Quality Assurance for Drilled Shafts Using Self-Consolidating Concrete

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Abstract

High concentrations of steel bars, large diameters and great shaft lengths, uncertain soil and ground water behavior during concrete hardening and potential contamination of concrete by slurry are among the reasons why owners call for extensive integrity tests of installed drilled shafts. Improvements to the existing practice will be possible with Self-Consolidating Concrete (SCC) whose superior flow properties reduce the possibility of voids, incomplete concrete cover around the reinforcement bars and other potential shaft defects.

The most commonly employed integrity test methods are Sonic Logging and Pulse Echo. Thus, to demonstrate the attractive properties of SCC and how these properties can be ascertained with standard test methods, two extensive test series were conducted on relatively large concrete specimens. Among the test results obtained were correlations between strength and sonic wave speed for both ultrasonic and lower frequency pulses. Strength, static elastic modulus and dynamic modulus were measured or calculated from measurements and compared with the flow properties of the concrete. In order to allow for early detection of potential defects, all tests were conducted within a short time of concrete placement. Low slump concrete specimens were also included in the study for comparison with the SCC specimens.

The paper describes the test series, the results obtained and provides information about the concrete mixes and resulting concrete properties. It demonstrates that the concrete quality can be assessed by standard integrity test methods and the relationship between the integrity test results and the concrete properties is merely a function of strength and elastic modulus, and is not dependent upon concrete flow.

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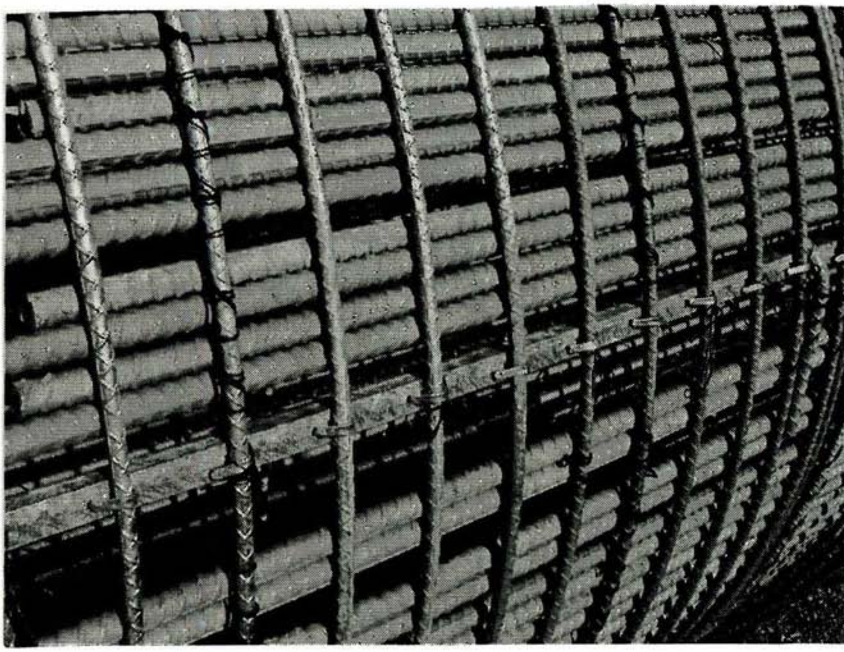

Figure 1. Rebar cage with unusually tight bar spacing

Introduction

Drilled shafts are massive concrete blocks cast underground and subject to a combination of normal forces and bending moments. Concrete may be placed by pumping, tremie or free fall, and flows from the center of the shaft through the reinforcement cage to the concrete cover area. Frequently, bending capacity requirements demand reinforcement cages with densely spaced reinforcing bars (as in Figure 1). At the same time, however, good concrete quality on the outside of the cage is a must to prevent degradation of the reinforcing steel.

Current methods of quality assurance attempt to measure the quality of the installed concrete by one or more of three methods: (a) Pulse Echo Method (PEM), (b) Cross-Hole Sonic Logging (CSL) Method and (c) Gamma-Gamma Method. All three methods require that the concrete has hardened before the test can be conducted. Because it is then too late to do anything simple if a flaw is detected in the concrete, enormous repair cost and time delays will occur. The available NDT methods for deep foundations have been described by Rausche et al. (2004) and a brief description is given below. Anecdotal evidence suggests that on most major drilled shaft construction sites where NDT was specified, some kind of defect assessment has caused painful delays, high costs and heated construction site disagreements. Firms involved in quality assurance testing for the deep foundation industry would like to reduce the adversarial tensions between construction and testing professionals, and it is in the interest of all foundation specialists that the quality of expensive deep foundations is beyond any doubt.

SCC has become a well developed and well accepted material in many areas of the precast concrete industry and in concrete construction. Basically, SCC is proportioned to include a High Range Water-Reducing (HRWR) admixture and produce superior workability when concrete is placed. Traditional concrete quality is often checked by a slump measurement, which should be around 150 to 200 mm for normal drilled shaft applications. For SCC, the slump flow is measured with a slump cone as the horizontal spread of the concrete. In the present study, the slump flows varied between 475 and 763 mm. This is particularly important in drilled shaft construction where concrete vibration is not practical and, at best, counterproductive. The SCC technology has been described by Nasvik (2003) in greater detail.

NDT Technology

The major drawback of the application of NDT to concrete construction is the need to wait several days after concrete placement before the quality of the finished product can be assessed. Frequently, conducting tests after only 2 or 3 days will show some areas with unsatisfactory strength and then the test will need to be repeated at a later date, after the compressive strength is better developed. Only when the test results are satisfactory can construction proceed. The following three methods and their variations cover most of the NDT in drilled shaft construction:

<u>Pulse Echo Method</u>

The test method was first utilized in the 1970s in Europe and in the US (Steinbach et al., 1975). However the method became widely accepted only after it became possible to apply digital signal processing methods. Using a small hand held hammer, the pile top is lightly hit and the ensuing pile top motion is measured with an accelerometer or geophone. A change in pile cross section or concrete quality causes a reflection which is apparent in the measured motion at the top of the shaft.

- Advantages: little pile preparation is needed and, therefore, spot checking is possible; quick and inexpensive; gives information about severity and vertical location of major defects.

- Disadvantages: records sometimes difficult to interpret, and not all records are conclusive; length limitation of 60 diameters under good circumstances; multiple defects or those below the limiting length cannot be detected; small defects (less than 20%) cannot be clearly detected; accuracy of length or distance results depend on assumed wave speed.

- Output: plot of the filtered, amplified pile top velocity vs. time. Records can be analyzed by signal matching or other techniques to yield an indication of defect size, however, these more advanced analysis methods require various assumptions and require experience and some luck.

- Related Method: Transient Response Method which requires also the measurement of the applied force and the calculation of the frequency response of the shaft to the hammer impact.

Cross Hole Sonic Logging (CSL)

This method is frequently used for drilled shaft evaluation and requires that water filled tubes (typically 50 mm diameter) be installed in the test piles over their full length. Test equipment includes an ultrasonic transmitter and a frequency matched receiver. The test procedure requires insertion of the transmitter and receiver in these tubes, lowering and raising them simultaneously while the transmitter continuously sends and the receiver acquires the ultrasonic signals. Wave travel time between transmitted and received signal vs. depth yields an assessment of the concrete quality.

- Advantages: clear resolution in vertical direction; no pile length limitation; somewhat simpler interpretation compared to other NDT methods.

- Disadvantages: Some disagreements about result interpretation is possible; piles have to be prepared with tubes prior to pouring concrete; well-aligned tube installation is difficult for smaller piles or those with no rigid reinforcement cage; checks only concrete between tubes; properties of concrete cover outside of reinforcement cage are usually not checked, although installation of inspection tubes outside of the cage can give some indication of outside concrete quality.

- Output: the First-signal Arrival Time (FAT) can be converted to wave speed, assuming the distance between the tubes is constant along the full pile length. Recently added analysis extensions include the energy of the signal received, and a calculated tomography result that can produce a 3-D display of the perceived shaft quality. Tomography requires that at least 6 scans of the pile are made. In cases where both horizontal and vertical extent of a defect must be delineated, the scans are made with the transmitter and receiver at different levels.

- Variations: Single Hole Sonic Logging (SHSL) is used to check the concrete quality in the neighborhood of the tube, where the transmitter and receiver are inserted in the same tube at some fixed vertical distance. This method can also be applied to smaller shafts.

Gamma-Gamma Logging (GGL)

This method replaces the ultrasonic signal source of SHSL with a radioactive source and requires installation of test tubes in the drilled shaft. The result is a count of photons received, which is inversely related to the density of the material that the radioactive material penetrated. This method is not as widely applied as the other two methods and was not included in the present study.

Advantages: the test involves some volume of concrete surrounding the test tube. Therefore, GGL can be used to draw conclusions on the quality of the concrete surrounding the reinforcement cage; estimates are, however, that the GGL inspection is limited to a zone of 75 mm thickness around the inspection tube.

- Disadvantages: requires tube installation and handling of radioactive material (losing a probe in an access tube can cause real problems); test needs some interpretation by experienced personnel and calibration for wet and dry conditions; for smaller piles or those with no rigid reinforcement cage, accurate tube installation becomes difficult; resolution in vertical direction and assessment of horizontal extent of defect not clear; requires handling and storing of nuclear material.

- Output: concrete density vs. depth plot.

EXPERIMENTAL STUDY

Robinson et al. (2005) have described the test program which forms the basis for the data discussed in this paper. The test specimens were relatively large: 760 mm long, 205 mm wide and 660 mm high (Figures 2 and 3). For the CSL testing, two 937-mm long tubes of 49-mm outer diameter and 5-mm wall thickness were placed in each mold at approximately 70 mm from each edge prior to casting.

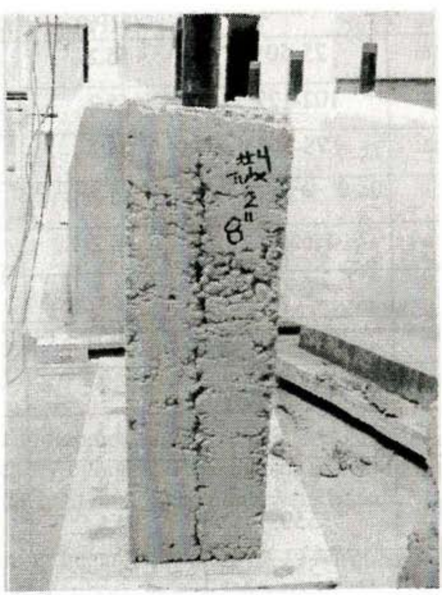

Figure 2. Conventional concrete specimen with 203 mm slump

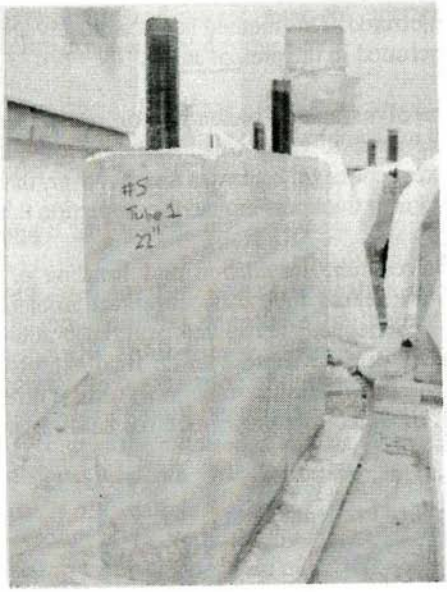

Figure 3. SCC specimen with 559 mm slump flow

Table 1. Summary of Mixes

Mix #	Concrete Type	Slump* or Slump Flow (mm)	Design Compressive Strength (MPa)	Remarks
1	Conventional	25-50*	55.2	
2	Conventional	102-127*	55.2	
3	Conventional	178-203*	55.2	
4	SCC	457	55.2	
5	SCC	559	55.2	
6	SCC	660	55.2	
7	Conventional	178*	20.7	
8	Conventional	178*	34.5	
9	SCC	559	34.5	
10	SCC	559	34.5	Retarded
11	SCC	559	34.5	Segregated
12	SCC	559	55.2	

Twelve concrete mixtures and 24 test specimens (two per mixture) were produced for the purposes of this investigation (Table 1). The first six mixes represented high strength concrete of the same compressive strength and the second set of six mixes, with different compressive strengths, were more typical of drilled shaft construction. Type I cement was used for this evaluation at three cement contents of 237, 357 and 476 kg/m^3, and at water-to-cement ratios (*w/c*) of 0.35 (Mixes 1-6 and 12), 0.54 (Mixes 8-11) and 0.75 (Mix 7). Naturally mined gravel and sand of glacial origin were used for the coarse and fine aggregates. A polycarboxylate-based HRWR admixture was used to achieve the required slump and slump flow of the conventional concrete and SCC mixtures, respectively. A viscosity-modifying admixture (VMA) was used in Mix 6 to stabilize the high slump flow (660-711 mm) mixture. A hydration control admixture (HCA) was added to Mix 11 to purposefully retard the mixture, relative to other mixes, for approximately two hours. A high dosage of the HRWR admixture was used in Mix 11 to purposefully segregate the mix. Selected conventional concrete and SCC mixture proportions are provided in Table 2.

Table 2. Concrete Mixture Proportions for Mixes 7-12

Material	Mix 7	Mix 6	Mix 9
Mixture Type	Conventional	SCC	
Cement, kg/m^3	237	468	355
Sand, kg/m^3	886	855	1049
¾+ River Gravel, kg/m^3	336	285	235
#67 River Gravel, kg/m^3	336	285	235
#8 River Gravel, kg/m^3	336	285	235
Water, kg/m^3	178	163	192
w/c	0.75	0.35	0.54
S/A	0.47	0.50	0.60
HRWR (mL/kg)	2.7	7.8	5.4
VMA (mL/kg)	-	1.3	-

Notes: 1 kg/m^3 = 1.685 lb/yd^3
1 mL/kg = 1.54 oz/cwt

For the assessment of the compressive strength and static elastic modulus for each mix at various ages, thirty cylindrical specimens of 100-mm diameter and 200-mm height were also cast for each mix. Specimens were tested at 1, 3, 7 and 28 days.

On June 21, 2004, testing began with the first 12 specimens of various slumps and slump flows. The second phase began July 19, 2004, when the lower strength specimens were prepared and then tested. Testing was completed on August 18, 2004.

The concrete was continuously poured into the center of the 660-mm tall form by freefall, thereby simulating realistic conditions encountered during drilled shaft construction. The 70-mm distance between each side of the form and the tube simulated a typical rebar spacing, thereby allowing for a check on the flow characteristics of the mix. No special effort was made to push concrete between the tube and the walls of the form. Figure 2 shows that the 200-mm slump concrete did not flow well around the inspection tube. On the other hand, as apparent in Figure 3, the SCC generated a perfect surface appearance.

For the application of PEM, the Pile Integrity Tester ™ (PIT) manufactured by Pile Dynamics, Inc. was used with three different impact devices: a 0.45 kg, Lexan tipped hammer, a 0.23-kg 35-mm diameter steel ball bearing, and a 0.01-kg 11-mm diameter ball bearing. The latter two impact devices are only practical for very short concrete elements. For actual drilled shafts, at least a 0.45-kg hammer should be employed. Evaluation of wave speed was done in both time and frequency domain. A typical record is shown in Figure 4.

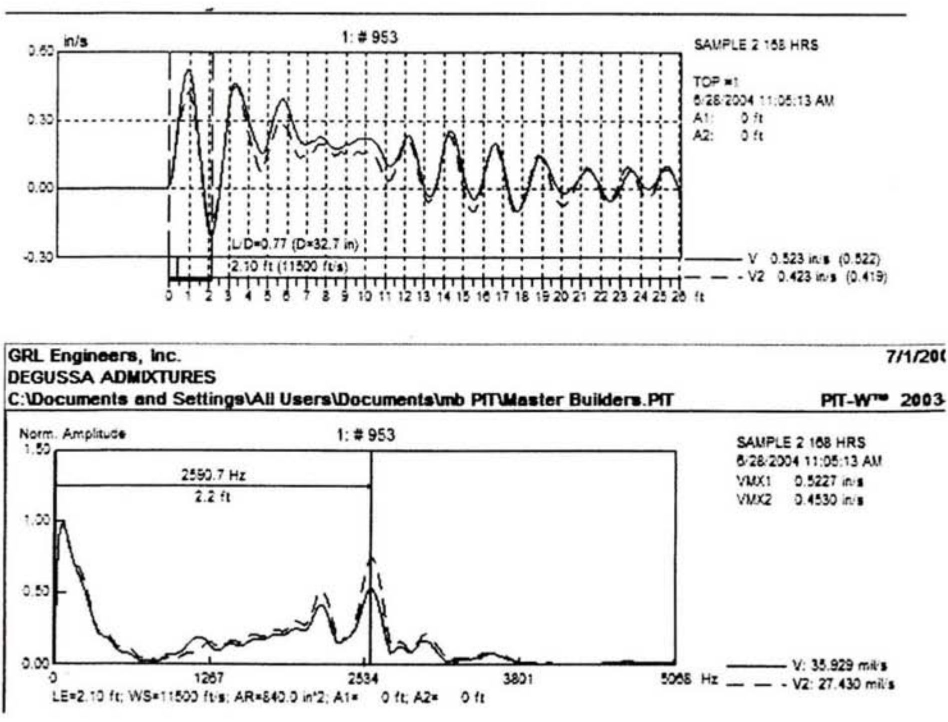

Figure 4. PIT record vs time (top) and frequency (bottom); both displays clearly show reflection from specimen bottom at 2.1 ft

CSL was conducted with the Cross Hole Analyzer™ manufactured by Pile Dynamics, Inc. The distance between the two tubes in each specimen is typical of tube spacings found on the perimeter of smaller drilled shafts.

Strength and wave speed development with time

For the construction manager, it is most important that the concrete be tested as early as possible. As shown in Figure 5, CSL records evaluated for wave speed vs specimen depth of the high strength, high slump flow mix (Mix 6) were rather erratic when tested only six hours after concrete placement. However, two hours later a consistent wave speed above 2,743 m/s was realized. After 24 hours, roughly 95% of the 168 hour wave speed of 4,115 m/s was measured. Under these circumstances, a 24-hour test is definitely feasible. PIT measured wave speeds were roughly 5% higher than CSL wave speeds. This is a test-specific difference due to the fact that the CSL stress wave must travel through water surrounding the probe inside the tube.

A result that is of more theoretical interest is the relationship between static and dynamic concrete modulus. For Specimens 12 through 24, i.e. those that represented potential conventional and SCC drilled shaft concrete, static modulus was directly measured on concrete cylinders under static compressive loads at various times after concrete placement. CSL measurements of wave speed, c (m/s), were converted to dynamic modulus, E_d (GPa), using the following relationship, which is based on the assumption of wave propagation in a slender, linearly elastic rod.

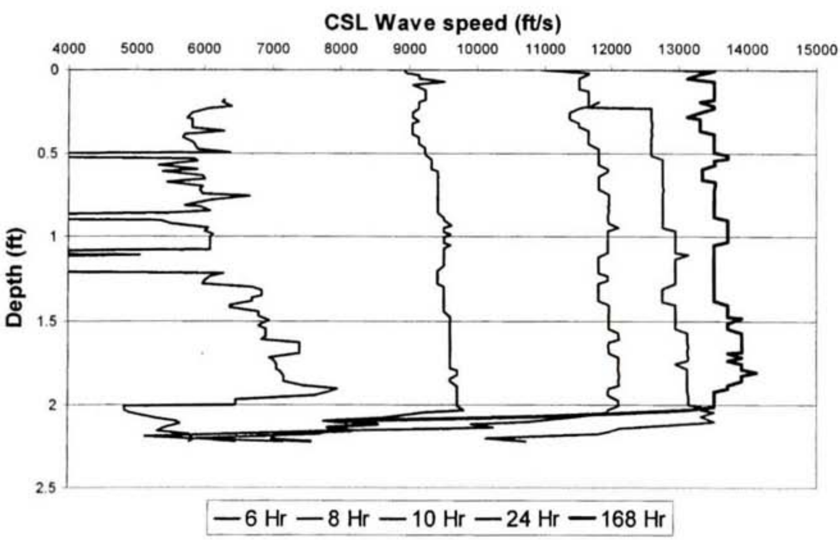

Figure 5. CSL wave speeds vs specimen depth for 5 different test times after concrete placement

$$E_d = K\rho c^2$$

where ρ is the mass density of the concrete, averaging 2,339 kg/m^3, and K depends on the Poisson's ratio of the concrete. Assuming the Poisson's ratio is the same for all concrete mixtures, K is a constant. The ratio of calculated dynamic modulus to measured static elastic modulus averaged between 1.1 and 1.6 at three to seven days after casting which are typical CSL or PET testing times.

This study also looked at predicting compressive strength from wave speed using the above dynamic elastic modulus relation and the following ACI equation:

$$E_{stat} = A\rho^{1.5} f_c^{0.5}$$

where E_{stat} is the static elastic modulus, f_c is the compressive strength of the concrete and A is a constant. Figure 6 shows the results of this study when the correlation between static and dynamic elastic moduli are appropriately accounted for. It should be noted that such correlation is not typically performed in current construction practice. Without such a correlation, the excellent relationship shown in Figure 6 would not be obtained. However, baseline correlations could be established if determining compressive strength from wave speed is deemed important or cost-effective for a particular project.

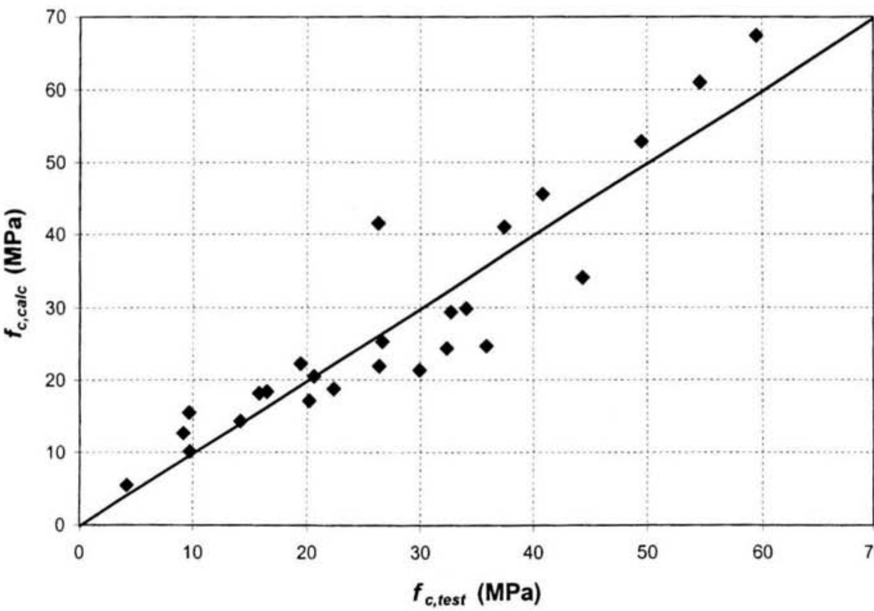

Figure 6. Compressive strength calculated from wave speed versus measured values

SUMMARY

A study was performed on the technical feasibility of using SCC in drilled shafts. It was found that this material has superior flow characteristics that would help to improve drilled shaft quality and acceptance, especially in heavily reinforced shafts. Compressive strength development was predictable and reliable.

The study also showed that standard NDT methods would be as suitable for SCC testing as they are for more conventional mixes. In fact, it should be possible to perform the tests after only 24 hours with reliable results. If properly calibrated prior to construction, the CSL wave speed showed promise in estimating static elastic modulus and compressive strength at the time of testing.

RECOMMENDATIONS

The next step in the implementation of SCC to drilled shafts would be to perform actual field comparisons between conventional concrete and SCC mixtures placed in shafts with demanding properties (e.g., high degree of reinforcement or under various wet and dry placement conditions) and partially excavating the shafts to demonstrate the difference in quality. Standard NDT testing would provide an effective tool for this comparison.

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