Underwater Concrete in Drilled Shafts: the Key Issues and Case Histories

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ABSTRACT: In construction of drilled shafts under water, placing concrete in the shafts is technically demanding and involves complex construction logistics. Past construction experience has demonstrated that high quality concrete can be placed in drilled shafts under water with a proper concrete mix and proper placement techniques. However, a significant number of failures have occurred which have resulted in excessive cost overruns and delays. These problems may have occurred because proper underwater concrete construction techniques have not been widely disseminated within the industry. This is a technical area where competent design and sound construction planning can achieve a significant reduction in both risk and cost. This paper will discuss some key technical issues in the concrete mix design, concrete production and placement for the drilled shaft construction. The paper also describes two lesson-learned case histories from drilled shaft construction projects.

INTRODUCTION

Placing concrete in the shafts is one of the most critical and complex operations that often determine success or failure of many drilled shaft construction projects. If the concrete is placed under water, the construction is even more technically demanding and involves complex construction logistics. A number of failures have occurred due to improper concrete mix or improper construction procedures. The following sections present some important technical issues that are frequently encountered in underwater construction of drilled shafts.

CONCRETE MIX DESIGN

Because concrete placed underwater is inherently susceptible to cement washout, laitance, segregation, cold joints, and water entrapment, it must possess some unique properties that are not otherwise required. The following list outlines the essential and unique requirements for concrete placed underwater:

1. Flowability: the concrete must be able to flow around and fully encase reinforcing steel bars. In practice, the interpretation of flowability is specific to the application for a given project. Therefore, the level of concrete flowability must

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be specifically defined and fully understood by all the parties involved in the design and construction for a given project.

2. Self-compaction: the concrete must solidate itself under its own weight without entrapping any water and laitance. It should be pointed out that the self-weight of concrete is substantially reduced by its buoyancy in water. This differs from the so-called self-comsolidating concrete normally placed in the dry.
3. Adequate cohesion: Cohesive concrete prevents segregation, excessive bleeding or cement wash-out. A high degree of cohesiveness in concrete improves homogeneity and strength of the underwater concrete. The required degree of concrete cohesion, however, depends on many variables for a specific project. For a given mixture, an increase in flowability tends to reduce cohesion and vice versa. Nevertheless, modern engineering practice has proven that proper mixture proportions can provide for highly flowable concrete with adequate cohesion characteristics.
4. Retention of workability: underwater concrete often entails transportation of a large quantity of materials over distance, which may create logistic problems with regard to the time lapse between concrete mixing and concrete placement. In such cases, the concrete mixtures must be able to maintain all the desirable properties (such as flowability, cohesiveness, and self-compacting characteristics) over a reasonable work window.
5. Adequate in-place concrete strength: The mix design should account for some inevitable wash-out of cement by water during concrete placement, which leads to loss of in-place concrete strength. Commons measures to ensure the in-place concrete strength include use of a low water-to-cement ratio, typically below 0.45 and relatively high cementitious materials content, typically above 650 pounds per cubic yard of concrete. Use of silica fume and anti-washout admixtures is also very effective for increasing in-place concrete strength.

Concrete mixture proportioning is essentially a trial-and-error optimization process. The process should be guided by a set of governing variables and an understanding of how each variable affects the concrete. Based upon past experience and research (Yao, Berner, and Gerwick, 1999), the authors found that five key variables have the most significant effects on workability of underwater concrete:

1. A water-to-fines ratio of concrete: When the ratio is within an optimum range of 0.85 to 1.0 by volume, the concrete can be made to be very flowable by use of water-reducing agents, while still maintaining adequate cohesion to prevent segregation. The fines content is defined as the total amount of cementitious materials and aggregates finer than 100 µm.
2. Particle packing characteristics: The gradation, maximum size and proportions of coarse aggregates have critical influence on the concrete flowability. Coarse aggregates in tremie concrete are normally in the range of 50-55% of total aggregates. Maximum size of aggregates should be limited since large aggregates tend to increase the propensity for segregation of highly flowable concrete.

3. Composition and content of cementitious materials: Partial replacement of Portland cement with fly ash or ground granulated blast furnace slag improves the concrete workability and reduces the heat of hydration. Use of silica fume improves the anti-washout characteristic of the concrete.
4. When placing concrete under water or slurry through a prefabricated reinforcing steel cage, the clear spacing between steel bars should be at least 5 times the maximum nominal size of coarse aggregates in the concrete. This requirement greatly exceeds code requirements for spacing of bars in above water concrete placement, but is necessary for underwater concrete, because the driving force to produce concrete flow under water or slurry is reduced by half due to buoyancy.
5. Dispersion characteristics of solid particles in concrete: water-reducing and anti-washout admixtures can substantially enhance the performance of underwater concrete.

Concrete Production, Delivery, and Placement

Proper concrete production, supply, and placement are critical in achieving high quality concrete and cost-effective construction. The choice of a proper underwater concreting plan for a project has to be ultimately determined by site conditions, engineering requirements, availability of equipment and contractor's preference. Only general comments are given in this paper.

Good quality underwater concrete is obtained through a continuous placement at a constant placement rate. Any prolonged interruption in concrete placement imposes high risks for defective concrete. Efforts should be made to ensure adequate and continuous concrete supply to the placement. The location of a concrete batch plant is an important consideration in logistics planning and has a significant impact on construction cost, risk, and quality control. An on-site batch plant has the main advantage of providing more reliable control of the concrete workability at the point of placement, because the time between concrete batching and placing is relatively short. This option, however, requires a significant investment in equipment.

Alternatively, a batch plant may be located off the project site, and concrete is transported by transit mixers to the point of concrete placement near drilled shafts. This frequently creates problems with regard to the time lapse between concrete mixing and concrete placement. When the construction logistics indicates the possibility of substantial time lapse between concrete mixing and placing, adequate considerations should be given in planning to ensure the concrete maintains the required properties (e.g., flowability and cohesiveness) at the point of placement. The required work window should take into account concrete delivery time, the duration for each placement, delay due to site access and potential interference of other onsite activities. Consideration should also be given to delays of concrete delivery due to traffic congestion and equipment breakdowns.

Once the concrete batch plant is selected, the effective mixing time is critical in determining the peak concrete production and placement rates. It is desirable to determine the mixing time in field mock-up tests taking into account the essential field variables. The mixing time should be such that all the concrete ingredients are fully dispersed and the concrete reaches the desired workablity.

The most common concrete placement methods in drilled shaft construction are the tremie method and pump method. These two methods function in fundamentally different manners. While tremie placement deposits concrete solely by gravity feed in an open-to-atmosphere system, the pump method utilizes surges of pump pressure to deliver concrete in a closed system. As a result, the technical requirements and inherent risks with the two methods are substantially different.

The tremie method is a way of placing underwater concrete by means of gravity flow. The tremie system basically consists of a rigid pipe suspended vertically through the water and a hopper fixed on top of the pipe to receive concrete. With the tremie method, there exists a "hydrostatic balance point" at which the gravity force inside the tremie is in equilibrium with the resistance to flow such as the hydrostatic pressure, the friction between the concrete and tremie wall, and the resistance of previously placed concrete. Thus, the concrete placement rate can be reliably controlled by the speed in which concrete is fed to the hopper. Although good quality concrete has been placed by both tremie method and pump method, past experience and studies have found that the tremie method encounters less construction problems than the pump method (Yao and Gerwick, 2004, and HERON, 1973). There are two main reasons for this phenomenon. The first is related to the concrete flow rate. When pumping concrete down directly to its deposit area, the pump pressure surges plus self-weight of the concrete are at times much greater than the hydrostatic balance head outside the pump line. Thus, the concrete exits the pump line at an uncontrollably high speed, causing significant disturbance to the concrete that has already been deposited. Secondly, a pump system is closed to the atmosphere. If concrete is being pumped down into deep water, concrete may fall at a rate faster than the pump output. As a result, a vacuum will be created in the pump line. The vacuum pressure so created will suck away the cement paste from aggregates, causing segregation of the concrete. American Concrete Institute provides recommendations as good practice for both the tremie placement method and the pump placement method for underwater concrete. The engineers and contractors need to be aware of the distinctions and different requirements between the two placement methods.

QUALITY CONTROL

Due to inaccessibility for inspection of underwater concrete placement, there is significant uncertainty with the quality and integrity of underwater concrete in drilled shafts. Strict enforcement of engineering requirements and quality control must be imposed for underwater concreting. Attention is directed to the following aspects of the underwater concrete in drilled shafts:

1. Bottom condition of drilled shafts - The bottom of the drilled shafts should be cleaned of sediments just prior to placement of underwater concrete.
2. Initial start of placement - The bottom of the tremie pipe should be sealed with a cap prior to installation in the drilled shaft casing. The tremie pipe should rest on the bottom of the drilled shaft. It should then be sounded to confirm that the pipe

is dry prior to filling with tremie concrete. The pipe should then be lifted 4 to 6 inches to dislodge the cap and commence placement.

3. Conditions of the concrete delivery system (leakage, plug or spill over) - Before using a tremie pipe, all the joints should be checked for possible leakage.
4. Concrete flowability at the points of placement, slump and slump flow.
5. The rate of concrete placement should ensure a continuous and smooth concrete flow within the drilled shafts.
6. The depth to the top tremie concrete surface at various locations - Continuous soundings at predetermined locations should be performed for every 5' concrete rise during the entire placement.
7. Persistent monitoring of all concreting operations including any start and completion of concrete placement, and embedment depth of the tips of tremie pipes in concrete. The tremie pipe should be clearly marked to indicate the depth of the tremie tip. Lateral movement of the tremie pipe should be avoided, and vertical movements of the tremie pipe fully controlled to prevent loss of the tremie seal at the bottom.
8. Frequent checking on the watertightness and tremie seal of the concrete delivery pipes - Any leakage or loss of tremie seal of the delivery pipes will certainly result in substantial concrete defects in the shafts.
9. Volume of concrete produced vs. volume of in-place concrete measured by sounding - If the in-place concrete volume measured by sounding is less than that produced and fed into the tremie, it is an underrun of concrete. If the in-place concrete volume is more than that fed into the tremie, it is an overrun of concrete. In general, underrun indicates a possibility of loss of concrete, possibly leaking through a skirt or cut-off wall. Overrun is indicative of serious segregation of the concrete. The segregation may be caused by a leaking joint in the tremie, or loss of the tremie seal. More than 5% deviation of the measured concrete volume from the theoretical value may be a cause for concern. If the deviation is more than 10%, the concrete placement should be halted and the cause be investigated.
10. Delays of concrete delivery and any construction joint in the shaft.
11. Confirmation - Cross –Sonic- Logging or similar means should be conducted to confirm that sound concrete has been attained.

CASE STUDIES

The most common concrete defects found in drilled shafts and their causes are summarized below.

1. Voids or lenses in concrete and excessive wash-out of cement due to loss of tremie pipe seal during tremie concrete placement;
2. Voids behind the steel cage due to loss of concrete workability during placement, or insufficient clearance between reinforcing steel.

3. Significant washout of concrete and trapping of water in concrete due to unbalanced concrete surface or placing concrete directly through water
4. Necking of the shaft due to cave-in of the soft zone of the ground (e.g., thick clay seams in rock);
5. Entrapment of debris in concrete due to insufficient bottom cleaning prior to concreting.

Case A. On a 19-km (12 miles) long below-grade railway trench project in California, over 9,000 reinforced concrete drilled shafts were constructed below the underwater as a part of the secant pile/retaining wall system. Underwater concrete was placed in these drilled shafts. After excavation of the railway tunnel, a large percentage of the exposed drilled shafts were found to have significant defects as follows:

1. The most common defects in the piles were vertical and horizontal grooves outside the reinforcing steel bars, especially the bundled vertical bars (Figure 1 and Figure 2). The grooves are often accompanied with sizable voids with entrapment of silt. These defects show the evidence of stiff concrete flow patterns and poor concrete consolidation in these areas. These defects typically occur when underwater concrete at the time of placement loses the capability of flowing around and fully encasing the reinforcing bars;
2. Most break-out and soil contaminated areas contained inferior concrete. Typical evidence of inferior concrete quality in these areas is lack of cement paste due to cement wash-out, concrete segregation, and lack of consolidation of the concrete;
3. Many break-out areas showed very poor bond of concrete to reinforcing bars. The poor bonding was due to stiff consistency of the concrete during placement, lack of concrete consolidation, and entrapment of silt;

It is evident that the defects were mainly due to the fact that the concrete lost its capability of flowing around and fully encasing the reinforcing cages during placements. In this case, a polycarboxilate-based high-range water reducing admixture was used without any set-retarding admixture or low-range water reducing admixture. It was not until the very end of the construction that a slump retention test was performed under the field condition. The field test indicated that the concrete experienced rapid slump loss in approximately 90 minutes after the initial batching and mixing, which is generally shorter than the time for delivering and placing the concrete in each drilled shaft. In the past, this type of defect was not uncommon in drilled shafts and reinforced concrete slurry walls.

Case B. A 2500 meter long new bridge under construction in California has 17 bents within its main span. Each bent is supported on 8 or 9 shafts in a 3 by 3 grid. The drilled shafts consists of 2.2m diameter rock sockets drilled into the rock below 2.5m diameter concrete filled steel casings.

Due to an unforeseen geological problem on this project involving instability of the rock socket portion of the shaft, shaft construction was forced to adopt a rotated-casing method for drilling the rock socket that typically ranged from 50 to 100 meters below the water surface. Use of the rotated-casing method solved the problem of cave-in during drilling, but completely changed concrete placement logitistics. The tremie concrete would now be placed as the temporary rotated casing was being withdrawn. The rotated casing was 2.2 meter diameter and fit inside the 2.5 meter diameter permanent steel casing. Thus, there was an abrupt change in size of the concrete pour as the tip of the temporary rotating-casing passed the tip of the permanent casing. The concrete was now able to flow beyond the limits of the temporary casing which had been confining the concrete. As the concrete level dropped inside the temporary casing to fill the suddenly larger pile, mixing occurred with debris and slurry trapped between the temporary casing and the permanent casing (see Figure 3). In some cases, further mixing also occurred as the soil at the tip of the permanent casing caved in. Although concrete overpour was implemented in an attempt to flush debris and laitance out of the permanent portion of the shaft, not all of the debris and laitance due to the mixing could be carried to the top of the tremie concrete. Both debris and laitance were entrapped inside the drilled concrete shaft.

Non-destructive tests (i.e., Gamma-Gamma Logging and Crosshole Sonic Logging) were performed on each shaft. The tests showed that the rock socket portion of the shaft were almost entirely free of anomalies. However, the portion of the tremie concrete inside the permanent casing contained numerous anomalous or defective zones. About 87 percent of the shafts required extensive mitigation of the concrete with significant cost and schedule overrun.

The key issue on this project was sudden enlargement of the drilled shaft cross section. When placing concrete through a withdrawing temporary casing, special attention should be paid to the zone of sudden changes in tremie concrete pour size. Efforts need to be made to minimize the mixing of concrete and slurry in these zones, including enforcing an adequate positive hydrostatic head of tremie concrete inside the casing, slow-down of raising the temporary casing passing these susceptible zones, and reducing tremie concrete placement to minimize washout. Furthermore, the concrete mix must be highly flowable and cohesive so that the laitance and debris would be pushed to the top of the tremie concrete.

CONCLUSIONS

High quality concrete can be placed underwater in drilled shafts. However, proper concrete mix and proper placement techniques are essential as well as performing effective non-destructive testing to confirm sound concrete.

REFERENCES

Yao, S.X., Berner, D.E., Gerwick, B.C., “Assessment of Underwater Concrete Technologies for In-the-Wet Construction of Navigation Structures”, U.S. Army Corps of Engineers Publication, *TR INP-SL-1*, 1999.

Yao, S. X., and Gerwick, B. C., “Underwater Concrete Part II: Proper Mixture Proportioning” and “Underwater Concrete Part III: Construction Issues”, *Concrete International*, February and March 2004

Netherlands Committee for Concrete Research, “Underwater Concrete”, HERON, 1973

ACI 304R-00, "Guide for Measuring, Mixing, Transporting, and Placing Concrete", Chapter 8 "Concrete Placed Under Water", American Concrete Institute, 2000

Figure 1 Defective concrete in drilled shafts

Figure 2 Concrete defect due to the lack of concrete flowability during concrete placement

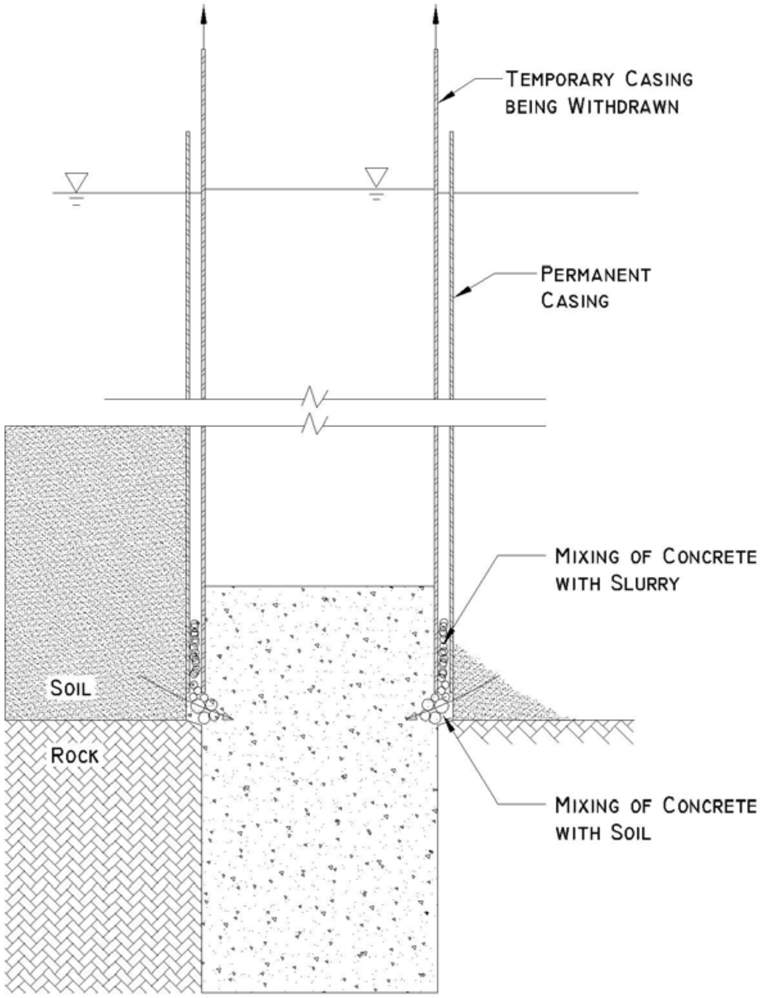

Figure 3 Schematic of the mixing of concrete with slurry and soil during withdrawal of the temporary casing