CHALLENGES AND RECOMMENDATIONS FOR QUALITY ASSURANCE OF DEEP FOUNDATIONS

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Although Quality Control (QC) during construction is preferable for deep foundations, there are many instances when it is necessary to resort to Quality Assurance (QA) methods if, for various reasons, QC is not possible. Non Destructive Testing (NDT) methods for deep foundations are indirect approaches, i.e. in complex situations they do not provide complete information and need to be augmented by additional testing and/or analyses.

While the challenges are varied for the different deep foundation types and the different test methods they are the same in many different countries. Experience of the tester is often mentioned as being most important for a successful quality assurance. In addition, reliable testing equipment for the best possible measurements and complete construction documentation for a meaningful data interpretation are minimum requirements for a successful test outcome. Another problem is the widely varying cost of the QA tests. For that reason the specifying engineer or authority has to be aware of what can reasonably be expected so that technically feasible specifications can be written for optimal cost and minimal construction delays.

This paper discusses the most common NDT methods with a view on how these methods are applied world wide. It summarizes features of specifications, recommendations for test procedures and advanced analysis methods which can help to overcome uncertainty in the quality assessment of the foundation. Finally, the authors propose a decision tree for various QA methods, deep foundation types and soil properties.

Introduction

Quality control (QC) and quality assurance (QA) of deep foundations are much more difficult than QC and QA of other construction elements because any potential defects are well buried deep in the ground. Although the so-called concretoscopy has been developed, employing transparent inspection tubes together with a fiber optic scope (Samman et. al., 1997), allowing inspection of the concrete immediately adjacent to the transparent tubes, it is improbable that a thorough visual inspection of a massive concrete structure will be possible in the near future.

The method by which QC can be performed during the deep foundation installation depends on the type of foundation element. For example, driven pile installations are inspected by either merely maintaining blow count records or performing dynamic monitoring (Likins et al, 2000) while augered cast-in-place (ACIP) piles can be checked with electronic volume and depth measurements (Piscsalko et al., 2004). In particular, in Europe, ACIP equipment manufacturers often furnish automated monitoring devices for grout volume and auger position measurement together with the drilling equipment. In the US this type of electronic monitors are in most cases independently manufactured. Because of the great variety of drilling and concreting methods, drilled shaft inspection and micropile construction monitoring is not as easily described and conducted. For good quality control of all types of deep foundations, the experienced inspector is often considered the best means for achieving a good quality foundation.

Even after thorough QC, quality assurance is often needed, for example, when difficult soil conditions exist or a review of construction/ monitoring records indicates problems or inconsistencies. QA requires either a direct or indirect inspection of the completed product. Direct inspection would be a destructive process, because it would mean extracting a pile or shaft. Non-destructive QA of deep foundations is, therefore, only possible with indirect methods. There are very few such indirect methods available. As described by Rausche 2004, the most common available methods are Cross-Hole Sonic Logging (CSL) and Low Strain Testing (LST; also called Pulse Echo Method). Occasionally, Single Hole Sonic Logging (SHSL) and the Transient Response Method (TRM) are employed. These two latter methods, however, do not materially differ from CSL and LST. Gamma-Gamma Testing also provides an indirect QA method; however, probably because it involves radio-active material and provides somewhat limited information, it does not enjoy as widespread an acceptance as CSL and LST.

As discussed below, both CSL and LST have limitations which are well known to the experienced test engineers. For that reason, experience in performing the field test as well as the data interpretation is often quoted as being absolutely imperative to prevent false integrity assessments, be they positive (accepting a defective pile) or negative (rejecting a sound pile). Obviously, false positives delay agony while false negatives cause them immediately.

The following attempts to provide the QA responsible construction professional a guideline for selecting the type and frequency of QA and QC. This discussion will only concern itself with aspects of structural integrity (integrity QA) and not with design or load testing procedures necessary to assure that the foundation can safely carry a load with acceptable settlements in a particular soil type.

Discussion of Available QC Methods

Monitoring of Driven Piles

Either merely counting blows or measuring force and velocity (dynamic monitoring or high strain test, HST) are QC methods normally required by building codes and/or specifications (e.g. AASHTO, 2007). In addition, closed ended pipe piles can and should be visually inspected after installation. The simple blow counting method can reveal structural defects, for example by a decrease in blow counts when a monotonically increasing driving resistance is expected. Comparison of carefully kept driving logs from different piles also will help detect piles with structural distress.

HST generally reveals serious structural damage although the resolution is somewhat limited in the vertical direction leading possibly to false positives if the defect is short or the gap very small. False negatives may occur when signal are affected by mechanical noise (e.g. due to high bending and/or spurious vibrations) or electronic noise (power lines, water), so review of data quality by experienced engineers is the first defense. Because of its power to both reveal structural defects as well as provide information on pile bearing capacity, a large number of codes and specifications require or encourage HST; Beim and Likins (2008) present a summary of codes covering HST on driven piles.

Monitoring of ACIP Construction

The most basic method, measuring the volume as a function of auger position during grouting, is avoiding problems under normal soil conditions. Electronic volume measurement is preferable to the mere observation of the number of pump strokes because of the uncertainty of the pump performance (Piscsalko et al, 2004) and the difficulty of accurately observing auger position at the same time. Only when the soil conditions involve major voids would the volume measurement be insufficient. In that case knowing the pressure at the bottom of the auger would be helpful. Although claims have been made that auger bottom pressure measurement is routinely possible, it is difficult and, for that reason, not commonly done. Automated monitoring of ACIP construction is required by ICE, 2007 and AASHTO's GEC No. 8 (Nichols et al., 2008).

Monitoring of Drilled Shaft and Micropile Construction

Drilled hole inspection and surveying is only of help for large diameter shafts. Condition of the shaft sides and bottom are not easily assessed, particularly for shafts cast under slurry. After the hole has been drilled, concrete pouring or micropiles grouting should be monitored as well as possible. Unfortunately, measuring the concrete volume corresponding to the, usually manually measured, depth is much more complex than for ACIP. Grout volume measurements for micropiles and associated pressure (if employed) is easier measured and encouraged. However, a geology with voids is likely to cause problems.

Discussion of Available QA Methods

The CSL Method

The CSL method utilizes an ultra sonic signal source and receiver and measures concrete wave speed between pairs of inspection tubes which are installed in the shaft as vertically and parallel as possible. The method provides valid results for shafts of virtually any length. The first arrival time (FAT) of the signal in the receiver tube divided by the probe distance (the probes are usually kept on the same level but may also be operated at different levels) is the concrete wave speed. Measurements are usually taken every 2 inches (smaller distances are possible) leading to a vertical defect detection resolution of the same distance. With multiple tubes installed, tests between tube combinations can evaluate the extent of any defect over the cross-section.

The CSL relies on a determination of concrete wave speed as an indicator of concrete quality. Unfortunately, only a very weak correlation exists between concrete wave speed and strength. In fact, the signal may be dissipated and the wave speed reduced by minute water flow induced channels which do not affect the concrete strength. Also, a low wave speed is generally tolerated in one shaft, as long as there is no sudden decrease at a certain depth. For example, the whole shaft may have a 3300 m/s wave speed (4000 m/s is an average value, world wide). However, if the wave speed suddenly decreased to 2600 m/s, i.e. by more than 20%, the concrete quality would be considered flawed. A neighboring shaft may have an average wave speed of 4000 m/s, but if a cross section were discovered with only 3100 m/s wave speed, it also would be considered flawed. Thus evaluation of only relative changes, with no consideration of absolute values, leads often to confusion and disagreement.

Relative signal strength is a second indicator of concrete quality although it is not calculated in the same manner by the various equipment manufacturers and therefore not standardized. An improved defect evaluation which involves both signal strength and wave speed values has recently been published (Likins et al., 2007) and this method is summarized in Table 1.

Complicating CSL evaluation of a potential defect, its existence and location along the shaft length are not the only important aspects, but also the horizontal extent of any defect over the cross section. Quantification of the affected area must either be based on the location of the tube pairs affected or it must be calculated using a tomography approach. The tomography approach may be helpful in extrapolating the normal shaft interior CSL results to the important concrete cover area outside of the reinforcement cage. Whether or not such extrapolations are accurate cannot be stated at this time. Sometimes it may be helpful to repeat the measurements by vertically offsetting the transmitter and receivers, particularly for the perimeter measurements, thereby adding information about the extent and location of a defective area.

Frequently, tube debonding near the top of the shaft is blamed for low and/or delayed signals (if a tube debonds from the concrete it will poorly transmit the ultrasonic signal to the concrete). For that reason, if one and only one tube suggests such a defect, the defect is clearly localized, and that result is often ignored.

Table 1: Proposed quality rating based on relative FAT increase and/or signal energy decrease (Likins et al., 2007)

Evaluation	FAT increase		Energy reduction
(G) Good	0 to 10%	and	< 6 dB
(Q) Questionable	11 to 20%	or	6 to 9 dB
(P/F) Poor/Flaw	21 to 30%	or	9 to 12 dB
(P/D) Poor/Defect	>31%	or	> 12 dB

CSL is standardized in the US by ASTM 6760 and in France by AFNOR, 2000. These standards only state the purpose of the tests, how to conduct them and provide limited guidance as to data interpretation and reporting. In the UK, ICE, 2007 lists CSL as one of the approved integrity test methods. Also in China it is referenced as one of the approved integrity test methods (JGJ 106, 2003).

<u>The LST Method</u>

The LST method requires a light impact from a hand held hammer; this generates a pile top motion which is measured with a sensitive accelerometer or geophone and displayed in the form of velocity versus time after signal amplification and filtering. The hammer mass typically varies between 0.5 and 3 kg; it is normally cushioned with a material like hard nylon to generate impact frequencies below 5000 Hz.

The LST has the advantage that it can be applied to any pile with no need to plan in advance, which allows reasonably random selection of piles for testing. While piles with doubtful installation records should be chosen for testing, selection other random production piles for testing will evaluate the overall pile quality and aid in interpreting unusual records. However, clients as well as testers have to be aware of various factors affecting the measurement as well as the results typically shown in a report.

1. The measured pile top motion may be strongly affected by

    a. Contaminated, loose or otherwise unsound pile top concrete,
    b. Smoothness of impact spot,
    c. The choice of hammer type, weight and cushioning,
    d. The location of the impact and measurement point at the pile top,
    e. The method and strength of motion sensor attachment ,
    f. The quality, i.e. amplification and resolution, of the processing equipment.

2. The processed pile top motion record may be affected by

    a. The number and consistency of individual records averaged,
    b. The digital data processing methods utilized such as magnitude of exponential amplification, curve smoothing, and curve straightening.

3. The interpretation of the record may be affected by

    a. The available analysis methods,
    b. The number of piles tested (establishment of a reference record is a means of establishing acceptable record features for unclear records).

4. The limit of the method is reached

    a. at the depth where the reflected stress wave reaches an undetectable magnitude due to pile internal damping (young concrete) or external (soil) resistance,
    b. below a major change of cross section or concrete quality, crack or splice.

These factors have to be reviewed during the testing and reporting process. Thus, for simplified reporting and better comprehension by the report user, LST records are often classified (Rausche et al., 1992). The following is a simple approach; a more detailed classification exists, for example, in DGGT, 1998.

- A – Acceptable pile; the record is clear of any reflections which would indicate a defect.
- B – Bad pile; the record contains clear indications of a major reflection from a possible defect well above the pile toe.
- C – Continuous pile but with some defect; a signal from the pile toe is apparent, however, an additional defect indication exists. In general, additional analysis requiring quantification of that defect is necessary.
- D – Doubtful records; no toe signal exists or is unidentifiable often because the pile top condition produces vibration signals which mask the reflection from the pile toe.

In summary, LST poses challenges to the testing professional. If the piles are classified as "A", no further work or worry is needed. Any other outcome may require additional testing or analysis work. Peer review by experienced engineers of the data processing and interpretation is strongly recommended. This is only possible if the plotted record contains all processing information (e.g. amplification, filtering, velocity magnitude etc.)

In the US ASTM 5882 describes the minimum requirements for a properly performed test. AFNOR, 2000 similarly states only the purpose of the tests and how to conduct them. This norm also gives information as to data interpretation and reporting. In the UK, ICE, 2007 recommends that all ACIP are subjected to integrity testing and LST is generally the only feasible test for this pile type. The Eurocode only suggests that LST "may be used" if there are uncertainties. Similarly, in Germany, a set of recommendations for pile testing (DGGT, 1998) states that LST may be applied when doubts exist in the quality of a foundation and "to verify the adequacy of the piles. The method may also be employed as a part a quality control program. In the latter case, all piles should be tested. For larger foundations, 10% of all piles should be tested or at least 3 piles of every type."

In China 10 % of driven piles and 20% of drilled shafts require QA by LST. In the areas with bad soil conditions, such as Shanghai and Tianjin, 20% of driven concrete piles and 30 to 40% of drilled shafts have to be tested by LST. Non-redundant (single) pile foundations require 100% LST test.

The Call for Experience

Because of the complexity of the QA methods they are either (a) discredited (e.g. many, particularly contractors who have installed the piles, claim "they do not work") or (b) it is suggested that only experienced professionals should perform this work. As for (a), the methods do work within their limitations, and considerable collaborating evidence of defects has been obtained form coring or excavation. As regards experience, experience comes from bad results due to inexperience and can only be gathered on the job. Unfortunately, experience with LST is in short supply. Also, experience is difficult to measure, for example:

- Years since the tester performed a first test may hide the fact that the tester has not done much in the interim,
- Years of doing data collection alone yields no experience in data interpretation, and, lacking interpretive skills, the tester cannot judge data quality,
- Years of doing testing with improper equipment or methods do not help,
- Experience may be limited to certain subsoil and/or foundation types,
- Experience may lead to a personal (conscious or subconscious) bias

Instead, of either not using QA or only with very experienced LST professionals, it is recommended that initial test programs include these methods so that they can be qualified for a particular site and foundation type. Furthermore, the authors strongly recommend that reports issued by the relatively inexperienced are peer reviewed by more experienced practitioners.

When To Go Beyond Standard QC?

The authors recommend the procedures discussed below under the following scenarios:

- Important buildings and those whose failure cause harm to humans and/or high economic loss (Schools, hospitals, airport terminals, high rise buildings, expensive buildings, long span and major bridges, …),
- Difficult ground conditions (voids, karst, artesian ground water pressures, highly variable soil conditions, …),
- Lack of local experience with a construction method and very long piles or large piles.

Proposed Procedures

Driven Piles

1. Initial test program conducted on production piles (smaller jobs, say with less than 50 piles) or special indicator piles (larger jobs).

    a. Test program may involve static test and always HST. The HST should include a restrike after an appropriate wait time to allow soil strength changes, usually set-up.
    b. If less than 90% of ultimate capacity is achieved, repeat test after driving test pile deeper or driving a new test pile.
    c. Test program develops installation criteria for production piles (usually a minimum blow count, and sometimes coupled with a minimum depth;

sometimes a minimum penetration depth).

d. For solid concrete piles or concrete filled pipes of moderate length (less than 60 diameters or widths), LST may be checked as to suitability for QA of production piles.

2. Production piles are installed and tested on larger jobs:

   a. If LST is qualified perform on 10%; category D tests to be substituted with additional tests. If total number of piles in categories B and C is greater than 20% of the total number of tested piles, the percentage of tested piles should increase. Piles in category B or C should be checked using HST for acceptance.
   b. If LST is not possible, do at least 5% HST; if damage or defects are indicated consider capacity achieved and severity of defect when deciding on acceptance or rejection of the pile tested.

3. If installation conditions of production piles differ significantly from test piles or among each other, perform additional HST on the piles with unusual conditions.

ACIP

1. Initial test program conducted on indicator piles.

   a. Monitor automatically grout volume vs. auger depth; in difficult soil conditions, also monitor auger torque and pressure.
   b. Static test of at least 2 piles or at least 2% of all piles. If tests fail at less than 90% of required ultimate capacity, redesign piles and repeat test. Indicator Piles with a passing static test then become the minimum standard for all subsequent production piles installation (e.g. production piles to have at least the same grout volume installed).
   c. Qualify LST method by performing it on all test piles. Alternatively, qualify SHSL (diameter < 600 mm) or CSL.
   d. Establish the most economical/feasible/qualified QA method: either LST or SHSL or CSL.
   e. For larger jobs, qualify dynamic load test (HST) by correlation testing on static load test piles.

2. For production piles,

   a. If construction problems occur or static tests have low capacities during initial test program, perform QA on 25% of piles; increase amount of testing if problem piles are detected.
   b. If problem piles are discovered in (a.) perform “Additional testing” as described below.
   c. If QC produces unusual volume versus depth records, perform QA on these piles
   d. If no problems occur during initial test program, perform QA on 5% of piles or when unusual QC records are discovered.

      i. If “B-records” or defects covering more than 33% of cross section are found, perform “Additional Testing”.
      ii. If “C-records” or anomalies over more than 33% of the cross section are found then either calculations or “Additional Testing” should be performed to accept or reject pile.
      iii. for each record classified as “D” one additional pile test has to be performed.
      iv. If more than 20% of the test piles fall under categories B or C, all piles on the site have to be tested.

Drilled Shafts

1. Initial test program conducted on indicator shafts with a complete construction log, including concreting times and accurate volumes.

   a. Static test as per specifications.
   b. All test shafts with diameter > 600 mm to be equipped with inspection tubes for CSL; smaller diameter shafts to be equipped with one PVC tube for SHSL.
   c. Attempt to qualify LST method by performing it on all test shafts.
   d. Establish the most economical/ feasible/qualified QA method: either LST or SHSL or CSL.
   e. For larger jobs, qualify dynamic load test (HST) by correlation testing on static

load test shafts; if capacity is too high HST may be qualified for a lower proof test capacity.

3. For production shafts,

   a. Perform QA on first 5 shafts plus on 5% of all production shafts.

      i. If "B-records" or defects covering more than 33% of cross section are found, perform "Additional Testing".
      ii. If "C-records" or anomalies over more than 33% of the cross section are found then either calculations or "Additional Testing" should be performed to accept or reject shaft.

   b. For each shaft in i, ii or for each record classified as "D" perform QA on one additional shaft.

      i. If more than 20% of the test shafts fall under categories B or C, all shafts on the site have to be tested.

Additional Testing

If during QC a possibly or definitely defective pile (or shaft) has been detected, certain action has to be taken to resolve this potentially time and money consuming issue. The following measures may be taken:

- Replace pile; this is often possible where several smaller piles are part of a group, in other words where there is redundancy,
- If problem exists in upper part of pile, excavate, inspect and repair. The depth to which this action can be taken depends on site conditions (ground water level, etc.),
- If potential problem is detected in lower part of pile, calculate load at questionable cross section; if access inspection tubes exist, i.e. if SHSL or CSL was performed, consider grouting heavy reinforcement bars in the inspection tubes as a measure of repair,
- Retest after a waiting time; concrete may gain strength with time providing better and clearer records,
- If LST was performed, drill one or more inspection holes to depth just below potential defect and perform SHSL or CSL,
- If SHSL or CSL was performed core holes and inspect resulting cores past the depth of defect. Wash out and grout zones of defect,
- Perform load test as a check on both integrity of shaft and capacity of pile; if dynamic test is not qualified, perform load test statically.

It is most important that the above process or other measures of testing or repair are well defined prior to the beginning of testing so that no time delays occur because of disputes about the value of the testing or repair method.

Cost of Testing

Obviously, QA and QC are not free and the question often arises as to who bears the cost. Ultimately, all parties involved in a construction project benefit from a quality foundation and as such a certain amount of funds should be available for monitoring and testing. Further, more progressive codes and specification allow reduced global safety factors, or increased resistance factors for LRFD, which reduce overall foundation costs and easily justify the testing costs.

The foregoing discussion also has shown that the methods are not foolproof and that both false assessments and inconclusive results are possible. However, that should be considered a part of the cost of QC and QA. Only in the case where the "additional testing" has confirmed that a serious defect exists should the contractor be burdened with the cost of the associated testing and repair.

Summary

Without addressing details of monitoring and testing which are discussed elsewhere, this paper has attempted to show that both QC and QA have important functions in the deep foundations construction industry. It was also made clear that the available methods have limitations. To avoid false negatives, false positives or inconclusive results, it is therefore suggested to perform monitoring and testing already during a pre-construction test program such that the most effective method can be selected for further work at the project site.

Historically, HST monitoring has been successfully applied to driven piles and automated systems have made ACIP pile monitoring a very thorough procedure while no generally applicable methods exist for drilled shafts. However, even after a thorough monitoring program has been completed, when difficult soils or untried construction methods are encountered, the need exists for additional QA testing of the completed foundation element. QC and QA procedures for the three major pile/shaft types have been proposed. It is suggested that these or similar procedures be adopted to reduce the risk of foundation failure and improve the efficiency of the QC/QA process.

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