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Nondestructive Testing for Quality Assurance & Quality Control of Drilled Shafts at State Departments of Transportation

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16. Abstract
Most State Departments of Transportation (DOTs) routinely use nondestructive testing (NDT) to evaluate the constructed quality of drilled shafts. The primary objective of this study was to determine the state of practice for drilled shaft NDT among State DOTs. This objective was accomplished by conducting a survey of all State DOTs. A literature search was also conducted to determine the past, present, and future direction of NDT of drilled shafts. Common NDT methods and test procedures for drilled shafts were reviewed.

The study indicated that the use of NDT for QA/QC of drilled shaft foundations is a widely accepted practice worldwide. The four techniques commonly used to evaluate the integrity of drilled shaft foundations are sonic echo, impulse response, cross-hole sonic logging, and gamma-gamma logging. Significant findings of interest include a lack of understanding of the interplay of NDT design and mitigation, the prevalence of cross-hole sonic logging, and the reason for selecting the NDT method. Almost all State DOTs indicated that they would be interested in learning more about NDT methods for QA/QC of drilled shafts.

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SUMMARY

Nondestructive testing (NDT) to assess the integrity of pile foundations has existed for more than three decades. In about the last decade however there has been a sharp increase in the use of nondestructive testing for quality assurance and quality control (QA/QC) during drilled shaft construction. Several State departments of transportation (DOTs) have begun using the technology and many others have expressed interest. However, there is a lack of centralized information about which transportation agencies are using NDT, how it is being used, and which methods may be the most appropriate. The primary objective of this study was to determine the application of NDT as a means of QA/QC during drilled shaft construction among State DOTs. This objective was accomplished by conducting a survey of all State DOTs. A literature search was also conducted to determine the past, present, and future direction of NDT of drilled shafts. Common NDT methods and test procedures for drilled shafts were reviewed.

The results of the study indicated that the use of NDT for QA/QC of drilled shaft foundations is a widely accepted practice worldwide. The four common techniques used to evaluate the integrity of drilled shaft foundations are sonic echo, impulse response, cross-hole sonic logging, and gamma-gamma logging. The cross-hole sonic logging method is the most commonly used technique for QA/QC of drilled shafts and is considered by many to be the standard in the industry. It has seen the most technological advances in the last ten years. The sonic echo and impulse response methods are more popular outside the United States and have been relegated in many instances as secondary test methods or for forensic investigations. Gamma-gamma logging is the least popular method but it is sometimes used to complement cross-hole sonic logging when evaluating the integrity of drilled shafts.

The literature indicated that the FHWA and several State DOTs have been involved in many of the published research studies that have evaluated NDT methods for QA/QC of drilled shafts. In that regard, the transportation community seems to be on the forefront of the use of the technology.

The results of the survey indicated that more than three-fourths of the DOTs use NDT as a means of QA/QC for drilled shafts, and by far the most common method used is cross-hole sonic logging. Almost all State DOTs indicated that they would be interested in learning more about NDT methods for QA/QC of drilled shafts.

Almost all of the survey participants indicated that they were satisfied with the effectiveness of the NDT methods for QA/QC of drilled shafts but some expressed concern that an acceptance criteria has not been established or that the results are open to wide interpretation. Only two States perform all of their NDT testing of drilled shafts in-house. About one-half of the State DOTs indicated that the personnel performing/evaluating the tests receive training.

The majority of survey participants indicated that it was the responsibility of the hired consultant or contractor to define a defect or anomaly identified by NDT. The majority of States indicated that there was a procedure in place if a defect or anomaly is identified in a drilled shaft by NDT. The consensus on the course of action was that coring is performed and/or retests are conducted to verify the location and extent of the defect.

INTRODUCTION AND OBJECTIVES

Nondestructive testing (NDT) to assess the integrity of foundation structures has existed for more than 30 years. In the early days the primary use of NDT for pile foundations was forensic analysis. Recently, with the increase in computing power and data processing speeds along with a growing experimental database, there has been an increase in the use of NDT for Quality Assurance/Quality Control (QA/QC) during drilled shaft construction and for assessing in-situ conditions of existing piles.

A primary benefit of this technology for transportation agencies is the quality assurance aspect for new drilled shaft construction. A substantial cost savings can be realized if foundation flaws are detected early when repairs can be made. In 1988, the FHWA initiated a pioneering research study that evaluated several promising NDT techniques for quality control of drilled shafts (Baker et. al, 1989; Baker et. al, 1991). The results of that study led in part to implementation of NDT technology at several state Departments of Transportation (DOTs) as a means of QA/QC during drilled shaft construction.

Despite the use of NDT technology among some state DOTs there is a lack of centralized information about which transportation agencies are using NDT technology, how it is being utilized, and which methods may be the most appropriate. Since significant benefits of the technology can be realized, the primary objective of this study is to identify, document, and present the current application of NDT technology for QA/QC of drilled shafts among transportation agencies, and report on the state-of-the-art and future direction of the NDT industry as it relates to foundation structures.

The objectives of this research were accomplished by the following tasks:

1. Reviewing common NDT methods and test procedures used for QA/QC of drilled shafts.

2. Conducting a literature review of the past, present, and future direction of NDT of drilled shafts.

3. Creating and administering an email survey to determine the state-of-practice of NDT of drilled shafts among State DOTs.

4. Compiling and analyzing the collected survey data.

5. Preparing a final report documenting the findings of the study.

NDT METHODS FOR DRILLED SHAFT CONSTRUCTION

NDT in the context of this report applies to the non-intrusive evaluation of a newly constructed drilled shaft foundation to help identify anomalies, defects, or flaws, which may affect its foundation performance. The primary benefits of non-intrusive testing (versus intrusive testing such as coring) are the determination of the condition of the structure without compromising its structural integrity, the lack of disruption to the structure while tests are being conducted, and the relatively low cost of the evaluations. The advent of smaller and faster computers has aided in the usability of this technology.

As mentioned earlier, NDT to evaluate the integrity of pile foundations has been around for more than three decades. In about the last 15 years however, there has been a sharp increase in the use of NDT as a quality assurance tool for newly constructed drilled shaft foundations, where a substantial cost savings can be realized if foundation flaws are detected early and repairs made. This is especially important for drilled shafts constructed under inconspicuous conditions such as high groundwater table where caving can occur or where slurry is required.

NDT methods to test the integrity of drilled shafts can be categorized as either a *surface reflection* method or as a *direct transmission* method. The surface reflection methods are based on generating compression waves at the shaft head by an impact hammer (source) and measuring the reflected wave signals via a receiver(s) (geophone or accelerometer) located at or near the pile head. The reflected wave signals are then analyzed in the time or frequency domain and interpreted to detect irregularities in the concrete shaft. The direct transmission methods (or downhole methods) are based on generating compression waves or producing radiation emission from a source within a tube either pre-placed or cored into the drilled shaft. The receiver, which measures compression wave arrival time or radiation backscatter, is also located within a pre-placed or cored tube within the shaft. Collected data is typically plotted versus depth or in a graphical manner that permits correlation to shaft length for evaluation in the anomaly identification process. Careful data interpretation by experienced personnel to detect possible defects is critical to the success of any NDT program.

The most popular surface reflection methods for testing newly constructed drilled shaft foundations are sonic echo and impulse response, while the most popular direct transmission methods are sonic logging (single-hole or cross-hole) and gamma-gamma logging. The following paragraphs provide background information of these four methods in terms of general test principles and an overview of some of their strengths and limitations.

SURFACE REFLECTION METHODS

Sonic Echo

The sonic echo (SE) test is conducted by striking the top of the drilled shaft with a hammer to generate a low strain compression wave that travels down the foundation. The stress wave is reflected at a change in impedance, either at an anomaly (change in cross-sectional area or crack) in the shaft or the bottom of the foundation. A receiver located at the shaft head records the reflected wave signal. The wave signal is then processed and analyzed in the time domain. If the compression wave velocity of the material is assumed then the depth of the reflection source can be calculated. Conversely, if the length of the drilled shaft is known and the arrival time of the reflected stress wave is recorded, the compression wave velocity can be calculated. Figure 1 illustrates a typical sonic echo test setup and provides strengths and limitations of the method.

The sonic echo method is generally considered the least expensive NDT method because it requires little to no preparation time. Under the right conditions it can determine pile integrity and length. An inherent limitation with this method is the low amount of energy imparted at the source (shaft head), which quickly dampens as the stress wave travels down and back up the pile shaft. This is further exacerbated in stiff soils. Therefore, the method is limited to a length:diameter ratio of about 30:1 for concrete piles (Davis, 1995; ASCE, 2000). Also the method is highly dependent on interpretation of reflective wave energy and considerable experience is required to locate possible defects. It should be noted that some studies have indicated the surface reflection methods may miss anomalies up to one-half of the shaft cross section.

Impulse Response

The testing principles of the impulse response (IR) method are the same as for the sonic echo test except that a force transducer records the amount of force transmitted to the shaft head upon impact and the data interpretation is completed in the frequency domain. See Figure 1.

The recorded velocity and force signals are converted from the time domain to the frequency domain. The velocity spectrum can then be divided by the force spectrum to obtain a transfer function commonly referred to as the shaft mobility from which the dynamic stiffness can be obtained. The dynamic stiffness is sometimes used to quantify anomalies near the shaft head.

The strengths and limitations of the method are generally the same as with the sonic echo test with the exception that comparative information on the dynamic stiffness of the shaft head can be obtained. The costs of performing the tests are comparable to the sonic echo test. Being a reflective method, soil damping effects limit the depth at which useful information can be obtained.

DIRECT TRANSMISSION METHODS (DOWNHOLE METHODS)

Cross-Hole Sonic Logging

Cross-hole sonic logging (CSL) is a downhole method that requires placement of steel or PVC access tubes around the perimeter of a drilled shaft. Water (or similar fluid) must be used as a couplant to transmit the compression waves between the source and tube. Likewise, the tube must be in good contact with the surrounding concrete to transmit the signal. It is for this reason that steel tubes are generally preferred over PVC tubes. PVC tubes tend to debond or shrink away from the concrete as the shaft concrete cools producing a gap that prevents proper transmission of the CSL signals. The tubes are normally installed prior to concrete placement but can also be cored and installed into existing piles. A transmitter (source) that emits an ultrasonic pulse is lowered to the bottom of one tube while a receiver is lowered to the bottom of another tube. A typical test set-up is shown on Figure 2 along with the strengths and limitations of the method.

A recording unit measures the time it takes for the pulse to pass through the concrete between the tubes. Tests are repeated as the source and receiver are raised together along the length of the pile. The velocity and power of the signal is used to evaluate the integrity of the concrete between the tubes. The wave velocity is a function of the modulus and density of the concrete. Longer travel times correspond to slower wave speeds that indicate irregularities of the concrete between the tubes. A complete loss of wave signal indicates a major defect in the concrete. By vertically offsetting the transmitter and receiver as they are raised, it is possible to triangulate and better map the location of a defect. Alternatively, the data can be processed such that a three-dimensional visualization of the shaft can be obtained. This is commonly referred to as tomography and is similar in principle to imaging obtained by a CAT-scan or MRI.

A primary advantage of CSL is that it is not restricted by foundation depth like the reflection methods. Also, several defects within the same shaft can be identified which may not be possible with the reflective methods. High quality data allowing defect size and location can be obtained. The primary disadvantage is that access tubes must be installed prior to concrete placement, or for existing piles, coreholes must be drilled into the foundation. The relative cost is about 3 to 6 times the SE/IR methods (ASCE, 2000). Another disadvantage is that there is a significant amount of data interpretation needed to generate the plots typically used to identify anomalies, which introduces additional subjectivity confronted by the data analyst.

A variation of the cross-hole method is the single-hole method (SSL), whereby the source and receiver are positioned in the same access tube (usually on the same probe). The primary advantage of this setup is that it provides a degree of vertical resolution for locating and assessing a defect while requiring only one access tube. This method is generally more applicable to smaller diameter shafts (less than about 3 feet) where installation of multiple access tubes is not possible or warranted (Brettmann and Frank, 1996).

Gamma-Gamma Logging

Gamma-gamma logging (GGL), like cross-hole sonic logging, also requires pre-placement of access tubes around the perimeter of the drilled shaft. A gamma radiation source and receiver are lowered into the same tube. The source and receiver are housed in the same cylindrical probe. The intensity of the reflected radiation measured by the receiver, or “backscatter,” is recorded as the probe is withdrawn from the access tube. The principle of operation is similar to nuclear density devices used in earthwork inspection. A typical test setup is illustrated on Figure 3 along with the strengths and limitations of the method.

The intensity of the backscatter is related to the density of the material (concrete) surrounding the tube within a radius of about three to four inches from the center of the tube. Denser concrete surrounding the tube will absorb more radiation and result in less backscatter measured by the receiver. Conversely, less dense concrete or foreign inclusions will allow more radiation to be detected by the receiver. Variations of backscatter intensity therefore indicate variations in concrete density. The density of the access tube must be less than the concrete or else backscatter from the tube will obscure the results. Normally, PVC piping is used for the access tubes. The test is conducted in a dry tube.

Unlike CSL, debonding does not impact the gamma-gamma test and data collection. However, tube placement is critical. Tubes must be placed at least three inches clear of the edge of the shaft. The access tubes may be placed on the outside of the rebar cage in drilled shafts with six inches or more of cover. In this configuration however, care must be exercised so that the tubes are not damaged during installation.

Homogeneity of the shaft concrete density and not actual density values is typically of interest. However, if concrete density values are desired, the backscatter values must be converted to an equivalent concrete density through a calibration factor. This calibration factor may be obtained by performing gamma-gamma tests in a series of controlled test blocks with a known density.

The results are usually plotted as variation of bulk density versus shaft depth. Since the concrete should be of uniform density, abrupt changes in density indicate anomalies in the shaft. Caltrans has a process to identify anomalies in the material surrounding the inspection tubes. They deem an anomaly to exist where the bulk density readings are less than three standard deviations from the mean bulk density (Liebich, 2002; Speer, 1995).

The advantages of gamma-gamma logging are similar to the cross-hole sonic logging method with the exception that the quality of the concrete outside the reinforcement cage, where construction related defects often occur, can be evaluated. However, only the concrete within about three inches of the probe is investigated, much of the concrete cross section is not investigated. An additional disadvantage is the certification and licensing requirements associated with storage and transportation of a radioactive source. These requirements are virtually identical to the soil nuclear density gauges commonly used on transportation construction projects. The cost of the test tends to be slightly more than the cross-hole sonic logging method for small diameter shafts. However, gamma-gamma logging is more economical for large diameter piles where the number of tube combinations increase. The test is also highly repeatable and debonding of the tube from the concrete does not affect the test accuracy (Liebich, 2002).

LITERATURE REVIEW

A comprehensive review of the technical literature on the use of NDT for pile foundations was performed. The articles were obtained by searching DOT databases and by searching scientific and engineering databases. A total of 96 references were collected and reviewed as a part of this literature search. Of those, 35 references were used in preparation of this report and are listed in the reference section. Additional information about the literature review methodology may be found in the Appendix. The following paragraphs summarize the literature search by reviewing the past, present, and future trends of NDT related to drilled shaft construction.

HISTORICAL PERSPECTIVE

The origins of NDT methods for pile foundations were developed in Europe and the Middle East beginning in the 1960s. Cross-hole sonic logging (CSL), or cross-hole acoustic method as it was originally called, was first used in France in 1967. It was first used in the United States in 1986 and has been popular as an inspection technique for large diameter drilled shafts (ASCE, 2000). The origins of sonic echo (SE) and impulse response (IR) testing can be traced back to Holland and France, respectively, during the 1960s and 1970s (ASCE, 2000, Davis and Hertlein, 1991; Davis, 1995). The SE method was first used in the United States in 1972 (ASCE, 2000). The British were among the first to apply multiple NDT methods for quality control of drilled shafts (Davis and Hertlein, 1991). Gamma-gamma logging (GGL) was developed as a means of well logging in oil fields but adapted to drilled shaft construction in Israel in about 1975 (ASCE, 2000). It has been the primary acceptance test method for drilled shafts at Caltrans since 1991 (ASCE, 2000; Davis and Hertlein, 1994; Liebich, 2002).

The use of NDT methods for pile foundations appears to be and has been a widely accepted practice in many countries outside the United States for some 20 to 25 years. For example, 80 percent or more of drilled shafts in England are verified through NDT, while in France an increase in working stress for the pile foundation is allowed if at least 20 percent of the shafts show satisfactory NDT results (Hertlein, 1992). The use of NDT methods for deep foundations in Asian countries also dates back to the late 1970s (Robertson, 1982; Tijou, 1984).

In the United States, NDT for quality assurance of drilled shafts was uncommon until the mid 1980s when the use of reflective methods (SE/IR) was used almost exclusively (Haramy and Mekic-Stall, 2000; Olson and Auoad, 1998). Pioneering research was initiated by the FHWA in 1988 to investigate various NDT methods to evaluate defect detection in drilled shafts. Three class-A prediction studies have been performed since then by the FHWA. In the first study, various NDT methods were conducted on eleven drilled shafts constructed at two Caltrans sites in Northern California (Baker et. al, 1991). The second later study was performed on nine drilled shafts constructed at the National Geotechnical Experiment Site at Texas A&M University (Baker et. al, 1993; Likins et al., 1993). The results of these two studies indicated that surface reflection methods (SE and IR) could not reliably detect defects smaller than 50 percent of the shaft cross sectional area, whereas direct transmission methods (CSL and GGL) could detect multiple defects and small inclusions down to 12 percent of the shaft cross sectional area.

The third more recent study was conducted at the National Geotechnical Experimentation Site at the University of Massachusetts-Amherst (Iskander et al., 2001). Surface reflection (SE and IR) and direct transmission methods (CSL/SSL and GGL) were performed on six drilled shafts to detect planned and unplanned defects. The results of the blind prediction study indicated that both surface reflection and direct transmission methods could identify defects down to 10 percent or less of the shaft cross sectional area, with the surface reflection methods identifying some defects as small as 6 percent of the shaft cross sectional area. The study further indicates that both methods are heavily dependent on equipment and operator skill and false positives were reported. The results of these three studies indicate that the sophistication, accuracy, and level of detail of defect detection have improved over the years.

Several other case studies of the application of NDT methods for drilled shafts have been reported in the literature (e.g. Abar, 1994; Branagan et al., 2000; Brettmann et al., 1996; Briaud et al., 2002; Chernauskas and Paikowsky, 1999; Chernauskas and Paikowsky, 2000; Christopher et al., 1989; Davis and Hertlein, 1994; Davis, 1995; Finno and Chao, 2000; Finno et al., 2002; Haramy and Mekic-Stall, 2000; Olson et al., 1994; Speer, 1995). NDT consultants advocating their methods have authored many of these case studies. The FHWA and various State DOTs have been involved in a majority of the case study publications.

PRESENT DAY APPLICATIONS

The most reported NDT method for drilled shafts found in the literature is the CSL technique. It is generally considered the standard test method for evaluating the integrity of drilled shafts. The CSL method has seen rapid technological improvement within about the last ten years as evidenced by the increasing use of more advanced data acquisition and software systems such as the PISA system (Chernauskas and Paikowsky, 2000), and sophisticated imaging methods such as tomographic imaging (Hanna et al., 2000; Haramy and Mekic-Stall, 2000; Mekic-Stall, et al., 2002).

The second most reported NDT method in the literature is the SE and IR techniques. The method seems to be popular in Europe with more limited use in the United States. With the evolution of CSL and GGL, the SE/IR methods are being used more as secondary test methods or for forensic investigations. Important recent contributions to data analysis and interpretation techniques for the sonic echo and impulse response methods have been provided by researchers at Northwestern University (Finno and Gassman, 1998; Finno and Gassman, 2000).

The least reported NDT method in the literature is the gamma-gamma logging technique. It is interesting to note however that gamma-gamma logging for QA/QC of drilled shafts was reported in the earliest literature found (Priess, 1971; Preiss and Caiserman, 1975). Three reviews of the gamma-gamma method, its practical applications, and case studies were reported by Speer (1995), Liebich (2002), and Rucker and Verquer (2002).

FUTURE TRENDS

All NDT methods have benefited from advances in digital electronics, hardware and software improvements, miniaturization, and portability. This has made data acquisition, processing, and display easier and more convenient especially in outdoor environments (Hertlein, 1992; Chernauskas and Paikowsky, 1999; Chernauskas and Paikowsky 2000; Rucker and Verquer, 2002). Reflective tests (SE/IR) have benefited from continued improvement with interpretation methods and automated analysis, which have minimized the subjectiveness in the data interpretation (Davis and Hertlein, 1991). CSL and GGL are distinctly different techniques yet complimentary test methods because they examine different parts of the shaft cross section. The literature indicates that they are often used together successfully in a QA/QC program for drilled shafts.

Cross-hole tomography (a variation of cross-hole sonic logging) is becoming popular because an image of a defect can be visualized by collecting more data from staggered source and receiver locations (Olson and Aouad, 1994). By combining data from cross-hole sonic logging with state-of-the-art tomographic imaging technology, a 3-D image of the shaft interior can be created showing defective zones (Hanna et al., 2000; Haramy and Mekic-Stall, 2000; Mekic-Stall et al., 2002).

DOT SURVEY

METHODS AND FINDINGS

The primary objective of the study was to identify, document, and present the current application of NDT technology for QA/QC of drilled shafts among transportation agencies. A true representation of NDT utilization and application could only be obtained by attempting to report the practices of all 50 state DOTs. It was decided that the most efficient way to collect the desired information was by conducting an *email survey* of personnel familiar with NDT practice at each state DOT. The process was streamlined because the FHWA provided an initial list of contacts knowledgeable of NDT practices at all 50 state DOTs. Each person on the list was initially contacted by telephone to verify that they were qualified to comment on their State DOT practice for NDT of drilled shafts.

The survey questions were written by the author with guidance provided by engineers from the FHWA, Caltrans, and Arizona DOT who are experienced with NDT methods of drilled shafts. The survey underwent several revisions before a version was pre-tested. The finalized survey was emailed to key personnel at all 50 State DOTs beginning on March 4, 2003. The survey target population was personnel familiar with NDT practices at all 50 state DOTs. Therefore, the survey population and sample size was 50. Departments of Transportation in Puerto Rico and the District of Colombia were not included in the study.

The survey questions consisted of two parts. The first part was designed to determine if the State DOT used NDT for drilled shafts and their level of experience. The second part of the survey was aimed at determining specific NDT procedures and how NDT is implemented at their agency. Those who identified themselves as non-users of NDT were asked to stop after part one of the survey, while those who identified themselves as users of NDT were asked to continue with the second part of the survey. Additional information about the survey methodology along with a copy of the complete survey is provided in the Appendix.

Figure 4 identifies the State DOTs who participated in the survey. As shown, 44 out of 50 State DOTs answered the survey, which corresponds to a response rate of 88.0 percent. The figure also illustrates that the geographic distribution of the respondents more or less covers the entire country.

DISCUSSION

Survey Part 1 - The Use of NDT at State DOTs

The questions in part one of the survey were designed to identify the extent of use and experience of NDT of drilled shafts among State DOTs. The results of these questions are shown on the map and bar graphs on Figures 5 through 7 and explained below.

Not unexpectedly, the results indicate that almost all (97.7 percent) of the DOTs surveyed use drilled shafts. Moreover, more than three-fourths (79.5 percent) of the DOTs reported using NDT for QA/QC of drilled shafts. The geographic distribution of those DOTs using NDT is illustrated on Figure 6. When asked if their State used other verification procedures for QA/QC, more than three-fourths (79.1 percent) responded positively. The overwhelming alternative procedure mentioned by the respondents was coring followed by load testing using conventional means or by use of an Osterberg load cell.

A little more than one-third (36.4%) of the respondents indicated that their State was “very familiar” with NDT of drilled shafts, while nearly two-thirds indicated that their State was either “somewhat familiar” or “not familiar” at all. Almost all (93.0 percent) of the respondents indicated that their State would be interested in learning more about NDT methods for QA/QC. A couple of States indicated that they were contemplating whether to require its use on more projects.

Survey Part 2 - Implementation and Procedures of NDT at State DOTs

The second part of the survey was aimed at determining specific implementation practices and procedures of NDT for drilled shafts at the State DOTs. Only those who responded that their agency used NDT for drilled shafts participated in this part of the survey. Of the 44 total respondents, 35 participants continued with this part of the survey. The results of the survey questions are shown in the bar graphs on Figures 8 through 11 and explained below.

An overwhelming majority (94.2 percent) of the respondents indicated that CSL was the primary method of NDT their agency uses for drilled shafts. This finding is consistent with the literature that indicates that CSL is the standard test method for integrity testing of drilled shafts. Only one agency indicated that GGL was their primary NDT method while one other agency indicated that SE/IR was their primary test method. Several agencies indicated that they have used or have considered using multiple NDT methods.

It was somewhat surprising that nearly one-half (48.5 percent) responded that familiarity with the NDT method was the main reason why it was selected. It was anticipated that most of the respondents would indicate that selection of the test method is based on design requirements. This demonstrates the need to provide State DOTs with guidance on selecting appropriate NDT methods. Note that nine DOTs (25.7%) indicated a multiple response to this question, which is shown on the bar graph as a separate category.

The vast majority (82.8 percent) of the respondents indicated that the State was satisfied with the effectiveness of the method for QA/QC of drilled shafts, while 14.3 percent were not. Of those who were not satisfied, the common explanation was that a standard or acceptance criteria had not been established or that the results from a nondestructive test are highly subjective and open to interpretation.

Respondents were also asked under what shaft construction conditions do they always perform NDT. A little less than one-half (42.9 percent) responded that all of their drilled shafts constructed under slurry were tested with NDT, while one-third (33.3 percent) indicated that all of their drilled shafts constructed using temporary casing to control caving or groundwater were tested with NDT. Less than one-quarter (17.7 percent) of the respondents indicated that their agency uses NDT for all drilled shafts constructed in dry conditions without the use of temporary casing. More than one-half (60.0 percent) of the States indicated that they do not use a shaft imagery device prior to shaft concrete placement.

The States were also asked to identify personnel who perform the nondestructive tests and what if any training they receive. Figure 10 shows that less than one-half (40.0 percent) are consultants hired by the prime contractor. Only two respondents (5.7 percent) indicated that all of their testing was done in-house. A little less than one-half (45.7 percent) of the respondents indicated that personnel performing/evaluating the tests receive training. Almost the same amount (40.0 percent) indicated that they did not know if the personnel were trained. Most of the respondents indicated that training has historically been provided by outside consultants specializing in NDT, by the FHWA, or by the National Highway Institute. Two of the respondents indicated that training was provided in-house. When asked if the personnel performing/evaluating the tests receive certification, nearly one-half (48.6 percent) indicated that they did not know, while less than one-half (45.7 percent) indicated that they do not.

When asked who is responsible for defining a defect or anomaly identified by NDT, the majority of respondents indicated that it was up to the hired consultant or contractor. Some indicated that it was left up to the State or it was the responsibility of both the hired consultant and the State. The States were also asked what criteria are used to define a defect or anomaly. Most indicated that a possible defect is suspected if there is a delay in wave arrival time or the signal energy is weak. A few cited specific threshold criteria.

An area of concern expressed in the literature is what course of action should be taken if a defect is detected by NDT? According to Figure 11, about three-fourths (74.3 percent) of the survey respondents reported that there was a procedure in place if a defect or anomaly is identified in a drilled shaft. When asked what action is taken if a defect or anomaly is identified the general consensus was that coring is performed and/or retests are conducted (sometimes using other NDT methods) to verify the location and extent of the defect. Based on the results of the coring or retests, a remediation plan is prepared. The remediation methods mentioned include doing nothing if the defect is determined to be insignificant, grouting, or constructing a straddle shaft.

About one-half (51.4 percent) of the respondents indicated that the approximate cost of conducting NDT on a 48-inch diameter shaft that is 50 feet in length (excluding pre-installed tube costs) was greater than $750 per pile, while less than one-quarter (20.0 percent) indicated it would cost between $501 and $750. Those respondents that indicated the cost to be less than $500 per pile were those DOTs who owned their own equipment.

About half of the respondents (45.7 percent) indicated that they have case study results available of the application of NDT for drilled shafts with the majority of them willing to share the information.

CONCLUSIONS

The use of NDT for QA/QC of drilled shaft foundations is a widely accepted practice worldwide. The origins of NDT for drilled shafts can be traced back to the early 1960s and 1970s to Europe and the Middle East. The four common techniques used to evaluate the integrity of drilled shaft foundations are sonic echo (SE), impulse response (IR), cross-hole sonic logging (CSL), and gamma-gamma logging (GGL). The SE and IR methods are considered surface reflection techniques, while the CSL and GGL are direct transmission methods.

According to the literature the CSL method is the most commonly used technique for QA/QC of drilled shafts and is considered by many to be the standard in the industry. The SE and IR methods are more popular outside the United States and have been relegated in many instances as secondary test methods or for forensic investigations. The GGL test method was the first adapted for integrity testing of drilled shafts yet according to the literature sees somewhat limited use today. The CSL and GGL techniques are complementary test methods since they examine different parts of the shaft cross section and are sometimes used together when evaluating the integrity of drilled shafts.

The future of NDT of drilled shafts is moving toward continued advances in digital electronics, hardware and software improvements, miniaturization, and portability. Due to its popularity and promise, the CSL method has seen the most technological advances in the last ten years. A variation of CSL is cross-hole tomography by which a 3-D image of the shaft interior can be created showing defective zones by using state-of-the-art tomographic imaging technology. Better visualization of a defect can aid in determining a course of remediation.

The literature indicates that the FHWA and several State DOTs have been involved in many of the published research studies that have evaluated NDT methods for QA/QC of drilled shafts. In that regard, the transportation community seems to be on the forefront of the use of the technology.

An email survey was conducted in order to determine the state-of-practice of NDT for QA/QC of drilled shafts among State DOTs. The main findings of the survey are summarized below.

- More than three-fourths of the DOTs surveyed use NDT as a means of QA/QC for drilled shafts. By far the most common method used is CSL followed by SE/IR and then GGL. Nearly one-half indicated the NDT method was selected based on familiarity with the test method.

- Nearly two-thirds of the DOTs indicated that they are either somewhat familiar or not familiar with NDT of drilled shafts. Almost all indicated that they would be interested in learning more about NDT methods for QA/QC of drilled shafts.

- Almost all of the survey participants indicated that they were satisfied with the effectiveness of the NDT methods for QA/QC of drilled shafts but some expressed concern that an acceptance criteria has not been established or that the results are open to wide interpretation.

- Less than one-half of the state DOTs are using NDT on all drilled shafts constructed under slurry. Even less DOTs are using NDT on all drilled shafts constructed using temporary casing to control caving or groundwater or constructed in dry conditions without temporary casing.

- Only two States perform all of their NDT testing of drilled shafts in-house with the majority of States leaving the hiring of the NDT consultant up to the prime contractor.

- Nearly one-half of the State DOTs indicated that the personnel performing/evaluating the tests receive training, and a little less than one-half responded that the personnel do not receive some form of certification.

- The majority of respondents indicated that it was the responsibility of the hired consultant or contractor to define a defect or anomaly identified by NDT. Most of the DOTs indicated that the criteria used to define a possible defect or anomaly is a delay in wave arrival time or if the measured signal energy is weak.

- The majority of States indicated that there was a procedure in place if a defect or anomaly is identified in a drilled shaft by NDT. When asked what action is taken if a defect or anomaly is identified the general consensus was that coring is performed and/or retests are conducted (sometimes using other NDT methods) to verify the location and extent of the defect.

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APPENDIX

RESEARCH METHODOLOGY

Literature Review Methodology

Articles from conference proceedings, journals, and academic publications were obtained by utilizing the resources of the Kennedy Library at California State University, Los Angeles. Specifically, information on NDT of pile foundations was collected by researching the library's holdings and conducting a detailed search using the library's numerous technical databases and those available through the Department of Transportation. References not contained within the University's library holdings or not available on-line, were requested through interlibrary loan. A total of 96 articles, which included journals, conference proceedings and academic publications were found and reviewed. Of those, 35 articles were deemed pertinent and used in preparation of this report. They are listed in the reference section.

The databases that were searched were either free or available to the public, or fee-based subscription databases. The free databases used were available through the National Transportation Library (http://ntl.bts.gov) and include TRIS Online, DOTBOT, TRB Research in Progress, and TransStats. Some other useful information was found through Northwestern University's Infrastructure Technology Institute (www.iti.northwestern.edu) and the Federal Highway Administration NDE Validation Center (www.tfhrc.gov/hnr20/nde/home.htm).

The subscription databases were searched through the University's Library webpage and included PHAROS (CSU Libraries), Ei Tech Index, Applied Science & Technology, WebSpirs, ASCE Online Journals, IEEE Xplore, Academic Search Premier (EBSCOHost), General Science Abs, Science Direct, WorldCat (World Library Catalog), PapersFirst, and MELVYL (UC Libraries).

Some of the keywords that were used included: *non-destructive testing, nondestructive testing, non-destructive evaluation, nondestructive evaluation, nondestructive, destructive, NDE, NDT, quality control, quality assurance, QA, QC, QA/QC, pile, deep foundation, drilled shaft, foundation, new foundation,* and *existing foundation*.

State DOT Survey Methodology

An integral part of this study was to identify the state-of-practice of NDT for QA/QC of drilled shafts among DOTs. The steps described below accomplished this objective.

Contact Key Personnel at each State DOT:

One of the initial tasks of this study was to identify key personnel at each DOT who was knowledgeable about the use of NDT at their agency. An initial contact list of state engineers at each DOT was provided by the FHWA. Each of these engineers was called to verify their knowledge of NDT practice at their State. At a minimum, these contacts referred us to knowledgeable personnel at their agency. Additional contacts not on the FHWA list were found by searching each State DOTs official website. Finally, the two lists were compiled into one complete alphabetized list showing State DOT, name, title, address, email, and telephone number.

Create and Administer Email Survey:

The email survey was designed using Microsoft Word forms template and was write-protected. It was created by the author with assistance from engineers from FHWA, Caltrans, and Arizona DOT who are knowledgeable about the use of NDT of drilled shafts. The survey underwent five revisions before being pre-tested to verify usability. Suggestions and comments from CSULA Analytical Studies Office were also incorporated.

The survey is broken down into three parts: Participant Information; NDT Usage and; NDT Procedures and Implementation. The survey questions were multiple choice, numeric open-ended, and text open-ended. A copy of the survey is shown at the end of this appendix.

The finalized survey was sent to personnel at each DOT identified previously beginning on March 4, 2003. Follow-up emails were sent to all non-respondents on March 19 and again on April 7. A total of 44 responses were received, which corresponds to a response rate of 88.0 percent.

Compile and Analyze Survey Data:

The results of the returned surveys were tallied and written comments were compiled into a single list. Bar graphs were created to display the tallied results. Bar graphs of those questions that provided useful information are presented in this report. The written comments were summarized and generalizations compiled.

The survey target population was personnel familiar with NDT practices at all 50 state DOTs. Therefore, the survey population and sample size was 50. Survey research methods suggest that for small populations (less than 100,000) an adequate sample to provide sufficient accuracy is 50 percent of the population size (Rea and Parker, 1997). Since the response rate was 88 percent of the population size, the findings and observations made in this report are believed to be representative of the DOTs across the country.

U.S. Department of Transportation Federal Highway Administration

Email Survey

The Use of Non-Destructive Testing for QA/QC Of Drilled Shafts at State Departments of Transportation

PURPOSE:

The purpose of this survey is to determine the state-of-practice of Non-Destructive Testing (NDT) for Quality Assurance/Quality Control of drilled shafts at State DOTs. It is being sponsored by the FHWA and administered by California State University, Los Angeles.

The study was initiated by requests from several State DOTs to learn more about the use of NDT methods to monitor the construction of drilled shafts. Several States have been using the technology for years while others are looking to use the technology in the near future. The FHWA is looking to determine the use of this technology and this survey is one means used to achieve this goal.

The survey is being administered to all State DOTs. Your answers will remain confidential. They will be combined with others to establish overall practices. Your participation will provide valuable information that will guide future FHWA efforts.

INSTRUCTIONS:

- Please answer the following questions related to the use of NDT at your agency. Use your tab key or mouse to scroll through the questions. Provide answers in the shaded areas.
- The survey will take 15 to 20 minutes or less.
- You may forward the survey to someone more appropriate within your agency.
- When finished, please email completed surveys to **mtufenk@calstatela.edu**. Surveys may also be mailed to: California State University, Los Angeles, Civil Engineering Department, 5151 State University Drive, Los Angeles, CA 90032; Attn. Mark Tufenkjian.
- Any questions regarding the survey may be directed to the above email address or by calling (323) 343-4434.

Thanks for your participation!

PARTICIPANT INFORMATION *

<table>
<tr><td>Name:</td><td colspan="4">Organization:</td></tr>
<tr><td rowspan="2">Title:</td><td colspan="4">Address</td></tr>
<tr><td>Street:</td><td>City</td><td>State</td><td>Zip</td></tr>
<tr><td>Telephone:</td><td colspan="4">Email:</td></tr>
</table>

* This information is optional but recommended. It will remain **confidential** and is only needed in case follow-up information is necessary.

NDT USAGE

1. Does the State utilize drilled shafts for its projects?

☐ Yes

☐ No. Why not?

☐ Don't Know

2. Does the State use Non-Destructive Testing (NDT) for Quality Assurance/Quality Control (QA/QC) of drilled shafts?

☐ Yes

☐ No

☐ Don't Know

3. Does the State use other verification procedures (e.g. pile load test, coring, etc.) for QA/QC of drilled shafts?

☐ Yes. Please specify methods:

☐ No

☐ Don't Know

4. What best describes your State's experience with NDT of drilled shafts?

☐ Very Familiar (Routinely use NDT methods)

☐ Somewhat Familiar (Occasionally use NDT methods)

☐ Not Familiar (Never use NDT methods)

☐ Don't Know

5. Would your State be interested in learning more about NDT methods for QA/QC of drilled shafts?

☐ Yes

☐ No

☐ Don't Know

IS THE SURVEY OVER?

Look at your answer to question number 2. If you answered:

"Yes"	**Please continue with the survey.**
"No"	**You are finished with the survey.**
"Don't Know"	**You are finished with the survey. However, if possible please forward the survey to someone more appropriate within your agency.**

NDT PROCEDURES & IMPLEMENTATION

6. Which method(s) of NDT does your agency use for drilled shafts (check all that apply)?

☐ Cross-Hole Sonic Logging

☐ Gamma-Gamma Logging

☐ Impact Echo / Impulse Response

☐ Other. Please specify:

7. Is your State satisfied with the effectiveness of the method(s) for QA/QC of drilled shafts?

☐ Yes

☐ No. Please explain why for each method checked in question number 6:

☐ Don't Know

8. Which is the <u>primary</u> method of NDT your agency uses for drilled shafts?

☐ Cross-Hole Sonic Logging

☐ Gamma-Gamma Logging

☐ Impact Echo / Impulse Response

☐ Other. Please specify:

9. Which is the main reason why your State selected the primary NDT method?

☐ Availability of personnel

☐ Design requirements

☐ Familiarity with the method selected

☐ Consultant recommendation

☐ Contractor recommendation

☐ Don't Know

☐ Other. Please explain:

10. Which other method(s) of NDT has your agency considered but not selected for QA/QC of drilled shafts?

- ☐ Cross-Hole Sonic Logging
- ☐ Gamma-Gamma Logging
- ☐ Impact Echo / Impulse Response
- ☐ None
- ☐ Other. Please specify:

11. Which shaft imagery device(s) does your State use prior to concrete placement?

- ☐ Shaft Inspection Device (SID)
- ☐ Caliper/Sonic Logging
- ☐ None
- ☐ Other. Please specify:

12. Do the shaft design requirements affect the selection of the type of NDT for pile acceptance?

- ☐ Yes. Please explain how:
- ☐ No
- ☐ Don't Know

13. Does your agency utilize NDT on 100% of drilled shafts constructed under slurry?

- ☐ Yes
- ☐ No. Please estimate the percentage that it does: %
- ☐ Don't Know

14. Does your agency utilize NDT on 100% of drilled shafts constructed using temporary casing to control caving or groundwater?

- ☐ Yes
- ☐ No. Please estimate the percentage that it does: %
- ☐ Don't Know

15. Does your agency utilize NDT on 100% of drilled shafts constructed in dry conditions without temporary casing?

☐ Yes

☐ No. Please estimate the percentage that it does: %

☐ Don't Know

16. Who performs the NDT on drilled shafts?

☐ In-house Specialist

☐ Consultant hired by the State

☐ Consultant hired by the Design Consultant

☐ Consultant hired by the Prime Contractor

☐ Consultant hired by the Sub-Contractor

☐ Don't Know

☐ Other. Please specify:

17. If your agency has its own equipment, what equipment is used to perform the tests?

Explain:

18. How is the equipment calibrated? (If a specification or operating standard is used, please reference.)

Explain:

19. Approximately how much does it cost to conduct a test per pile (excluding pre-installed tube costs, if applicable) assuming a 48-inch diameter shaft that is 50 feet in length?

☐ Less than $250

☐ $251 to $500

☐ $501 to $750

☐ More than $750

☐ Don't Know

20. What criteria are used to define a defect or anomaly?

Explain:

21. Who is responsible for defining a defect or anomaly?

Explain:

22. Is there a procedure in place if a defect or anomaly is identified in a drilled shaft by NDT?

☐ Yes

☐ No

☐ Don't Know

23. What action is taken if a defect or anomaly is identified in a drilled shaft by NDT?

Explain:

24. Do the personnel performing/evaluating the tests receive training?

☐ Yes. Please specify by whom and the interval of training:

☐ No

☐ Don't Know

25. Do the personnel performing/evaluating the tests receive certification?

☐ Yes. Please specify by whom and explain the certification process:

☐ No

☐ Don't Know

26. Do you have any case study results available of the application of NDT for drilled shafts?

☐ Yes

☐ No

☐ Don't Know

27. **Would you be willing to share this case study information as a part of this study?**

☐ Yes

☐ No

28. **Provide any additional information or clarification of answers below:**

Explain:

END OF SURVEY

TALLY SHEET FOR SURVEY QUESTIONS 1 THROUGH 9

Question	1			2			3			4				5			6				7			8				9						
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	x			x			x			x				x			x				x			x						x				
	x			x			x			x				x			x				x			x										x
	x			x			x			x				x			x		x		x			x				x		x	x			
	x				x			x				x			x																			

TALLY SHEET FOR SURVEY QUESTIONS 10 THROUGH 16

Question	10					11				12			13			14			15			16						
State	CSL	GG	IE/IR	Nne	Oth	SID	C/S	Nne	Oth	Y	N	DK	Y	N	DK	Y	N	DK	Y	N	DK	InSp	ConS	ConDC	ConPC	ConSC	DK	Oth
				x				x			x		x				x			x						x		
				x		x					x				x	x					x				x			
				x			x				x		x			x				x						x		
				x				x			x		x				x			x					x			
			x				x			x			x			x				x		x						
				x				x				x		x			x			x			x					
									x		x			x			x			x					x			
		x				x			x		x			x			x			x		x	x			x		
		x	x					x		x				x			x			x					x			
				x				x		x					x		x			x			x	x	x	x		
				x				x			x			x				x		x					x			
				x		x					x		x			x			x				x					
				x					x		x		x			x				x					x			
	x		x					x			x			x		x				x						x		
		x					x				x			x											x	x		
				x				x			x		x			x				x					x			
				x		x					x		x						x				x		x			
		x					x		x		x			x		x			x							x		
		x	x					x			x			x			x			x					x			
				x				x		x				x			x			x						x		
				x		x			x		x				x		x			x					x			
		x						x		x				x			x			x			x					
		x	x			x					x		x			x			x						x			
		x					x		x	x			x			x				x		x			x			
				x				x			x		x			x			x							x		
				x				x		x				x			x			x			x		x			
				x				x			x			x			x			x			x					
		x	x					x			x		x				x			x			x		x			
								x			x			x			x			x			x					
				x				x			x			x			x			x					x			
				x					x		x		x					x	x						x			
		x						x		x			x				x			x					x			
				x				x			x		x				x			x						x		
			x					x			x			x			x			x					x			
		x	x					x			x			x			x			x		x						

TALLY SHEET FOR SURVEY QUESTIONS 19-27

Question	19					22			24			25			26			27	
State	L250	251-500	501-750	M750	DK	Y	N	DK	Y	N	DK	Y	N	DK	Y	N	DK	Y	N
				x		x			x				x			x			x
				x		x					x			x		x			
			x				x		x				x		x			x	
				x		x					x			x		x			
	x					x			x				x		x			x	
					x	x					x			x		x			x
				x			x				x			x		x			
				x			x		x				x			x			
		x				x					x			x	x			x	
			x				x				x			x	x			x	
				x		x			x			x			x			x	
				x		x					x			x		x			
			x			x			x					x	x			x	
				x		x			x				x			x			x
				x		x					x			x	x			x	
				x		x			x				x		x			x	
		x					x		x					x	x			x	
			x				x			x			x		x			x	
					x	x					x			x			x		
				x			x		x				x			x			
				x		x					x			x			x	x	
				x		x					x			x		x			x
			x			x			x					x		x			
		x				x			x				x		x			x	
				x		x					x			x		x			x
					x	x				x			x			x			x
		x				x				x			x		x			x	
				x		x			x				x		x			x	
			x			x				x			x		x			x	
					x		x				x			x		x			x
					x	x			x			x			x			x	
				x			x				x			x			x	x	
				x		x				x			x			x			
				x		x			x				x		x			x	
			x			x			x				x			x		x	

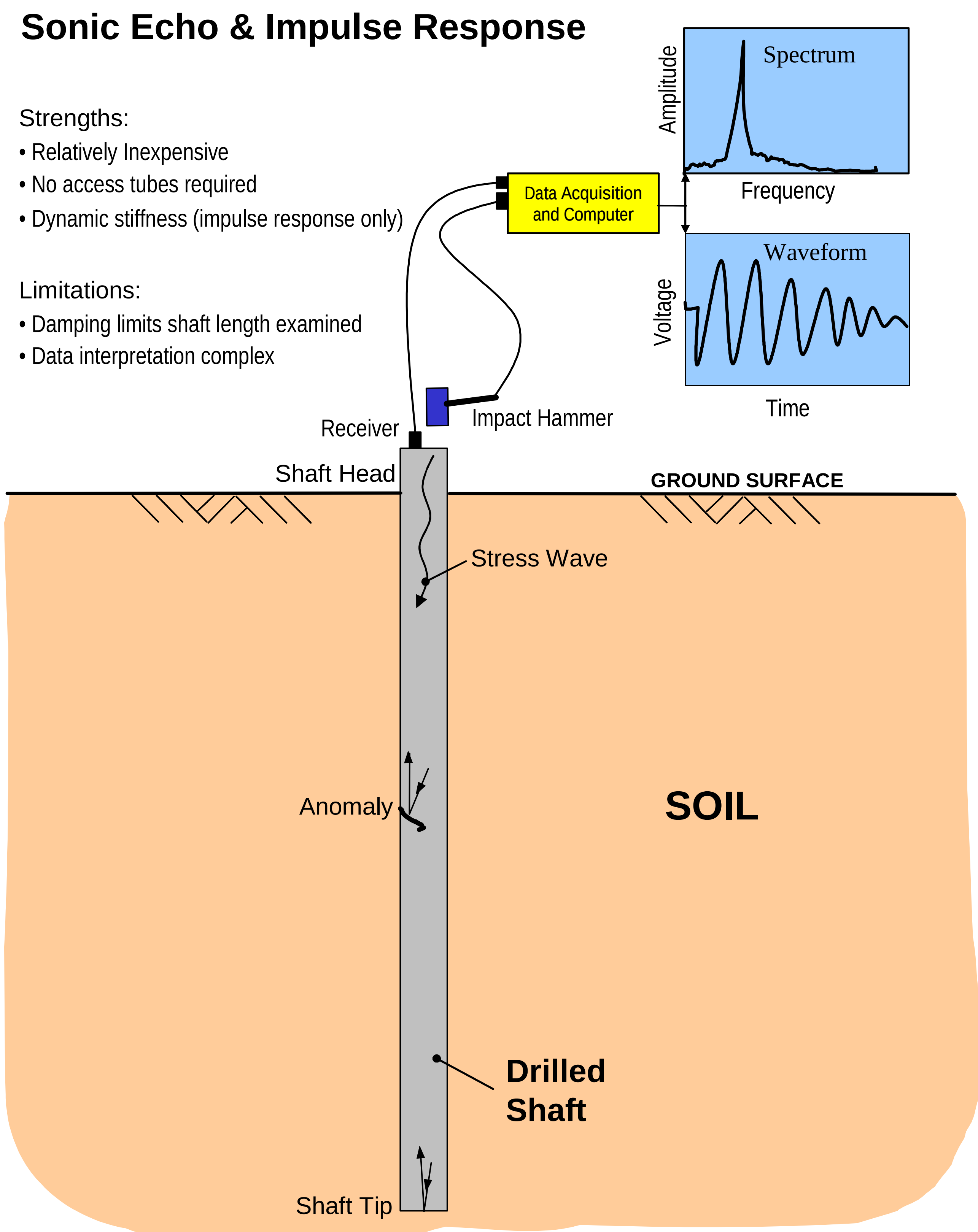


Figure 1. Typical test set-up for sonic echo and impulse response methods.

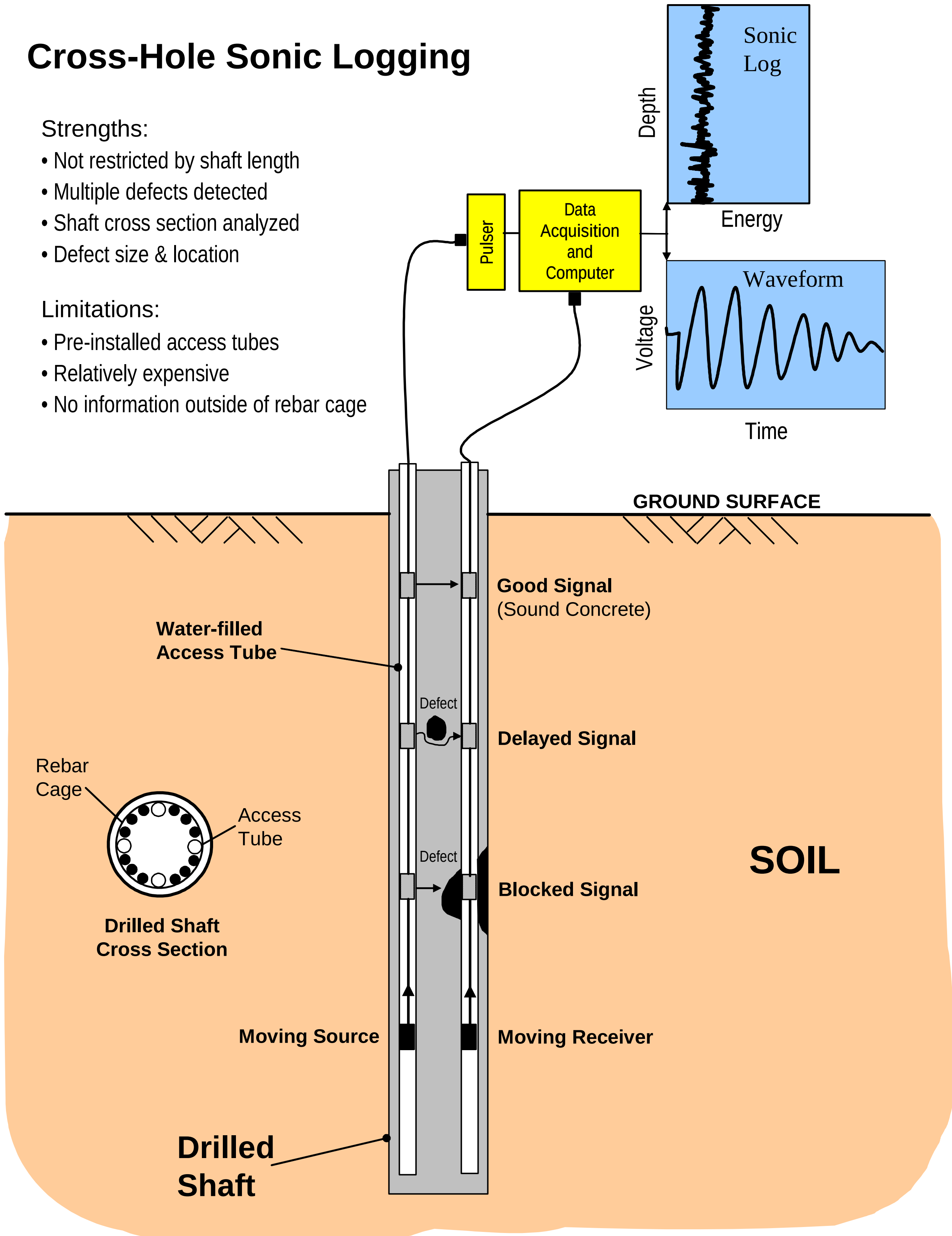


Figure 2. Typical test set-up for cross-hole sonic logging method.

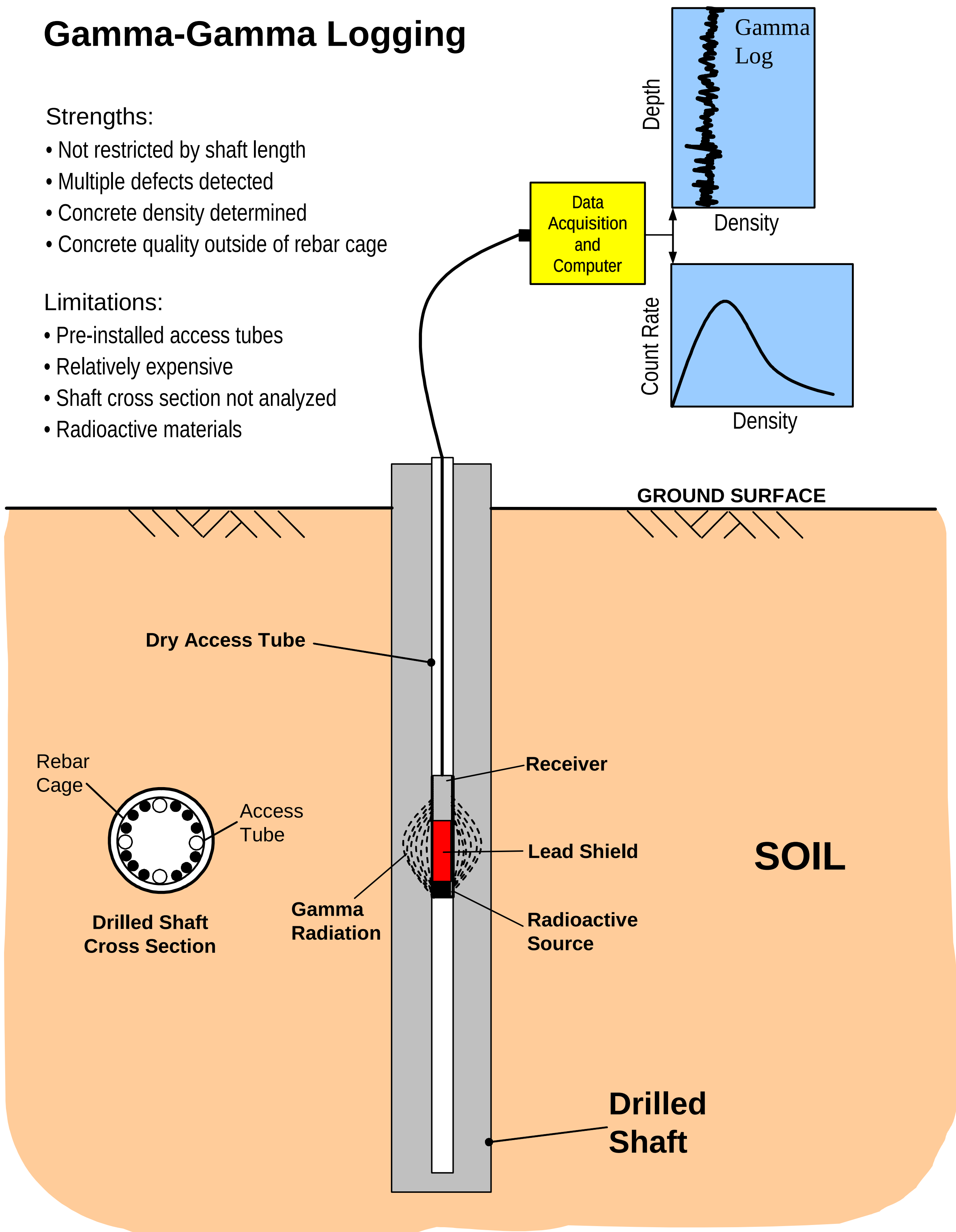


Figure 3. Typical test set-up for gamma-gamma logging method.

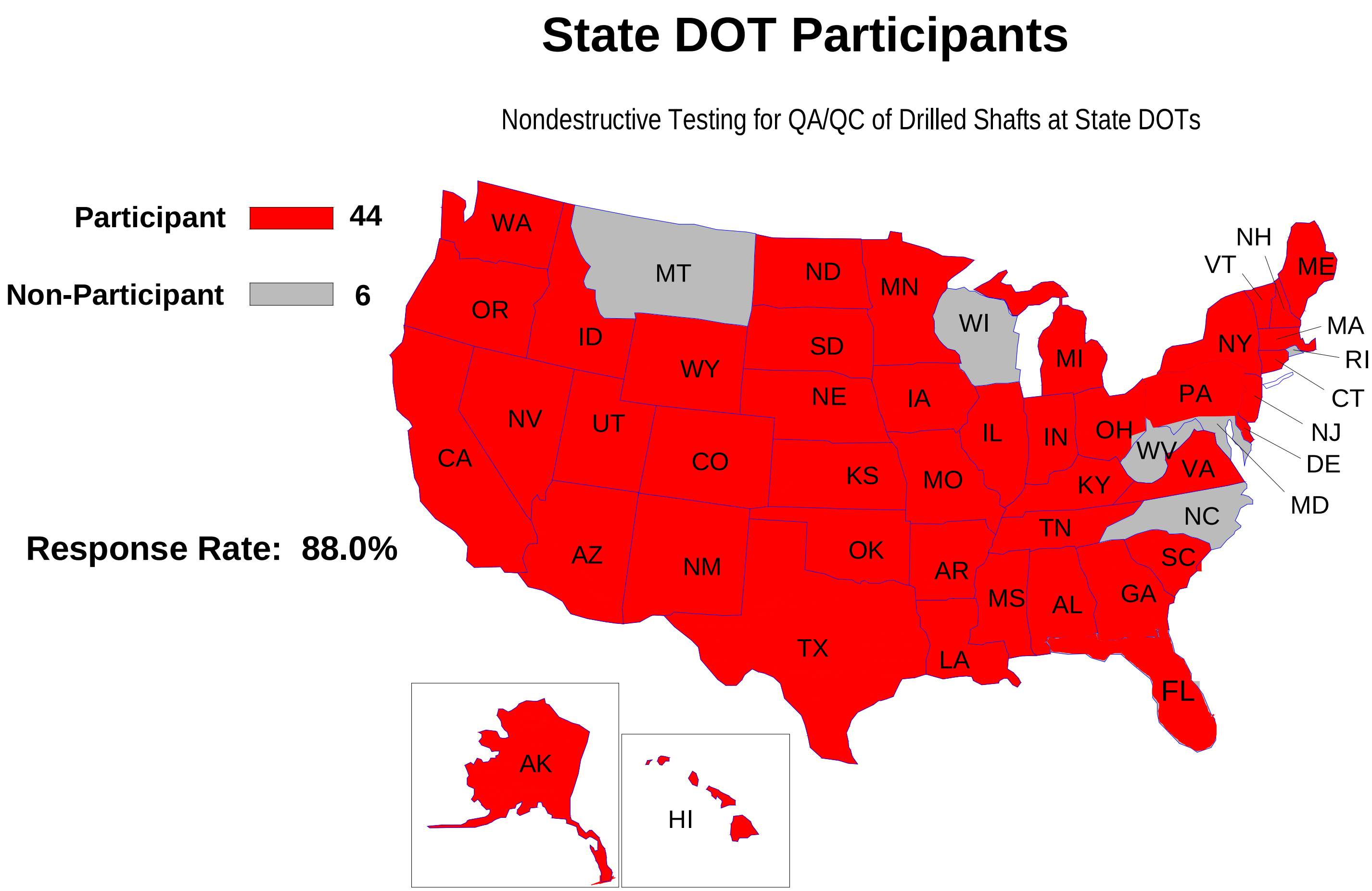
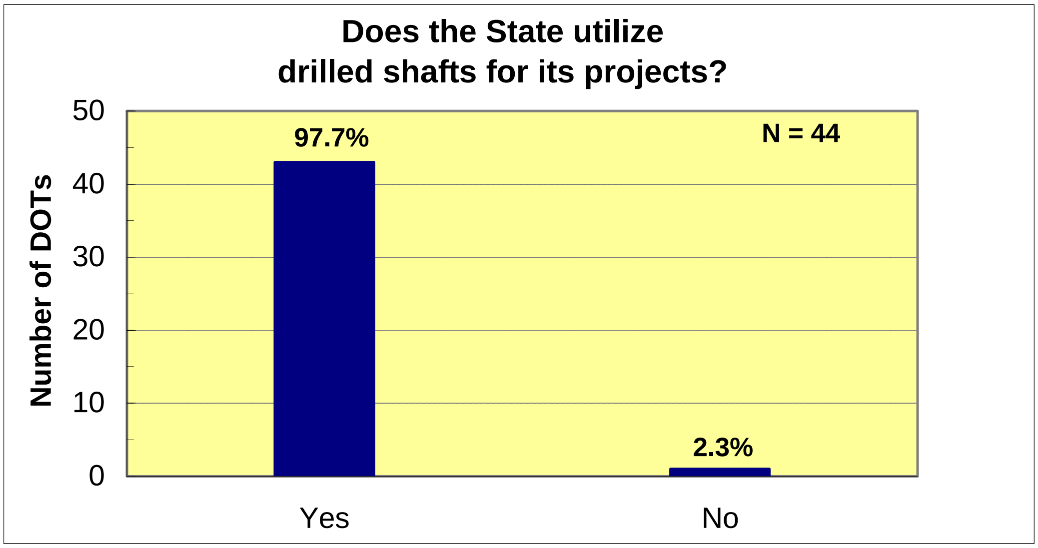


Figure 4. State DOTs who participated in the email survey.



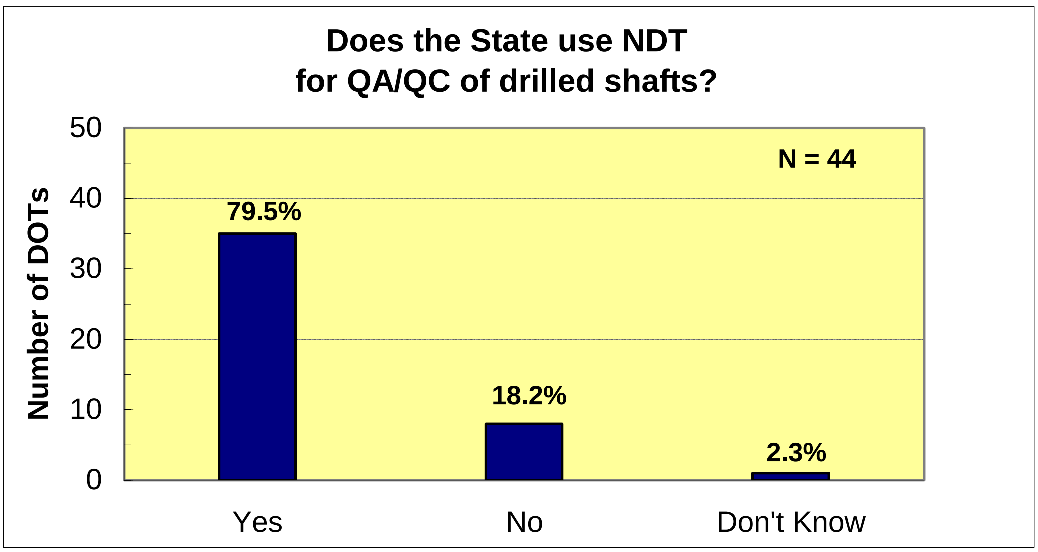


Figure 5. DOT survey results.

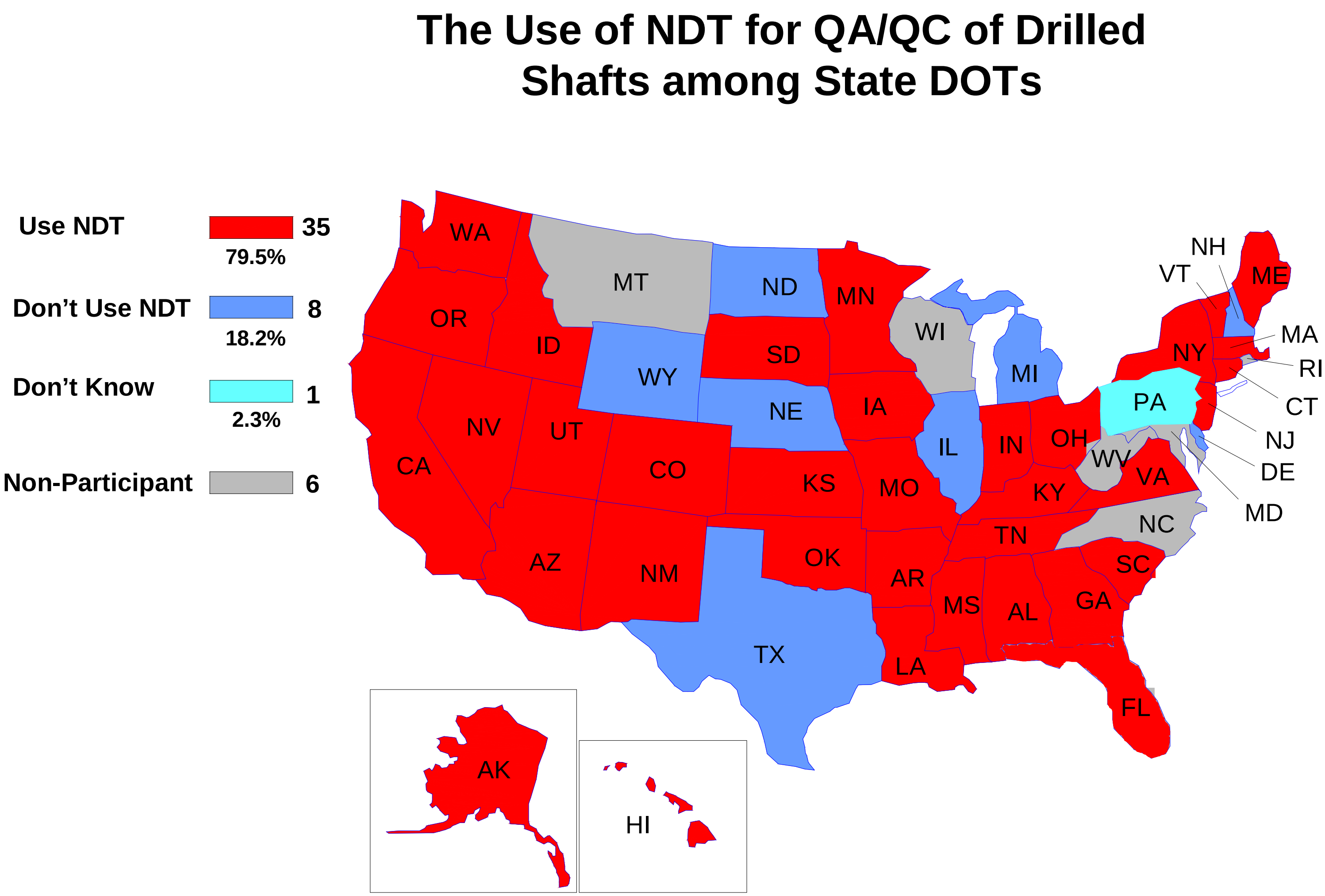
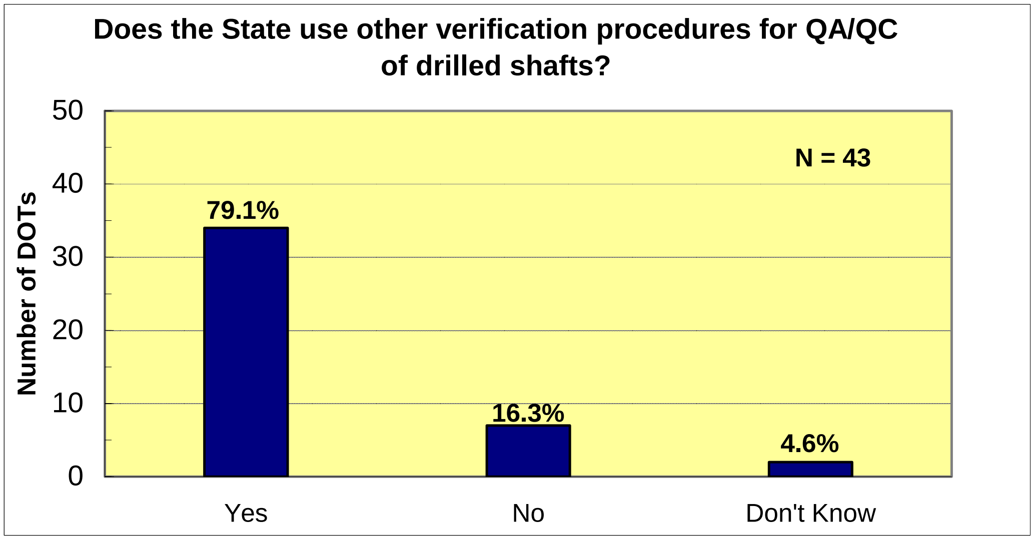
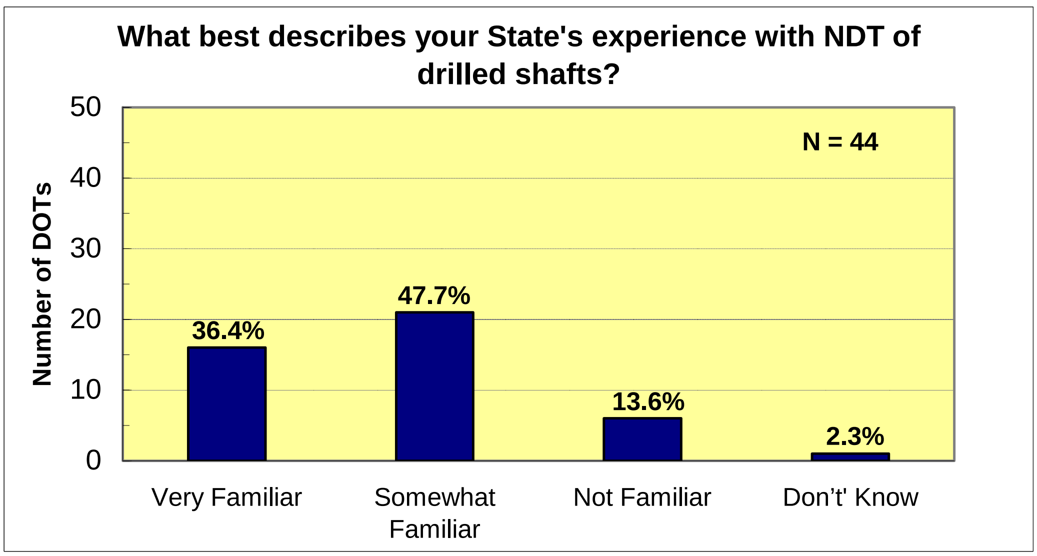


Figure 6. The use of NDT for QA/QC of drilled shafts among State DOTs.





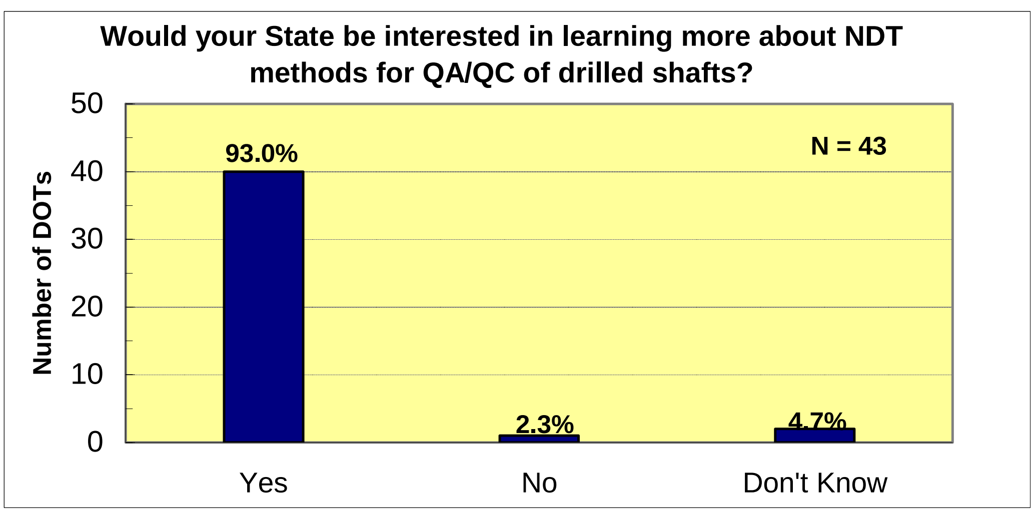
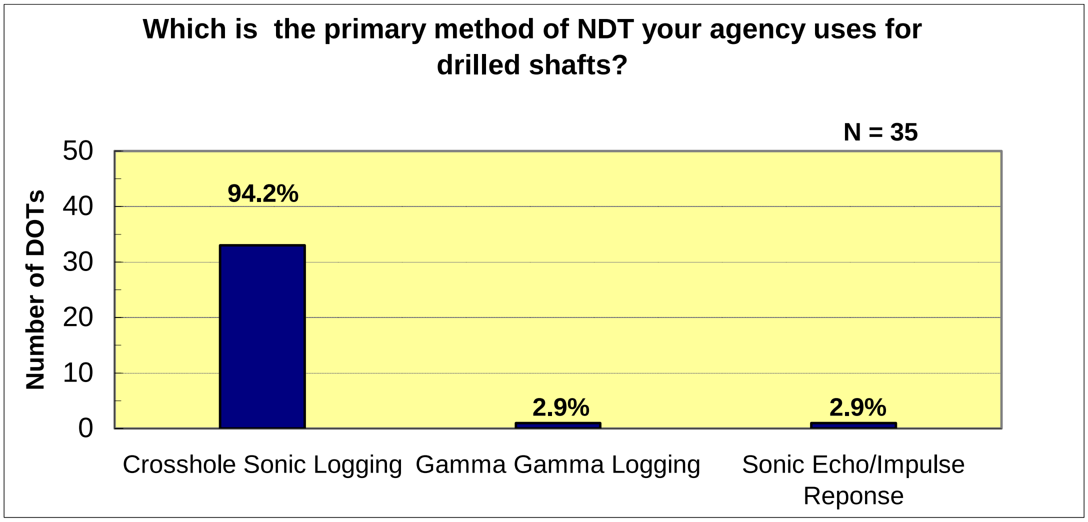
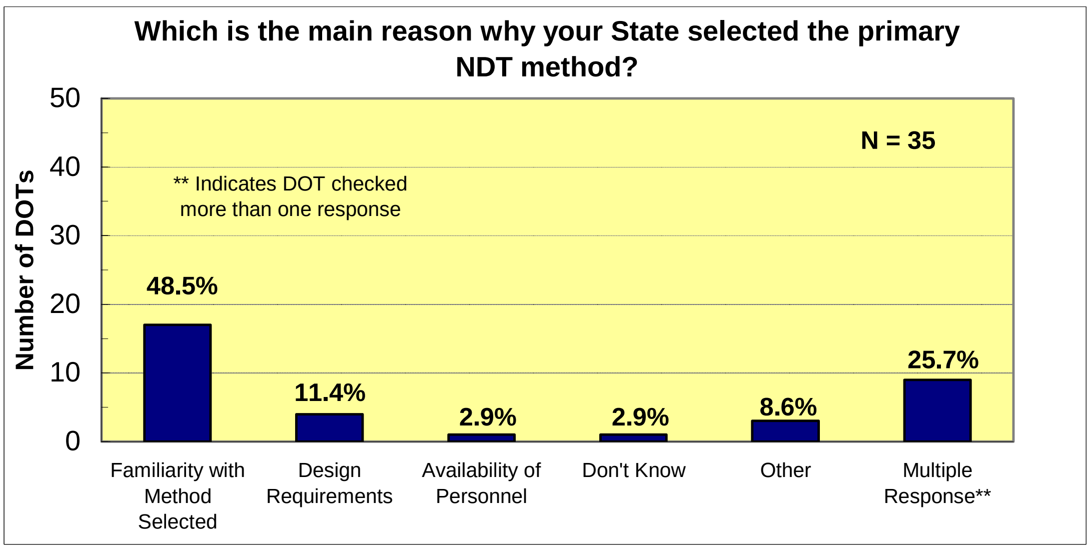


Figure 7. DOT survey results.





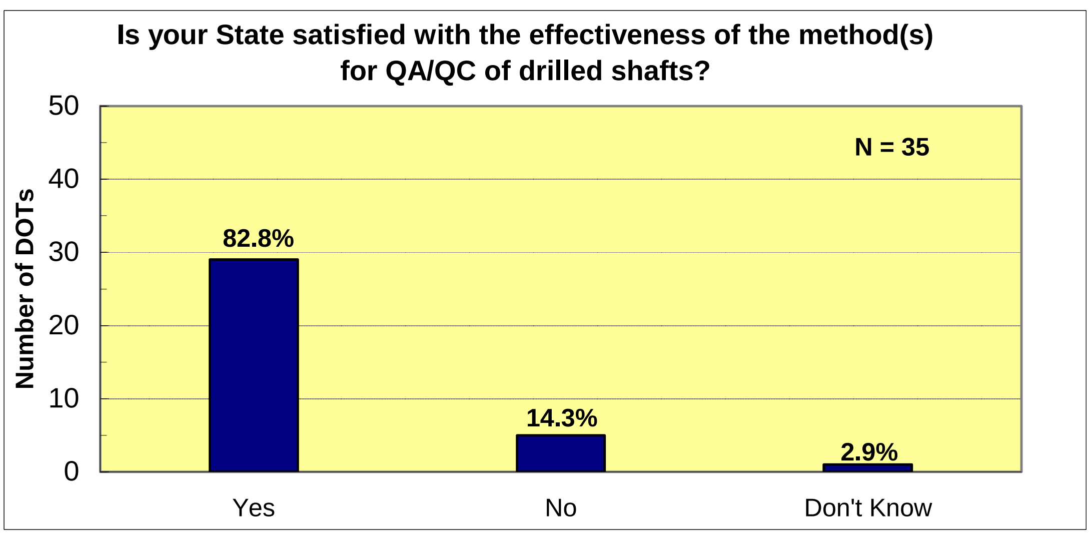


Figure 8. DOT survey results.

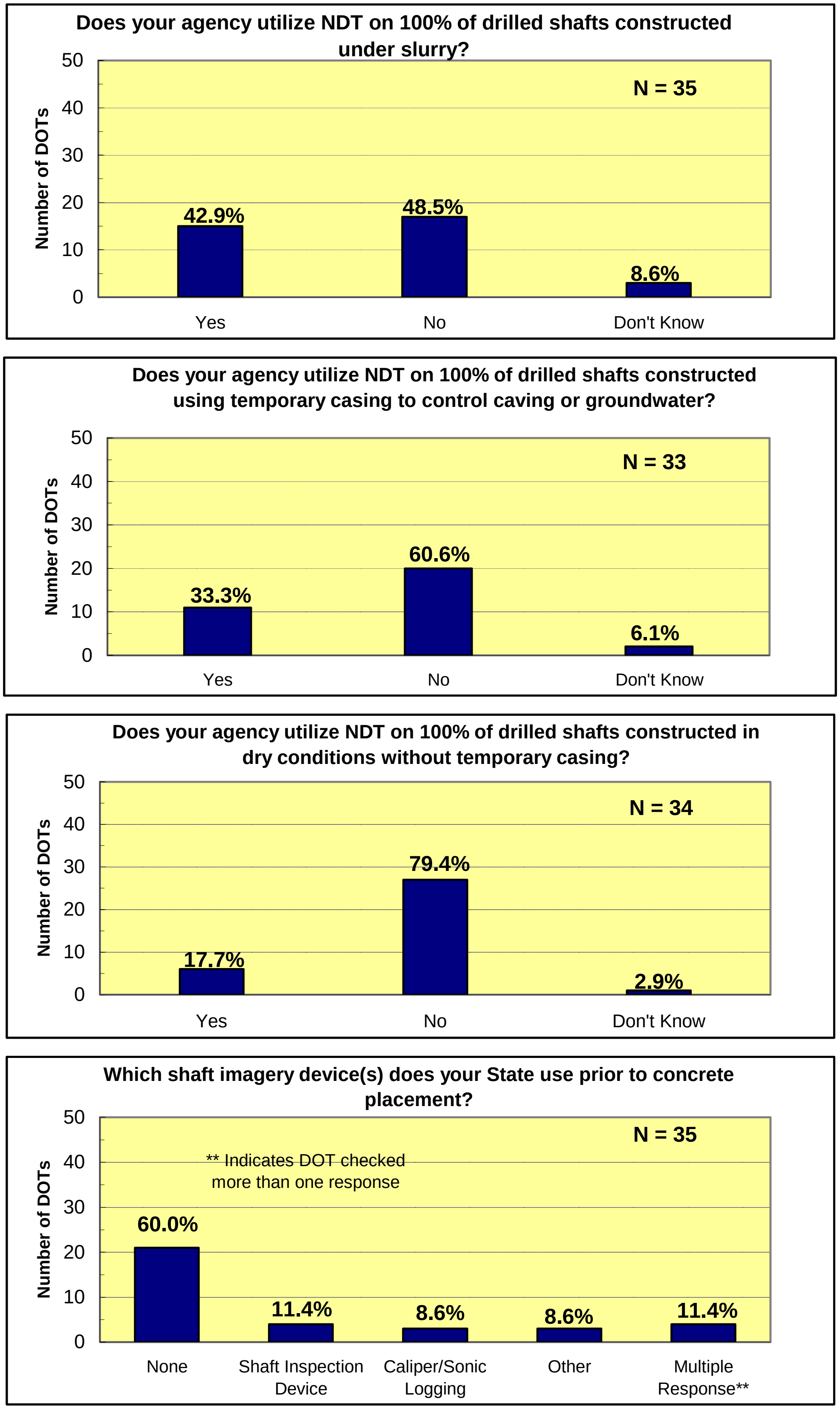


Figure 9. DOT survey results.

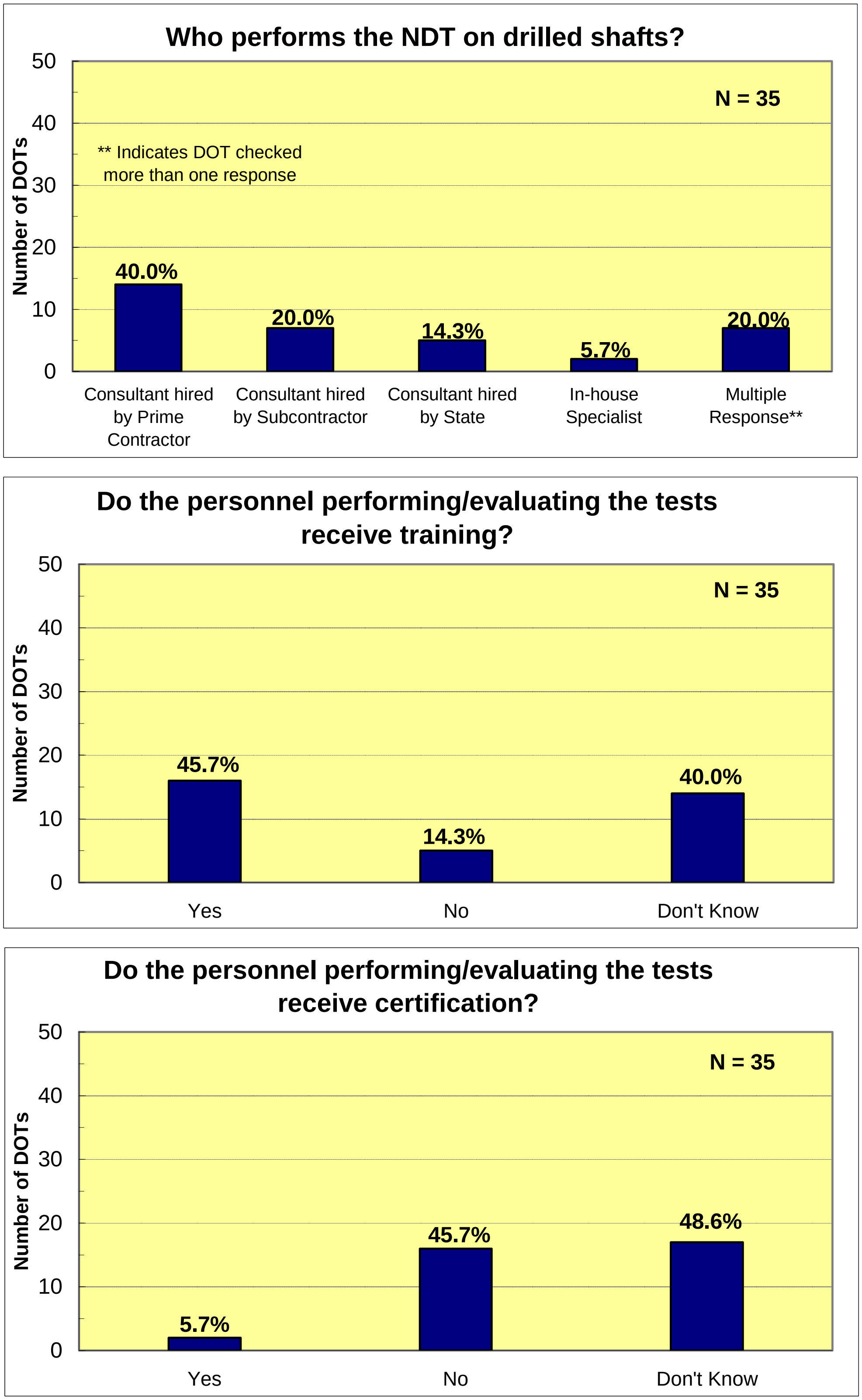


Figure 10. DOT survey results.

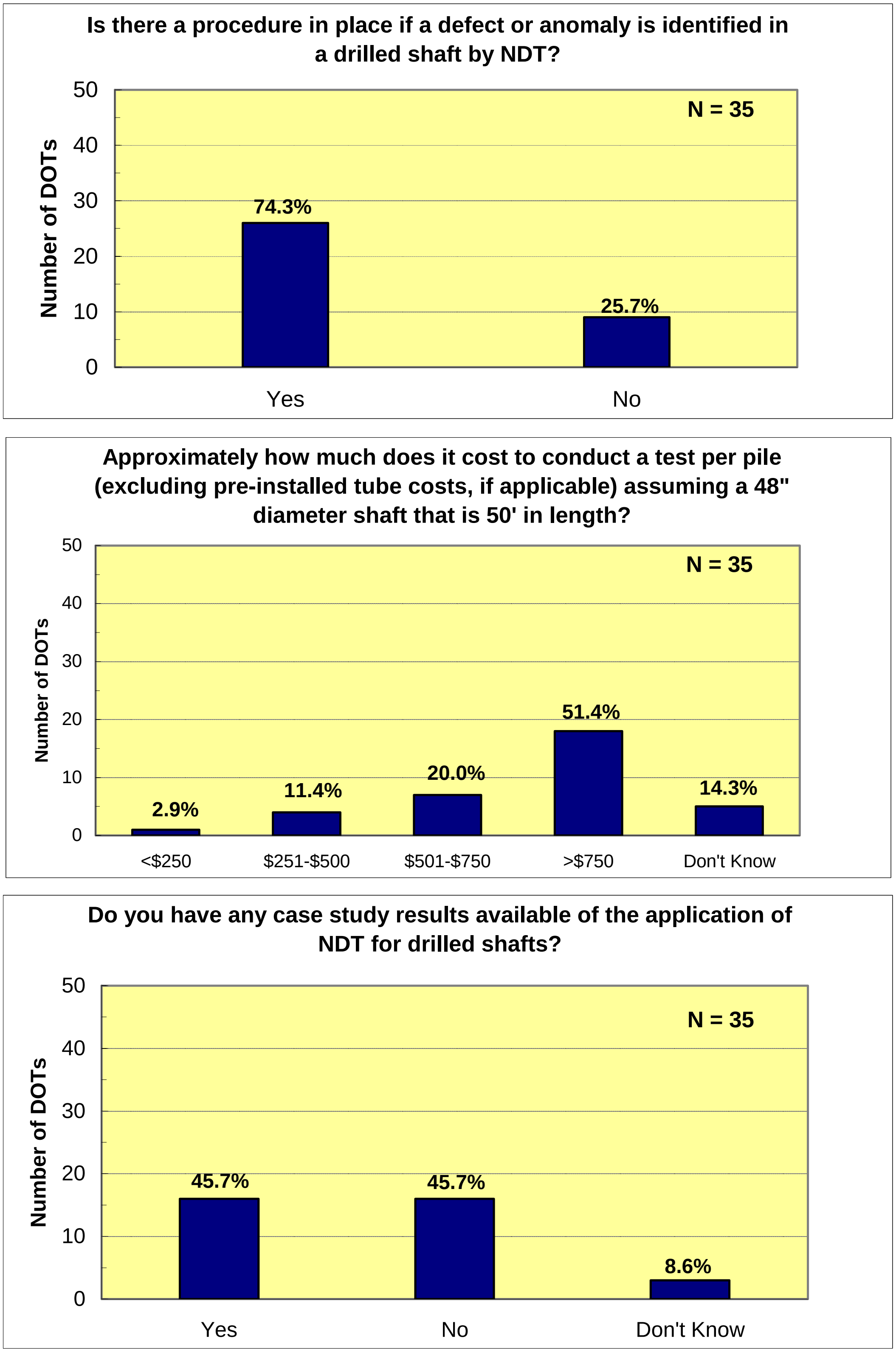


Figure 11. DOT survey results.