to excavate, or may have special concerns for stability of the excavation during the extended time required to complete the excavation.

Other than the typical tools and equipment used for conventional drilled shaft excavation, large and deep excavations are often accomplished with an increased use of:

- Permanent casing
- Temporary casing installed using oscillators or rotators
- Reverse circulation drilling
- Combinations of coring, drop chisels and hammergrab tools in lieu of augers

With shaft excavations in excess of 8 ft diameter, the use of permanent casing is usually very desirable from a constructability standpoint. Permanent casing is particularly useful in forming the shaft through water and penetrating soft shallow strata which may be unstable. Attempts to remove large diameter casing in these shallow depths adds time to an already lengthy construction process in which the concrete must remain fluid and introduces additional risk.

Large diameter permanent casing is most effectively installed in advance of drilling and most often installed using vibratory hammers, although large offshore-type impact hammers have also been used (Figure 1). If a large hammer is required to install the casing, extraction of a casing would require an even greater force due to the time-dependent setup of the soil resistance in side shear (so leave it in place!). In some cases, the installation of a deep permanent steel pipe followed by excavation below may be considered as a type of steel pipe / drilled shaft composite pile. The axial resistance within the depth of permanent casing can be significant in proportion to the overall axial resistance of the shaft and may be included in the design.

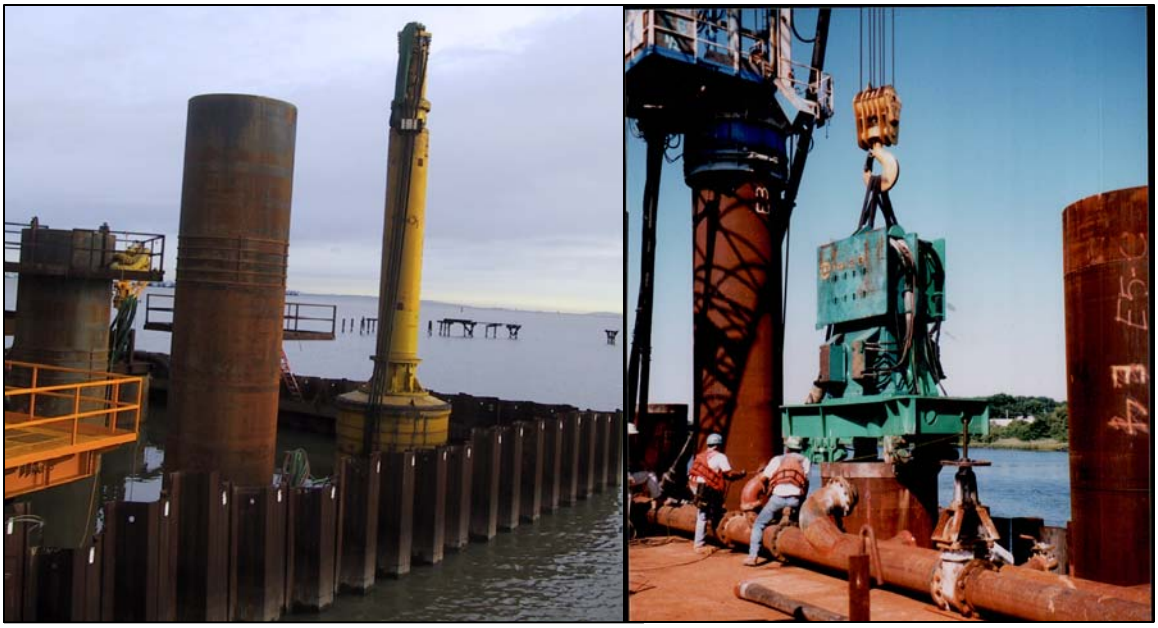

Figure 1 Installation of Permanent Casing

Temporary casing to the full length of the shaft excavation may be used when the risk of excavation collapse is significant. For large and deep drilled shaft excavations, full length temporary casing is most effectively installed using hydraulic oscillator or rotator equipment, in advance of the excavation (Figure 2). The casing installed with this equipment is typically high strength steel, often double-wall, with flush fitting joints between segments. Segmental casing is used to achieve the great depths required. The development of this type of equipment has been instrumental in advancing construction of large deep shafts, because of the large torque and lifting forces that can be generated. In many cases, the thrust applied during removal of the casing requires substantial pile foundations to be installed in support of a template.

Figure 2 Oscillator Equipment for Installation of Segmental Casing

Another reason for using casing is the time required for completion of large deep shafts, which could be a concern if bentonite drilling fluid were used and the exposure time must be limited. Many specifications call for limiting the exposure time to a maximum of four hours for an open hole with bentonite slurry because of concerns relating to filter cake buildup and subsequent reduction in side shear capacity. The minimum length of time required to complete bottom cleaning operations, place rebar, and start concrete placement in a large shaft can easily exceed this limit.

Reverse circulation drilling techniques are often used to advance shaft excavations to great depth. With reverse circulation drilling (Figure 3), drilling fluid (usually water) is circulated by lifting the fluid through the center of the drill string, usually with an air-lift pumping system, and with fluid resupplied by pumping into the top of the shaft excavation from an external reservoir. Cuttings are removed from the base of the excavation by the circulating drilling fluid, which evacuates the material below the cutter head.

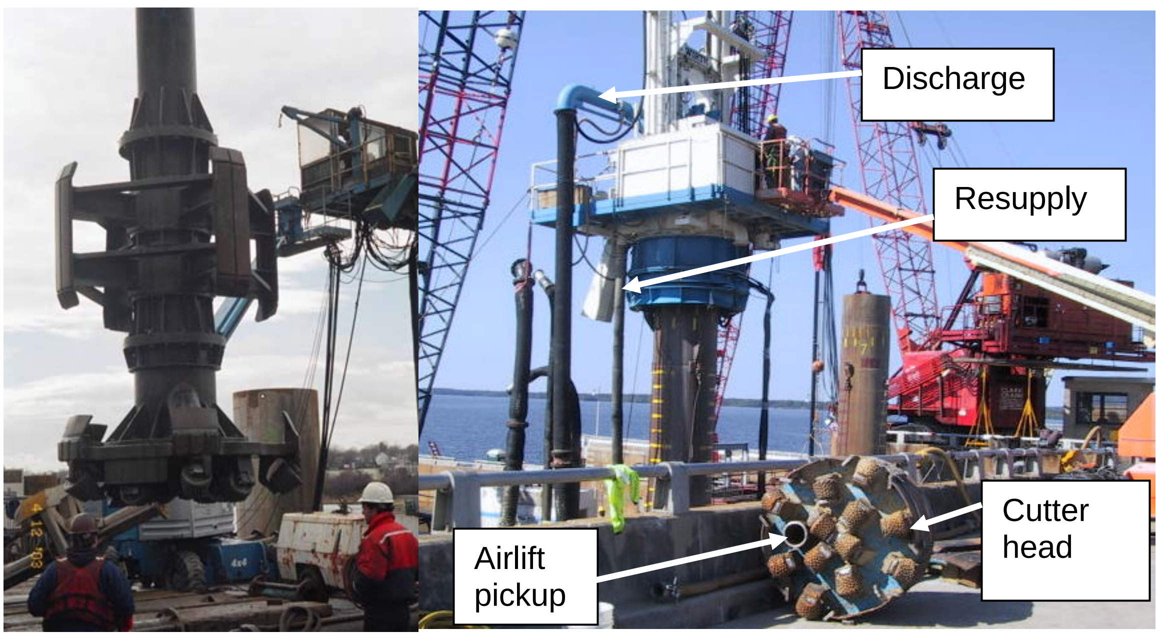

Figure 3 Reverse Circulation Drilling Equipment

An advantage of reverse circulation drilling is that the tool does not need to be cycled in and out of the hole to excavate the soil or rock as would be the case with conventional augers, and for shaft excavations at great depth this advantage can result in improved productivity. However, the time required for setup on each hole is significant.

Other tools often utilized on large, deep shafts include percussion tools such as drop chisels or hammergrabs. With large diameter excavations in hard material, chisels can assist in breaking up boulders or large rock fragments left after coring with core barrels or within segmental casing. A hammergrab tool can be more effective at removing large objects within the excavation than rotary drilling equipment. It is worth noting that the base of the excavation will not be as flat and level as would be accomplished using conventional rotary drilling equipment. However, effective bottom of hole cleanout can be accomplished using airlift tools or downhole pumping.

Figure 4 Chisel (left), Hammergrab (right)

GEOTECHNICAL SITE INVESTIGATION

Large drilled shaft projects require particular attention to construction issues during the geotechnical site investigation. In addition to the normal design parameters, critical information related to construction include:

- Rock characterization and compressive strength
- Groundwater and potential for artesian conditions during construction
- Boulders or cobbles
- Sequence of construction operations and potential effects

The author is aware of several cases in which characterization of rock was limited to properties solely for design intent to the exclusion of construction considerations, and costly differing site condition claims were the result. Proper sequencing of construction operations can also be critical, especially when there may be multiple contracts on a major project. For example, there is potential for lost ground around the shaft excavation due to cobbles and boulders and such soil movements can affect nearby operations or existing structures. Pile driving vibrations or vibrations from other sources can interfere with stability of shaft excavations.

One potential method of dealing with uncertainty in subsurface conditions on major projects is the use of a Geotechnical Baseline Report (GBR). This approach has been used on tunneling projects with success for years and has potential to improve our methods for defining conditions for bidding purposes on drilled shaft projects. A GBR is issued to specifically define geotechnical conditions as a baseline for bidding so that contractors can more fairly include "contingency" costs in their bid. Vague or exculpatory language is avoided in a GBR so that the basis for each bid is the same. Conditions that are more adverse than defined in the GBR (for example, more than 20 hours spent removing obstructions or boulders) are paid on a unit price basis. The use of a GBR has the potential to reduce the costly litigation associated with differing site conditions and improve the potential for true partnering on major drilled shaft projects.

DESIGN OF REINFORCEMENT FOR CONSTRUCTABILITY

Large, heavy reinforcing cages pose construction challenges of lifting, splicing, and placing the cage, and also from the standpoint of concrete flow through the cage. Multiple cranes, multiple pickup points or "tipping frames" may be required to lift the cage, as illustrated in Figure 5. Very long cages may need to be spliced while suspended over the hole, thus greatly increasing the exposure time during which the hole is open without agitation as discussed previously. Extremely congested reinforcing cages pose an impediment to concrete flow and can lead to entrapment of debris or low strength concrete outside the cage.

Figure 5 Lifting of Large Reinforcing Cages

Some of the key components that can facilitate constructability are:

- Bundle the rebar to increase openings through the cage
- Avoid tight spacing in transverse reinforcing (spirals or hoops) by bundling the bars
- Avoid the use of multiple cages, which pose an extremely difficult condition for concrete placement underwater
- Utilize the permanent steel liner to reduce the longitudinal reinforcement and to provide confinement so that the transverse reinforcement is reduced.

The issue of utilizing the permanent steel liner for structural design has tremendous potential to improve constructability. In addition, the use of a permanent steel liner for bending stresses can provide a foundation with excellent strength and ductility in flexure for extreme event loads such as seismic or vessel impact forces. When reasonably cleaned using a wire brush or hydro-jet on the interior of the casing after drilling, good bond at the steel/concrete interface can be achieved. The confinement provided by the steel liner eliminates the need for tightly spaced spirals or hoops.

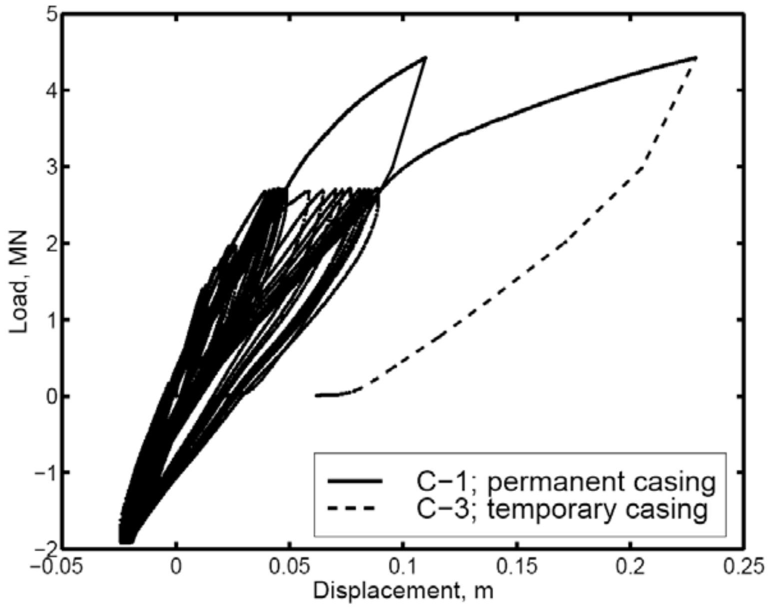

Figure 6 Comparison of Lateral Response of Two Drilled Shafts

The data presented on Figure 6 illustrate a comparison between two 8 ft diameter drilled shafts subjected to cyclic lateral load testing for the Cooper River Bridge in Charleston, SC (Brown and Camp, 2002). The more flexible shaft C-3 was constructed using a temporary casing that was removed prior to testing while shaft C-1 included a permanent casing of 1 inch wall thickness. Shaft C-1 displaced less than ½ as much at similar load and had significant additional strength in bending when shaft C-3 was at yield. Other than the casing, both shafts were reinforced similarly. The casing for shaft C-1 was installed with a vibratory hammer prior to drilling and no special cleaning tools were used.

CONCRETE PLACEMENT TECHNIQUES

Critical issues relating to underwater placement in large or deep drilled shafts include the initiation of flow through the tremie and control of concrete during casing removal. Gravity tremie placement is preferred over sealed pump line systems for deep shafts, although pumping into the top of the gravity tremie provides an excellent delivery system. A sealed pump line in a very deep shaft can result in negative pressures within the line that can lead to segregation and blockage within the line (Yao and Bittner, 2007). For very deep shafts, the use of an open segmental tremie is generally required; a sealed tremie with a closed end plate would be so buoyant and long that control of the empty tremie is difficult.

With an open tremie pipe, the initial charge of concrete is separated from the fluid in the pipe using a plug. The tremie plug will be compressed under very high pressures at depth and should maintain a sufficient width to keep concrete from bypassing the plug.

Even more critical than the plug, is the rate and volume of concrete delivery in the initial concrete charge to the tremie. With the extremely long tremie and large shaft diameter, many cubic yards of concrete may be required to achieve a head of concrete in the shaft above the bottom of the tremie. If a slug of concrete is discharged into the tremie without continuous resupply of concrete or control of the flow from the bottom, the inertia of this initial slug of concrete can result in a very low head of concrete inside the tremie which would result in a breach as the water or slurry flows back into the tremie. This breach can be avoided if the tremie operator can hold the tremie within a few inches of the bottom so as to control the flow from the tremie and maintain a head of concrete within the tremie that exceeds the water head in the shaft, as illustrated in Figure 7. It is important that concrete delivery at this initial stage be provided rapidly and continuously, if possible.

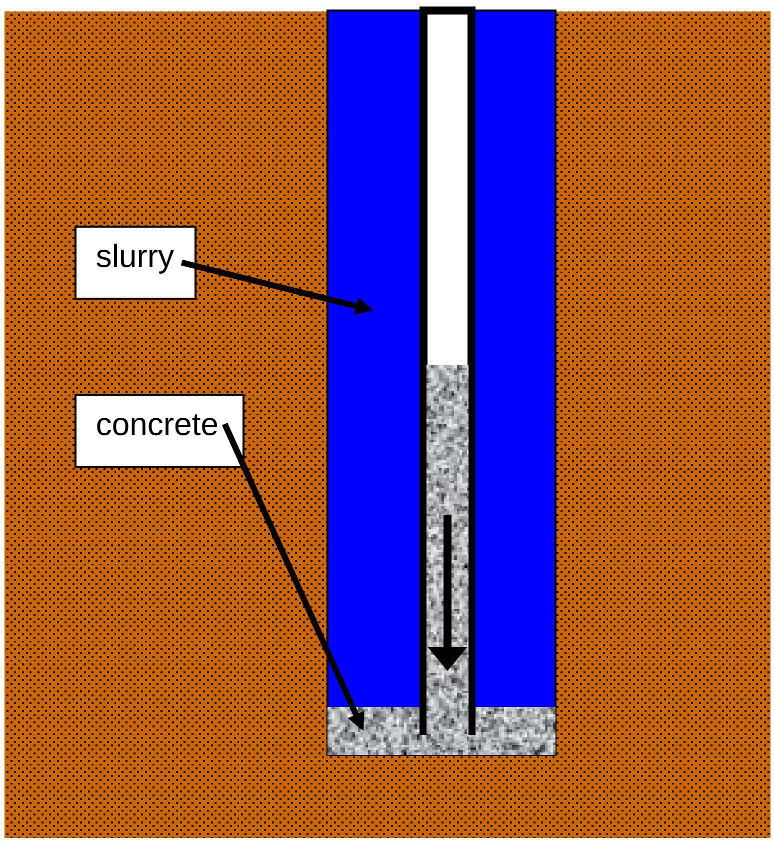

Figure 7 Initiation of Concrete Placement with Gravity Tremie

Concrete placement into a deep temporary casing also requires careful control of concrete volume during casing extraction. If there was difficulty in achieving a seal around the base of the casing during drilling, it is quite possible that some soil loss can occur around the outside of the casing with a resulting void. When the casing is extracted, the volume of concrete required to fill a void may result in a precipitous drop in the concrete level within the casing as shown in figure 8. In a similar manner to the tremie discussed previously (the temporary casing might be thought of as a very large diameter tremie), a drop in head of concrete within the casing can lead to a breach of the seal below the casing or tremie, if a tremie is used inside the temporary casing.

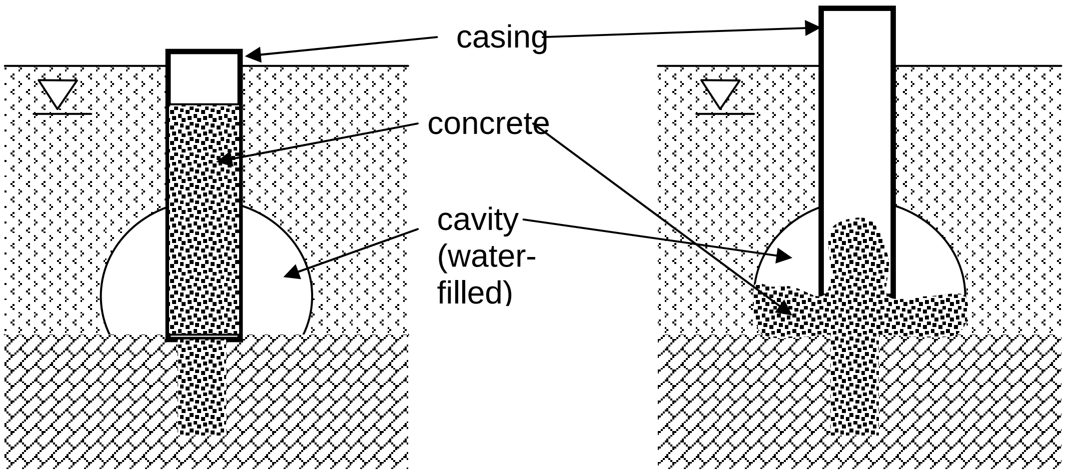

Figure 8 Loss of concrete into cavity during casing extraction (Brown, 2004)

Note that the withdrawal of a temporary casing from inside a permanent casing is subject to the same concerns regarding maintenance of a head of concrete within the inner temporary casing; water or slurry is typically present in the annular space between the two casings and must be displaced from the bottom up by the concrete.

THE NEED FOR HIGH PERFORMANCE DRILLED SHAFT CONCRETE

The most critical performance requirements for concrete are related to workability and thus the concept of "high performance" material emphasizes the construction aspects of the mixture in addition to hardened properties required to meet structural design requirements. Important components of a good mixture design and installation plan include requirements for workability for the duration of the concrete placement operations, passing ability, resistance to bleeding, and low heat of hydration.

In order to flow laterally from the discharge point and fill the shaft without entrapment of drilling fluids or laitance from the underwater surface of the fluid concrete, the concrete must flow smoothly through the reinforcing cage under its own buoyant weight without "piling up" near the tremie. A mixture with the desired workability will not result in more than a few inches of difference in height between the top of the concrete surface near the tremie and the concrete on the outside of the reinforcement as shown on Figure 9. The inability of the concrete to flow laterally can lead to entrapment of laitance (the contaminated concrete on the top of the rising column of concrete) and encapsulation of pockets of low strength as described by Brown (2004). Yao and Gerwick (2004) describe the desirability of underwater concrete to flow laterally in a "bulged" flow pattern with a relatively flat, smooth top surface rather than as a "layered" flow pattern which can result in steeply sloped and rugged top surface that increase the exposure of concrete surfaces to water.

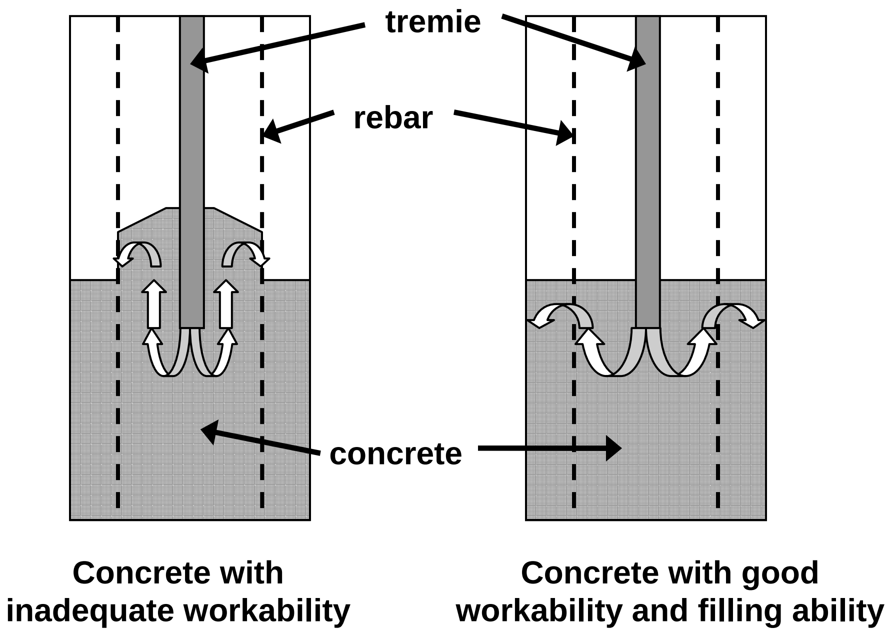

Figure 9 Concrete Flow in Under Tremie Placement

Workable concrete for tremie placement in drilled shafts must be a flowable, cohesive, self consolidating mixture that is easily placed without external vibration. Although the use of the term “self-consolidating concrete” or SCC has been used in recent years with reference to mixtures with ultra workability in conventional concrete applications, drilled shaft concrete has always been intended as a self consolidating mixture. Traditionally, drilled shafts have been constructed using slump as the sole indication of workability. Alternative methods to describe workability may have application in large diameter drilled shafts.

Concrete slump ranging from 175 to 225 mm (7 to 9 inches) has been found to provide adequate workability for drilled shafts up to 2.5 m (8 ft) in diameter if the reinforcing cage has openings not less than 150 mm (6 inches). For mixtures requiring greater workability, the use of slump flow and/or the L-box (or J-Ring) tests may be more suitable for assessing the properties of the fresh concrete. The slump flow is a simple test performed with a conventional slump cone, but measurements are performed on the diameter of the resulting fluid concrete mixture rather than the height of the cone. Based on some initial field trials of drilled shaft construction using SCC-type mixtures (Brown et al. 2005), slump flow requirements in the range of 450 to 600 mm (18 to 24 inches) appear suitable for drilled shaft construction.

Concrete mixtures can be designed with high workability by using suitable aggregates and gradation and the proper dosage of water reducing admixtures. Rounded gravel aggregate sources are preferred over crushed stone, and coarse aggregates with a No. 67 or No. 78 gradation are preferred over a No. 57 in terms of workability. In general, an increase in the sand content in proportion to coarse aggregate will provide increased workability and passing ability with less tendency for segregation; a sand to total aggregate ratio (by volume) from 0.44 to 0.50 has been found to work well in drilled shaft mixtures. Water reducing admixtures in current use include polycarboxylate-based materials, which are preferred over the older naphthalene-based water reducers that have the potential to produce a "flash set".

For large diameter shafts which can often require 300 to 500 m^3 (400 to 650 yd^3) of tremie-placed underwater concrete, retention of workability is critical. The dosage of retarding or hydration control admixtures must be selected to ensure that the concrete retains adequate workability to allow the tremie placement to be completed. Loss of workability will lead to difficulties in maintaining flow through the tremie, with attendant flaws in the shaft. It must be noted that hydration control is highly temperature dependent.

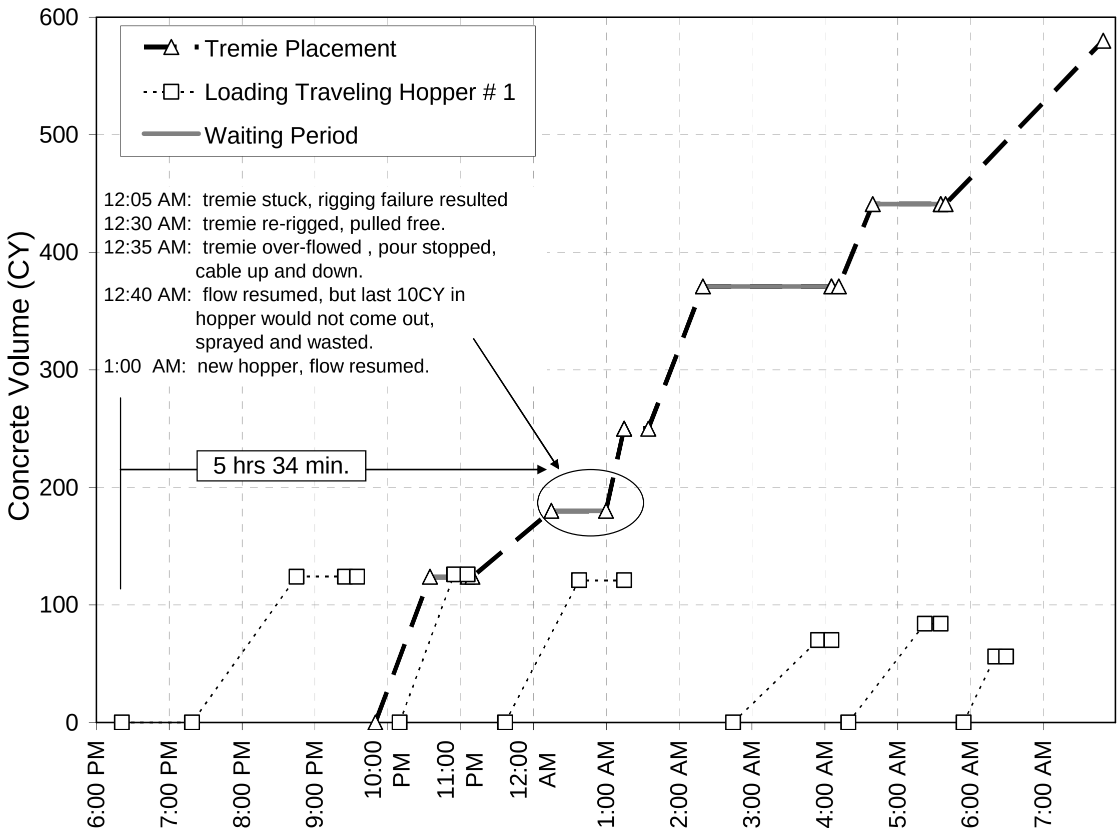

Figure 10 Placement Difficulties Associated with Loss of Concrete Workability

Difficulties with tremie placement associated with loss of workability are illustrated from a project record of over-water placement of concrete on a bridge project, shown on Figure 10. In this particular instance, there were difficulties and delays in loading the delivery barge (denoted as "traveling hopper") and the mixture had sufficient retarder to maintain workability for only about 4 to 5 hours. Approximately 5 ½ hours after the first concrete was batched, the concrete became stuck in the tremie and the crane operator had difficulty lifting the tremie (which then suffered a failure of the rigging). When the tremie was finally pulled free, concrete was unable to flow freely from the tremie and flow was resumed only after jigging the tremie up and down. Subsequent integrity test results revealed poor quality concrete at the elevation corresponding to this event and expensive shaft repairs were required.

For drilled shafts with such high workability requirements, a mixture with low bleeding is necessary. Mixture characteristics relating to bleeding are also closely related to those affecting segregation, and a concrete mixture with a very high workability requirement is more susceptible to bleeding and/or segregation concerns. Ground conditions also play a role; low permeability cohesive soils are more conducive to bleeding concerns than sandy soils which allow excess water in the mixture to escape. The worst conditions for bleeding occur when there is a long steel casing that prevents excess water in the concrete from escaping into the surrounding soil.

Low bleeding can be obtained by using more cementitious materials and by using viscosity-modifying admixtures (aka, anti-washout admixtures). ASTM C 232 is an available test method to assess potential bleeding in a concrete mixture, and drilled shaft concrete should exhibit little to no bleeding in this test. This test method is unable to subject the concrete to high pressure conditions present in deep shafts, however. Considerations of workability dictate that there is water in a mixture that exceeds the amount of water needed to hydrate the cementitious materials. Reduction in the water-to-cementitious materials ratio will reduce bleeding, but mixtures that are exceptionally high in cement content can have other problems related to heat of hydration and set time. The total cementitious content can be increased without increasing net portland cement content by using more fly ash or ground-granulated blast furnace (GGBF) slag. Viscosity modifying admixtures (VMA) can be effective at binding up free water prior to setting of the concrete.

When high dosages of fly ash or GGBF slag are used, the strength development will be slower when compared to mixtures with only portland cement. However, when cured, these mixtures may exhibit higher long-term strengths. In these cases it is advisable to test the specified compressive strength at 56 or 91 days in lieu of the normal 28 day specified strength for conventional concrete.

Control of temperature is important for drilled shaft concrete in order to control setting time and the heat of hydration. Excessive concrete placement temperatures will accelerate the rate of hydration significantly and reduce the concrete's workability. This effect is nonlinear and rate of hydration increases dramatically with temperature in excess of 70°F. The measurements presented on Figure 11 demonstrate the effect of initial temperature on the heat generated within the concrete as a function of time. This generated heat produces more rapid setting in the mixture and a significantly higher heat of hydration in mass concrete.

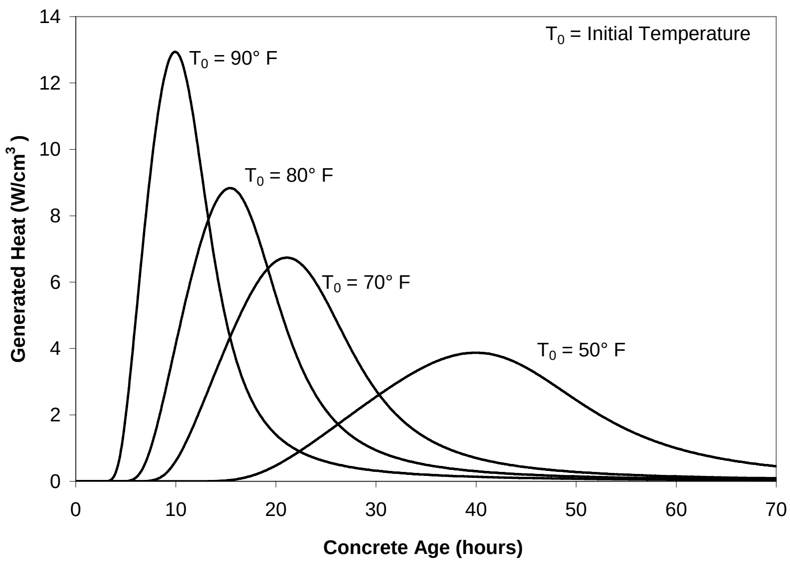

Figure 11: The effect of different initial mixture temperatures on the temperature development during adiabatic conditions (Schindler 2002)

The data from Figure 11 demonstrate the benefits of controlling the fresh concrete placement temperature in terms of controlling heat of hydration. Temperature controls at the batch plant can be achieved by substituting some of the mixing water with ice, or with liquid nitrogen thermal probes that are used to cool the concrete in the truck.

The use of Type II cement and high dosages of either Class F fly ash or GGBF slag are often the best options to control heat of hydration. Concrete mixtures with high dosages of fly ash or GGBF slag will tend to generate less heat of hydration and are also less prone to delayed ettringite formation (DEF); temperatures up to about 178°F can be tolerated without significant concerns of DEF.

SUMMARY

Large diameter and very deep drilled shafts require special efforts during construction to ensure reliability. Excavation techniques often differ from conventional shaft drilling techniques because of the size and depth and vulnerability to difficult subsurface conditions. Geotechnical investigations must be conducted in such a way as to address construction issues because of the costs and risks involved in construction. Reinforcement should be designed to improve constructability, and the use of permanent steel liners as an integral part of the structural design of the foundation is encouraged. The special concrete requirements for this application should be considered, and the author proposes that the concept of "high performance concrete" should be applied to drilled shaft mixtures to incorporate critical performance requirements related to workability. Specific performance requirements that are particular to drilled shaft applications are described, including workability for the duration of the placement operation, passing ability, resistance to bleeding, and low heat of hydration. Perhaps the most important guideline is that each drilled shaft project should have a specific mixture developed to meet the requirements for that project.

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