CHAPTER 1 – INTRODUCTION

1.1 PURPOSE AND OBJECTIVES

The purpose of this study was to addresses what constitutes a defect in a newly constructed drilled shaft foundation and how to relate identified defects in a velocity tomogram to engineering strength information for integrity assessment.

The overall objectives of this study were:

- Review and evaluate the current state-of-practice of nondestructive test (NDT) methods;
- Use a statistical analysis to define a "defect" in a crosshole sonic logging tomography (CSLT) image;
- Monitor and model changes in concrete temperature (velocity, density, and moisture) in a drilled shaft after concrete placement;
- Establish empirical relationships that correlate changes in a CSLT velocity image to changes in concrete strength.

The scope of work was carried out based on a three-step approach to identify and image anomalies within a drilled shaft and to relate percentage changes in 3-D tomographic velocity image to changes in concrete strength for engineering decision making. The three steps approach included:

1. *Anomaly Identification and Independent Verification* – In this step, various NDT methods including crosshole sonic logging (CSL) and gamma-gamma density logging (GDL) are used to identify and independently verify suspected **"anomalies"** in drilled shafts. In addition, CSLT method is used to create three-dimensional (3-D) velocity images of these anomalies.
2. *Defect Definition* – The second step addresses what constitute a velocity **"defect"** or a flaw in a 3-D CSLT velocity tomogram?[1] A statistical analysis is used to separate velocity distribution of sound concrete from velocity distribution of anomalous concrete. Based on this analysis, a cut-off velocity is established as a key parameter that separates this two velocity distributions. In this report, a defect volume is defined as having a velocity lower than the cut-off velocity.
3. *Defect Characterization* – In this step, changes in velocity values in the defect volume are correlated to changes in concrete strength and hence 3-D strength images are developed. Empirical velocity-strength correlation is established in the laboratory using cylinders with the same design mix as the shaft and allowing for maturity. This strength image will allow the engineer to perform modeling to evaluate the overall integrity of the drilled shaft foundation.

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[1] In this study, "anomaly" refers to a suspected deviation from homogeneity (uniformity) in a concrete structure. No determination is yet made regarding its exact size or extent. Statistical analysis is performed to obtain a cut-off velocity that is used in defining a "defect" volume with a velocity lower than the cut-off velocity.

This three-step approach was applied on twenty (20) drilled shafts from three (3) different projects:

- Dataset from two (2) research drilled shafts with planned defects from the National Geotechnical Experimentation Site (NGES), Amherst, Massachusetts;
- Dataset from twelve (12) production shafts (shafts used in a bridge project with unplanned defects) from the Jim Camp Bridge, Arizona Project;
- Dataset from six (6) production shafts from the Sevenmile Gooseberry, Utah Project.

1.2 DRILLED SHAFT FOUNDATION - BACKGROUND

Drilled shafts are deep or shallow foundation support elements formed by creating a drilled hole into which structural steel and concrete is cast or placed. The reinforcing steel is placed in the hole prior to concrete placement. Drilled shafts are typically used as deep foundations capable of supporting high, concentrated loads: they are the foundation of choice for heavily-loaded, seismically-sensitive structures as they can carry both axial and lateral loads.

The development of drilled shafts, more or less independently, in various parts of the world led to different terminologies (O'Neil and Reese, 1999). "Drilled shaft" is the term first used in Texas, while "drilled caisson" or "drilled pier" is more common in the Midwestern United States. "Cast-in-drilled-hole (CIDH) pile" is a term used by California Department of Transportation (CalTrans), and "bored pile" is common outside of the United States. These terms all describe essentially the same type of foundation.

Drilled shafts range from diameters of 46 cm (18 in) to greater than 3.6 m (12 ft) and to depths of 50 m (164 ft). The variation of shaft diameter is dependable on excavation depth. As the depth of excavation becomes greater, the diameter normally must increase. Several factors that influence the ratio of depth to diameter are: the nature of the soil profile, the position of the groundwater table, whether or not a rebar cage is required, the design of the concrete mix, and the need to support lateral loading. Ordinarily, the aspect ratio of drilled shaft, or its length divided by its diameter, should not exceed about 30. Cylindrical holes can be drilled with diameters of up to 6 m (20 ft), to depths of up to 73 m (243 ft), and with underreams up to 10 m (33 ft) in diameter, although such sizes are unusual. A typical schematic of drilled shaft construction with the loading is presentation in Figure 1 and a typical drilled shaft operation during construction is shown in Figure 2.

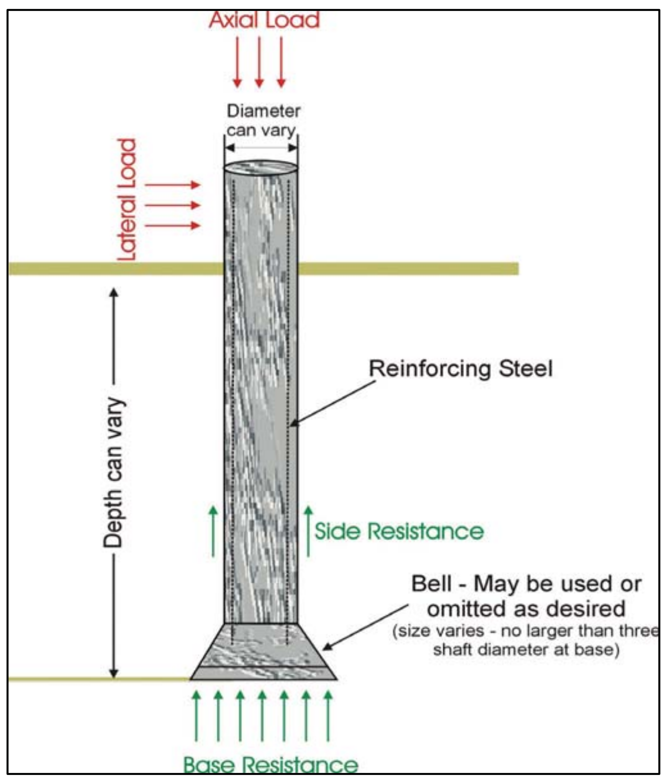

Figure 1. Schematic. Typical Drilled Shaft Foundation.

Figure 2. Photo. Drilled Shaft Construction.

Drilled shafts are designed and installed as either end bearing or friction type shafts or a combination. In the end bearing shaft, the structure loads bear on top of the solid rock in the rock socket. In the skin friction shaft, the structure loads bear on sides of the drilled shaft.

Drilled shafts are constructed straight, belled and rock-socketed using two different methods:

1. *Dry method* – construction of a shaft without excessive water interference. The dry construction method consists of drilling the shaft excavation, removing loose material from the excavation and placing the concrete in a relatively dry excavation. The rate of flow of water into the hole should not be more than 300 mm (12 inches) within a 1-hour period. No concrete is placed if there is more than 75 mm (3 inches) of water in the bottom of the hole. Casing can be used as temporary or permanent as described below:

   A. Temporary Casing Construction Method: The temporary casing construction method is used when excavations in the dry construction method, encounter water bearing or caving soil formations. A temporary casing is then placed into the impervious formation to produce a watertight seal at the bottom. During concrete placement, the casing is withdrawn.

   B. Permanent Casing Construction Method: This method consists of placing a casing to a prescribed depth before excavation begins. If, during dry drilling, caving or water bearing soils is encountered, the hole is filled with water and the excavation is advanced by drilling. Pressure grouting is required to ensure contact (bearing) between the casing and any surrounding soil layer that is used for lateral support.

2. *Wet or slurry methods* – constructing a shaft either with ground water or under water using tremie concrete. In this type of operation, drilling slurry (typically commercial bentonite clay mixed with water) or polymer slurry is used to stabilize the excavation or when ground water is encountered in the excavation that cannot be dewatered.

1.3 CURRENT NDT METHODS USED FOR DETERMINING THE INTEGRITY OF DRILLED SHAFT FOUNDATIONS

Nondestructive test (NDT) methods are used for quality assurance (QA) integrity testing of drilled shaft foundations, or other concrete structures, such as diaphragm slurry walls, auger-cast in place (ACIP) piles, shear pin wall, and dams. NDT methods are often called "small strain test" tests because a small seismic energy source, such as a hammer, is used to generate the seismic waves. These methods are used to identify and image flaws or "defects". Common structural defects include shaft necking and bulbing, "soft bottom" condition, voids, poor quality concrete, delamination, and honey-combing.

These tests can be divided into two groups: Surface NDT method, if access is required only at the surface of a foundation, and in-hole NDT methods, if access tubes are installed to the inside of the reinforcing rebar cage prior to the concrete placement as shown in Figure 3. In the following section, three in-hole NDT methods are discussed. Surface NDT methods, such as sonic echo (SE)/ impulse response (IR) or ultraseismic test (UST) methods, are not covered in this report.

Figure 3. Photo. Rebar Cage and CSL Tubes of Completed Drilled Shaft.

1.3.1 Crosshole Sonic Logging (CSL) Method

In the standard CSL method (Figure 4), ultrasonic transmitter/receiver probes are initially lowered to the bottom of a pair of access tubes. The two probes are then pulled simultaneously as to maintain near horizontal ray paths between them (*zero-offset logging*). The system is calibrated to measure the sonic wavefield at 5 cm (2.4 in) depth intervals throughout the length of the shaft. This test is repeated for all test paths along the outer perimeter as well as across the inner diagonal of the shaft. Good concrete condition will result in a near continuous vertical alignment of the waterfall-displayed data (and travel time picks). Longer travel times and lower signal amplitudes characterize anomalous zones, defined as defects, due to soil intrusions, voids, or poor quality concrete.

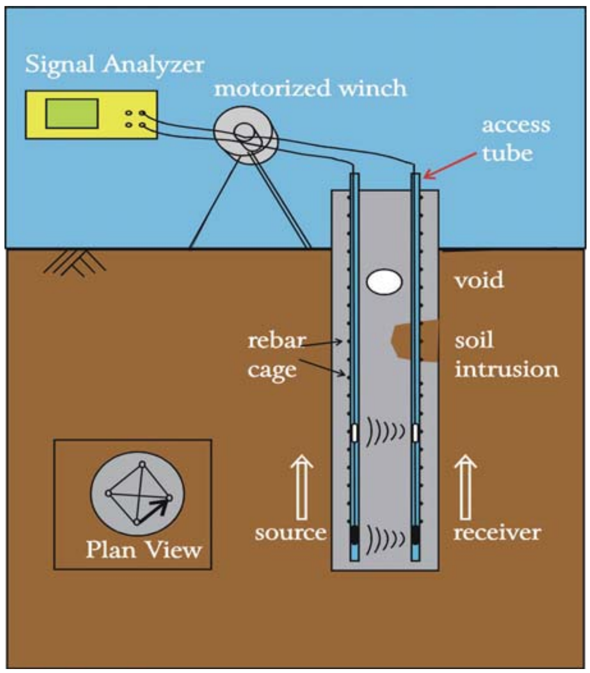

Figure 4. Schematic. Crosshole Sonic Logging (CSL) Field Setup.

1.3.1.1 Standard CSL Data Presentation Format

Figure 5 presents standard CSL logs (in waterfall 1-D display format) acquired between six (6) test panels on a test wall (with engineered defects) compared side by side. The wall geometry and defect locations are indicated on the top right hand side. In each CSL data plot, a full-waveform gray-scale vertical stack of the data traces is displayed as a function of depth in the right hand track. In the left hand track, the picked travel *time* arrivals (thin line) and signal amplitude (thick line) are also displayed. Depths, is shown on the vertical axis.

In Figure 6, the new format for the display of the CSL data on a single plot is shown. In this figure, the CSL results from a drilled shaft containing 5 tubes are plotted in 5 separate sub-plots from 5 different access-tube pair combinations, as indicated on the top label. Each individual sub-plot displays the velocity in black color and signal root mean squared (RMS) amplitude levels in magenta color. Also, in each separate sub-plot, the average velocity as well as 10%

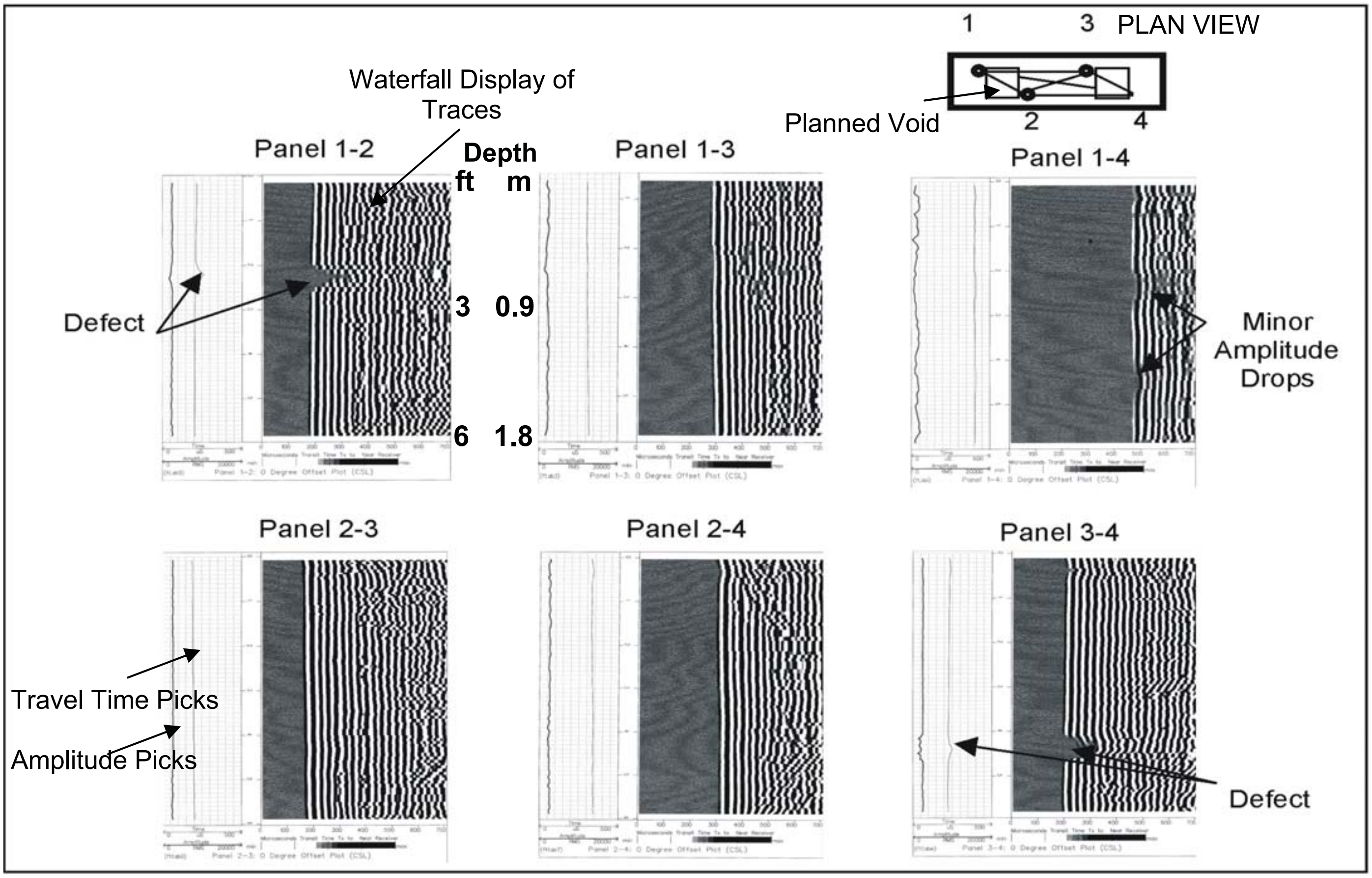

Figure 5. Graph. Zero-Offset CSL Dataset from a Test Wall with Engineered Defects. Data from All CSL Test Paths are Indicated.

drop in average velocity (questionable concrete) and 20% drop in average velocity (poor concrete) are displayed as vertical green, blue and red lines, respectively.

1.3.1.2 Defect Definition

Using standard CSL testing, "questionable" concrete condition is defined as a zone with a decrease (from median) in sonic velocity between 10% and 20% (or about 40%-65% of old strength); and, "poor" concrete condition is defined as a zone with greater than 20% decrease in sonic velocity (or about less than 40% of old strength)[2]. For details on the empirical relationship between sonic velocity and concrete strength, please refer to Sections 4.1.

[2] Example Specification: U.S. Federal Highway Administration (FHWA) Section 565 (1996) Specification for drilled shafts (construction requirement: integrity testing). Note that the correlation between velocity and concrete strength is from empirical relationships.

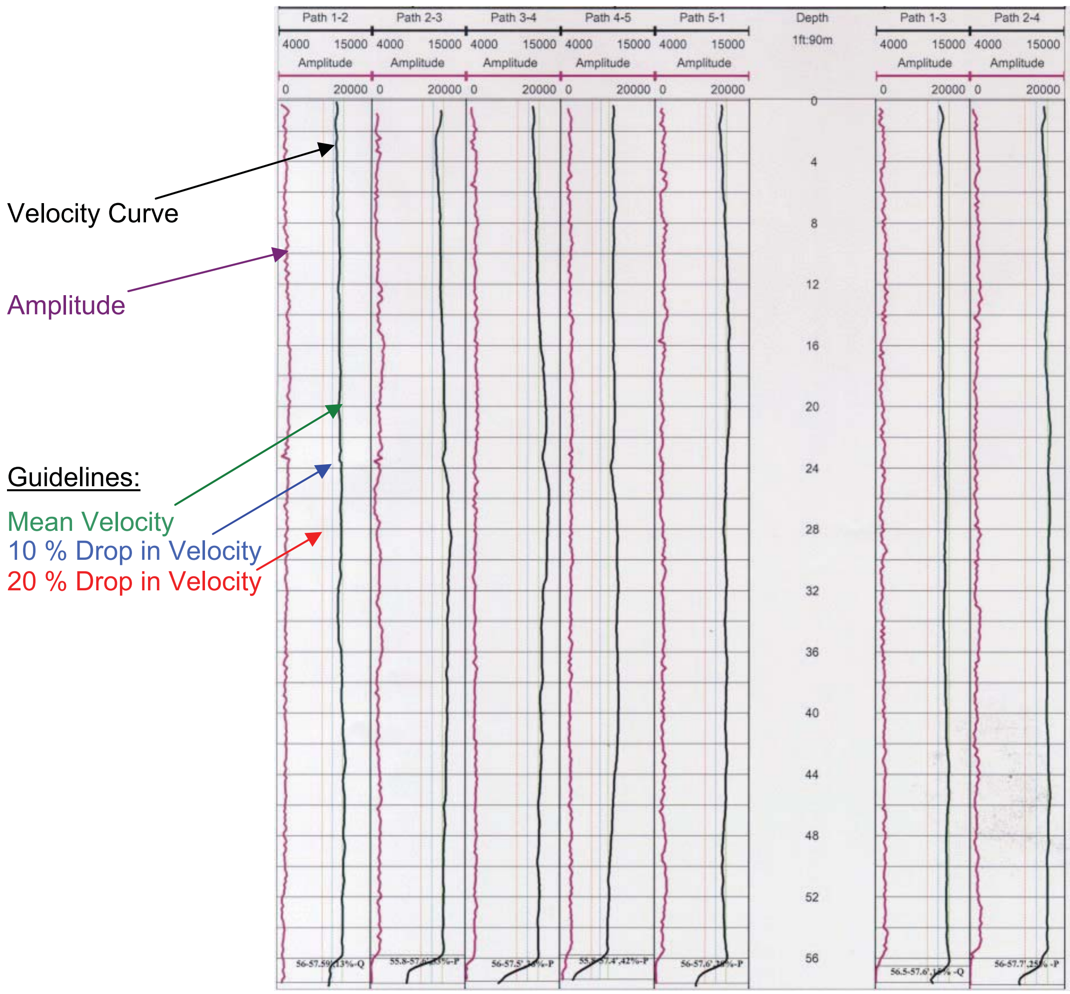

Figure 6. Graph. Single Plot Display Format for the CSL Data from a Drilled Shaft Foundation. Green Vertical Guideline Indicate Average Velocity and Blue and Red Vertical Guidelines Denote 10% Drop and 20% Drop in Velocity, Respectively.

1.3.1.3 Advantages of CSL

- Accurate characterization of soil intrusions or other anomalies throughout the shaft inside the rebar cage (between the tubes).
- Several defects at different depths can be detected by this method with high precision.
- It can be used to identify un-cured concrete especially in chemically retarded mixes.
- No special handling is required for the use of radioactive sources.

1.3.1.4 Limitations of CSL

- Tube debonding condition can occur with PVC access tubes especially above the groundwater table (where the temperatures are higher). No signal is obtained in the debonded zone.
- Only defects along the path of the sonic wave will be detected; it cannot detect anomalies outside the rebar cage.

- It cannot be used to detect shaft bulbing (increase in diameter).

1.3.2 Crosshole Sonic Logging Tomography (CSLT) Method - Offset Tomography

CSL data can be collected by initially offsetting either the source or the receiver and then pulling the two probes together as to maintain a constant non-zero angle between them (*Offset Logging*). In the CSLT method (Figures 7 and 8), data is collected by running a zero-offset log in combination with several positive offset (receiver is shallower) and negative offset (source is shallower) logs. This procedure is repeated for all possible access tube combinations to form a three-dimensional tomography dataset.

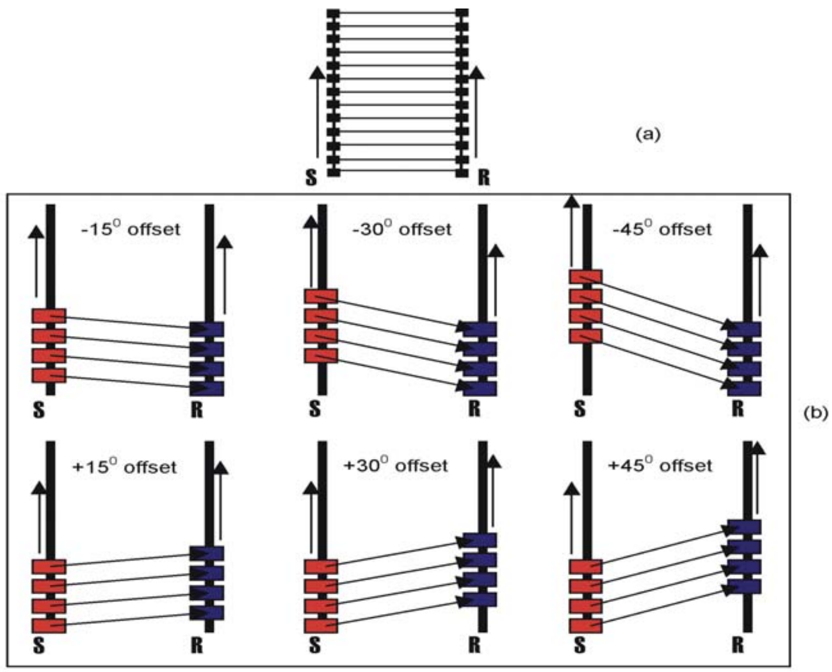

Figure 7. Schematic. Zero-Offset Vs Multi-Offset Tomographic Data Collection.

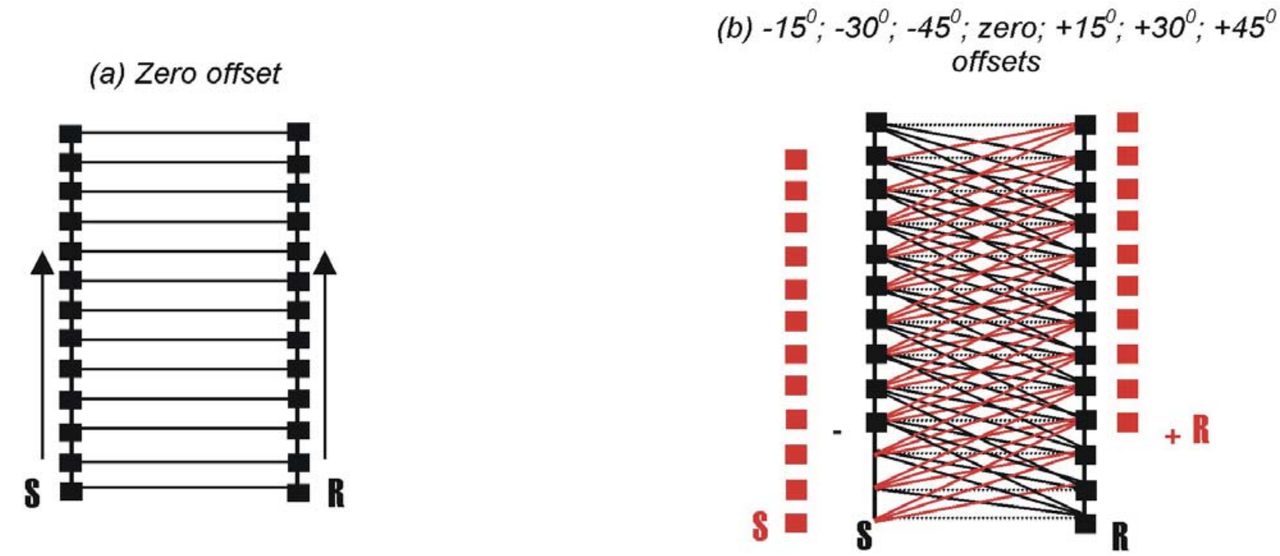

Figure 8. Schematic. Ray-Density with Zero-Offset Data Collection b) Tomographic Data Collection (Zero Plus Three Positive and Three Negative offsets).

1.3.2.1 CSLT Data Presentation Format

Typical three-dimensional tomography (CSLT) data presentation format is shown in Figure 9. In this figure, a soft bottom condition is indicated which extends to the interior of the shaft. 3-D images defined poor quality concrete zones shown in green and blue colors.

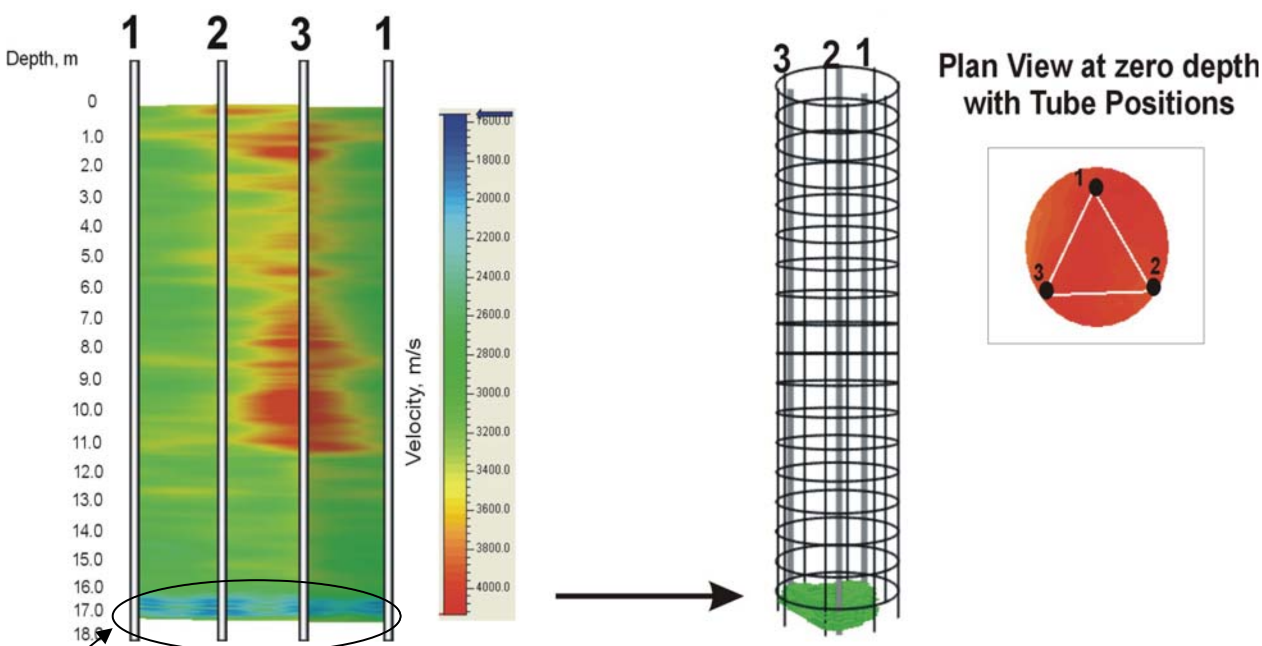

Figure 9. Schematic. Crosshole Sonic Logging Tomography (CSLT) Data Display Format.

Defect Zone

1.3.2.2 Advantages of CSLT

- Provides for two-dimensional area or three-dimensional volumetric *imaging* of defect zones for immediate engineering remediation.
- Can identify small horizontally elongated defects, such as cold joints, missed by the standard CSL technique.
- Attenuation tomography can be used for possibly identifying soil intrusions that end at the rebar cage or the fracture zones.
- Can be used in before and after surveys for monitoring the effectiveness of remediation.

1.3.2.3 Limitations of CSLT

- Data-intensive for non-automated field systems.
- Specialized analyses software is required for true three-dimensional imaging.
- Due to limited ray coverage, artifacts[3] can be present due to edge effects.
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1.3.3 Gamma-Gamma Density Logging (GDL)

In the 4-pi Gamma-Gamma Density Logging (GDL) test method (Figure 10), a weak Cesium-137 source is used to emit gamma rays into the surrounding material. A small fraction of the gamma ray photons are reflected back to the probe (due to Compton scattering) and their intensity are recorded by a NaI scintillation crystal as counts per second (cps). The measured count rate (cps) depends on the electron density of the surrounding medium, which is proportional to the mass per unit volume. The tool is calibrated by placing the probe in an environment of known density in order to convert the measured count rate (cps) into the units of density in g/cm^3 (lb/ft^3).

[3] Artifacts are erroneous velocity values produced by the tomographic matrix inversion process due to inadequate scanning (or aperture) of the test volume; inaccuracies in travel time picking; and non-linear and non-unique inversion of the travel time data. These artifacts mostly occur near the image boundaries.

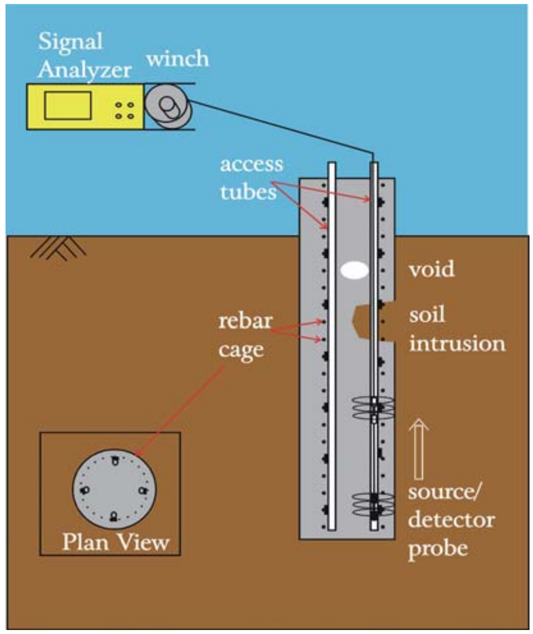

Figure 10. Schematic. Gamma-Gamma Density Logging (GDL) Field Setup.

In the GDL test, the radius of investigation is largely governed by 1/2 of the source-detector spacing. An optimal spacing is selected (generally about 35.6 cm (14 inch)) and the GDL test is performed from all tubes in order to obtain uniform coverage around the perimeter of the shaft. Good concrete condition will result in a near continuous alignment of the data. Anomalous zones—due to soil intrusions, poor concrete, or voids—are characterized by large low density (high count rate) deflection in the data.

1.3.3.1 Typical Data Presentation Format

In a typical GDL log (Figure 11), the measured gamma ray intensity count rate (cps) is presented in the units of g/cm^3 (lb/ft^3). In Figure 11, the GDL results are plotted in 4 separate sub-plots from the tested access tubes. Each individual sub-plot depicts the GDL results from 35.6 cm (14 inch) source-detector separation (corresponding to about 13-15 cm (5-6 inch) radius of investigation) presented in a magnified density scale of 2.1-2.9 g/cm^3 (130-180 lb/ft^3). Also, in each sub-plot, the mean as well as the -2 and the -3 standard deviation from mean curves are displayed as vertical guidelines. Depths, in meter (feet), are measured from the top of the shaft and are shown on the vertical axis.

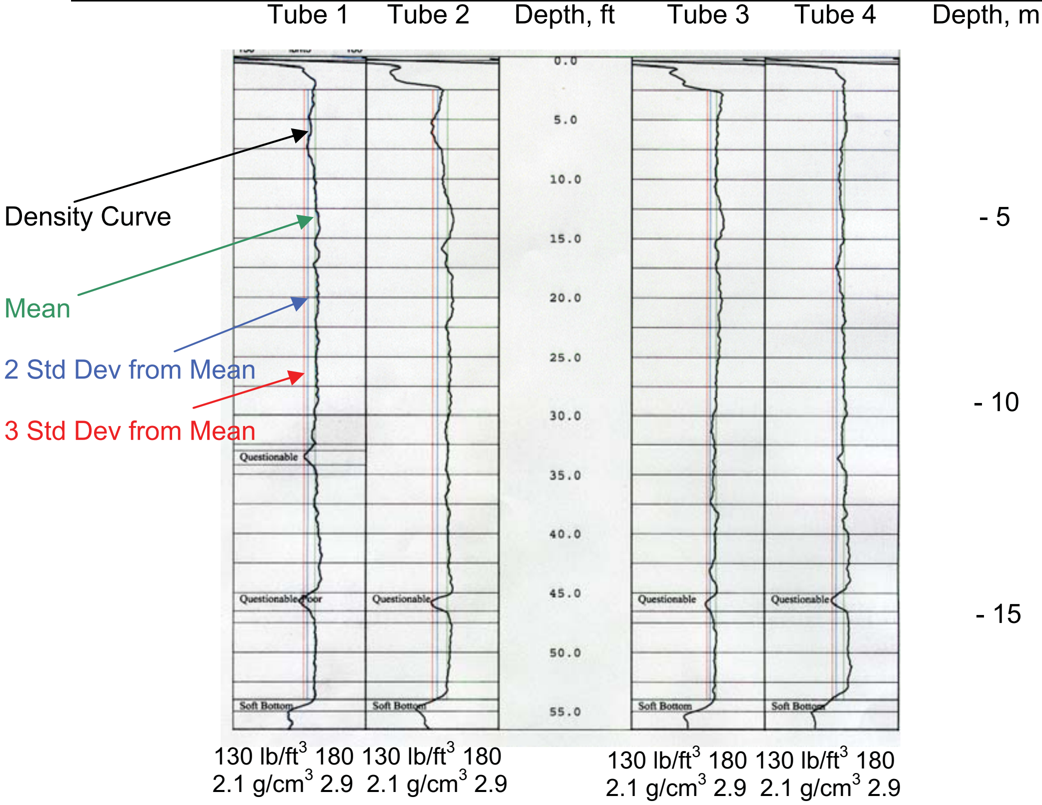

Figure 11. Graph. Gamma-Gamma Density Logging (GDL) Data Display Format.

1.3.3.2 Defect Definition

In the GDL testing, "questionable" concrete condition is defined as a zone with reduction in density between 2-3 standard deviations from mean and "poor" concrete condition is defined as a zone with reduction in density of greater than 3 standard deviations from mean.

1.3.3.3 Advantages of GDL

- Detects anomalies within a 13-15 cm (5-6 inch) radius around the inspection tubes both inside and *outside* of the rebar cage.
- Several defects at different depths can be detected by this method with high precision.
- Can be used for testing in fresh concrete while restoration is still feasible as the density of concrete changes minimally as it sets.
- Minimally is affected by the tube debonding condition.

1.3.3.4 Limitations of GDL

- Only measures concrete integrity along the outer perimeter of the shaft at about 13-15 cm (5-6 inch) radius from each tube (average tube-to-tube separation along the perimeter is about 76 cm (30 inches)). Therefore, no data is recorded along some portions of the perimeter and from the entire interior portion of the shaft.
- It cannot be used to identify young (heavily retarded) un-cured concrete.
- Special handling is required for the use of radioactive sources.

1.3.4 Other Specialized Logging Applications

Other geophysical logging probes can be used in this application to assess the condition of in-placed concrete. Currently, these single-hole logs are not in routine use by the industry, and include: 1) temperature logging for evaluating concrete curing condition; 2) neutron logging for measuring moisture content; 3) natural-gamma logging for assessing clay content; 4) optical and acoustic televiewer for visual inspection of defects through cored holes (or clear or PVC tubes); and 5) electrical and ground penetrating radar (GPR) logging for examining the condition and positioning of rebar within the cage.

In the next section, a brief description of neutron-moisture logging (NML) and temperature logging is presented. These two methods are used in this report. NML logs are used for verification of anomalies observed by CSL and GDL logs. Temperature logs are used for monitoring concrete curing rates in two (2) drilled shafts. Because of their limited use in this application, only brief method descriptions and advantages of these single-hole logging methods are provided.

1.3.4.1 Neutron Moisture Logging (NML)

In the neutron-moisture logging (NML) test method, an americium-beryllium neutron source in sizes of 1 to 5 Curies source is used to emit high energy neutrons into the surrounding material. Helium-3 detectors are typically used in recording the interactions that occur in the vicinity of the access tubes. Two different neutron-logging techniques can be used: 1)- geophysical neutron probes with a large source size (>1 Curie) and long spacing (>30 cm (11.8 in)) with radius of investigation of about 15-18 cm (6-7 inches) (as used in this report); and, 2)- engineering probes with a small source size (<100 millicuries) and short spacing (<30 cm (11.8 in)) with radius of investigation of 2.5-5 cm (1-2 inches). Three general types of neutron-porosity logs exist: neutron-epithermal neutron, neutron-thermal neutron (as used in this report), and neutron-gamma. Cadmium foil may be used to shield Helium-3 detector from thermal neutrons. Neutron-epithermal neutron logs are least affected by the chemical composition of surrounded material.

Fast neutrons, emitted by a source, undergo three basic types of reactions with matter adjacent to the access tubes (concrete, steel, and possibly moisture and soil) as they lose energy and ultimately are captured. These physical interactions include inelastic scatter, elastic scatter, and absorption or capture. In elastic scatter, the mass of the scattering element controls the loss of energy by the neutron. Light elements (mostly hydrogen element in water) are most effective in moderating, or slowing neutrons, whereas heavy elements have little effect on neutron velocity or energy. The moderating and capture processes result in the number of epithermal and thermal neutrons and capture gamma photons being inversely related to the hydrogen content of concrete, at source-to-detector spacing greater than approximately 30 cm (11.8 in). If detectors are located closer than 30 cm from the source, as in engineering moisture probes, the number of moderated and captured neutrons increases with increasing hydrogen content.

Typical NML logs are presented in a similar format as GDL logs with measured neutron counts per second (cps) displayed along with the mean and the -2 and the -3 standard deviation from mean vertical guidelines. High moisture zones are indicated by low count rates deflection in the data.

Benefits of NML. NML can used to investigate the presence of excessive moisture in a defect zone; especially, when such moisture is in contact with the rebar cage (vulnerability to corrosion).

1.3.4.2 Temperature Logging

Temperature probes employ a glass-bead thermistor along with a solid-state IC device. Most thermistor probes have an accuracy, repeatability, and sensitivity on the order of 0.02°C. They also are very stable over long periods of time, but they have the disadvantage of a nonlinear temperature response.

The standard temperature log records temperature as a function of depth. The sensor in a temperature probe only responds to the fluid in its immediate vicinity reflecting the thermal gradient in concrete.

Calibration of temperature probes needs to be carried out in a constant temperature bath, using highly accurate mercury thermometers. The bath and probe need to reach equilibrium before a calibration value is established. Onsite standardization cannot be carried out with great accuracy because no portable substitute exists for a constant-temperature bath. The only temperature that can be achieved and maintained for sufficient time to permit a valid calibration is 0°C in an ice bath.

Movement of a logging probe disturbs the thermal profile in the fluid column; therefore, the most accurate temperature log is made before any other log, and it is recorded while moving slowly down the hole.

Benefits of Temperature Logging. 1) Temperature logging can be used to evaluate the negative effects of the cracking resulting from uncontrolled mass concrete placement. Care must be taken for the maximum temperature reached in the shaft not to exceed the specified maximum allowable temperature (typically, 57°C (135°F)). Also, with the use of thermocouples, readings can be taken to insure the differential temperature from the center of the shaft to the outside edge of the shaft not to exceed the tolerance specified in the standard provisions (typically, 19°C (35°F)). 2) Temperature logging, as described in this report, can also be used during the first 7 days after concrete placement to identify shaft bulbing.