CHAPTER 1. INTRODUCTION

1.1 Purpose

This study focuses on the evaluation of the structural integrity of drilled shafts using the cross-hole sonic logging method. The objectives are to analyze the effectiveness of cross-hole sonic logging (CSL) surveys to characterize the integrity and bearing capacity of deep-drilled shaft foundations. Numerical analysis will be employed to isolate, control, and measure the effects of various phenomena.

This study simulates CSL surveys under various conditions commonly encountered in the field. The effects of the following factors on velocity propagation are examined:

1. Access tube-- including tube bending, sensor drift and orientation within the tubes, steel vs. PVC tubes, thermal expansion during concrete hydration, and tube debonding.
2. Rebar--including CSL signal reflection and dispersion, rebar thermal expansion, and rebar debonding.
3. Concrete hydration in typical ground conditions and at different curing times, using chemical hydration rates, heat transfer, and thermal stress.
4. Common defects will be introduced into the models, such as honeycombing, soil intrusion, and thermal cracking. Simulated CSL surveys will be evaluated for effectiveness to detect and classify these defects using simulated waveform analysis.

Next, numerical stress analysis will be performed on defects within the drilled shaft to estimate effects on bearing capacity and structural integrity.

A well-established, comprehensive numerical model based on the Particle Flow Code (PFC) method is used in this study. PFC is a Discrete Element Method (DEM) that uses combinations of small spherical elements bounded by springs of various stiffness to model the larger, more complex elements commonly used in DEM. This modeling method was selected because it supports solids, with effects of friction, interlocking, collisions, and cracking, as well as fluids and solid/fluid interaction. This method also has the capability to model dynamic crack propagation, seismic waves, and static loading in concrete, soil, and other geotechnical materials. The PFC method was also expanded to model a wider range of phenomena, such as concrete curing, heat transfer, thermal cracking, honeycombing, surrounding ground conditions, ground water effects, and corrosion.

The results of this study offer a method to process full-waveform seismic data collected from existing survey techniques and obtain a more accurate and comprehensive estimate of long term drilled shaft performance and structural integrity.

1.2 Cross-hole Sonic Logging (CSL) Surveys of Drilled Shafts

The most commonly used drilled shaft foundation down-hole integrity test is cross-hole sonic logging (CSL), also known as ultrasonic testing (ASTM D 6760-02). The cross-hole sonic logging technique is an indirect, low strain, non-destructive imaging method for detecting defects inside the rebar cage of a drilled shaft or diaphragm wall element. CSL has become a standard test for most transportation agencies, and is currently performed on most drilled shaft in the United States and other developed countries. Prior to the acceptance of CSL, quality assurance testing in the United States was performed only on a very limited number of drilled shafts primarily using the sonic echo and impulse response test. Gamma-gamma density logging tests are gaining popularity as combination backup tests to CSL for defect identification. Several variations of the CSL equipment and techniques exist, including a source (pulse transmitter) and a receiver simultaneously lowered in the same tube (single hole ultrasonic test, dubbed "SHUT"), a source and a receiver lowered in adjacent tubes, and a source and multiple receivers lowered in separate tubes. The single source and receiver in adjacent tubes is the most commonly used today. CSL has gained credibility based on tests that were successfully conducted in the United States on hundreds of shafts with depths up to 120 m (tested in China).

1.3 CSL Basic Theory

The CSL method is a "derivative" of the ultrasonic pulse velocity test. The basic principle of the CSL test is that ultrasonic pulse velocity through concrete varies proportionally with the material density and elastic constants. A known relationship between fractured or weak zones and measured pulse velocity and signal attenuation is fundamental for these tests. Research has shown that weak zones reduce velocities and increase attenuations. During CSL measurements, the apparent signal travel time between transmitter and receiver are measured and recorded. By measuring the travel times of a pulse along a known distance (between transmitter and receiver), the approximate velocity can be calculated as a function of distance over time. If a number of such measurements are made and compared at different points along the concrete structure, the overall integrity of the concrete can be assessed.

The first-arrival travel times (FAT) recorded during CSL testing are known as compressional, primary, longitudinal, or P-wave arrivals. The P-wave has discrete particle motion in the same direction as the wave is moving. The surface of the constant phase, or the surface on which particles are moving together at a given moment in time, is called the wavefront. An imaginary line perpendicular to the wavefront is called a ray path. It is often assumed that a beam of produced ultrasonic energy travels along the ray path (Robert E. Sheriff and Lloyd P. Geldart, 1995). Basic elements of the emitted wave during CSL testing are presented in Figure 1.1.

The following are definitions of terminology used with CSL analyses (Robert E. Sheriff, 1978):

- wavelength (λ) - distance between successive repetitions of a wavefront,
- amplitude (A) - maximum displacement from equilibrium,
- period (T) - time between successive repetitions of a wavefront,
- frequency (f) - number of waves per unit time,
- velocity (V) - speed at which a seismic wave travels, proportional to the frequency and wavelength ($V=f\lambda$),
- apparent wavelength - distance between successive similar points on a wave measured at an angle to the wavefront, and
- apparent velocity - product of frequency and apparent wavelength.

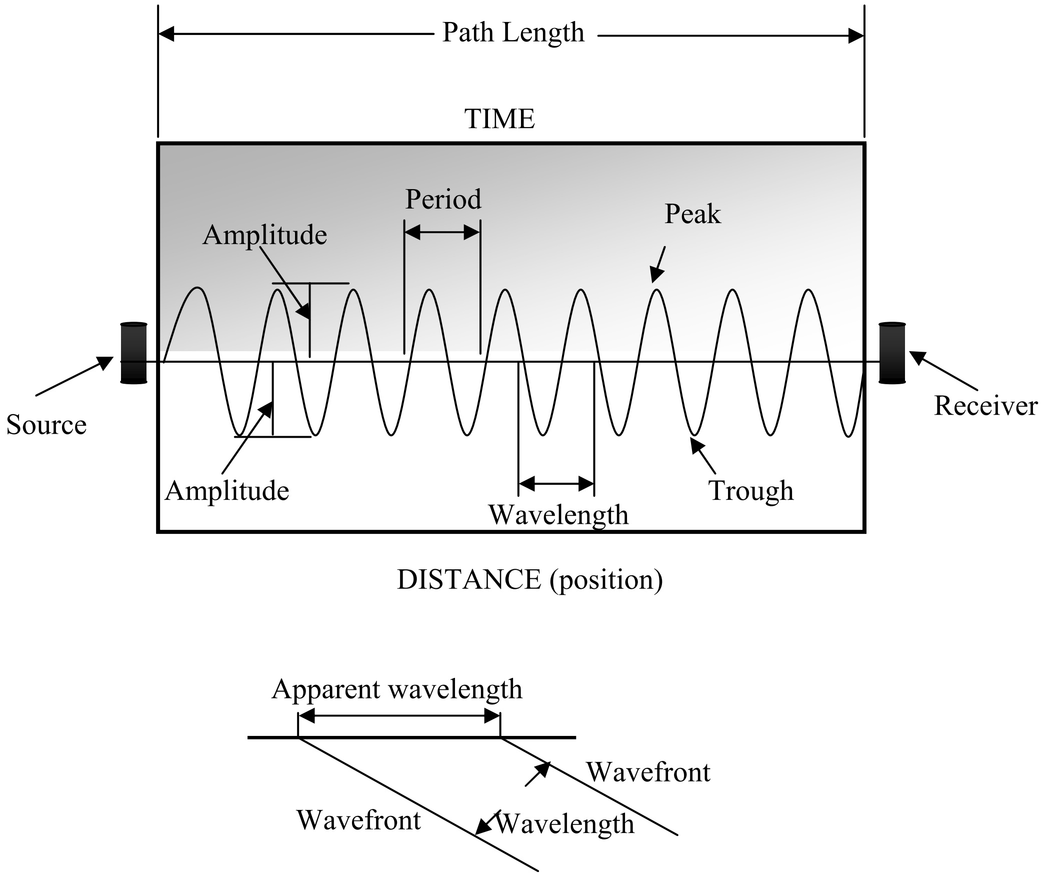

Figure 1.1. Plot. Basic Wave Elements

Velocity of the P-wave in homogenous "isotropic" media is related to the modulus and density of the medium through which the wave travels, and is given as:

$$Vp = \sqrt{\frac{(4/3\mu + k)}{\rho}} \quad , \tag{1.3}$$

where
Vp - velocity of the P-wave
μ - shear modulus of the medium through which the wave travels,
k - bulk modulus of the medium through which the wave travels,
ρ - density of the medium through which the wave travels.

$$k = \frac{E}{3(1-2\nu)} \tag{1.4}$$

$$\mu = \frac{E}{2(1+\nu)}, \tag{1.5}$$

where
ν is Poisson's ratio of the medium.

The P-wave velocity can then be written as:

$$Vp = \sqrt{\frac{E(1-\nu)}{(1+\nu)(1-2\nu)}}\ , \tag{1.6}$$

where

E - dynamic elastic modulus or Young's modulus

During CSL analysis, the first arrival times of the P-wave are picked using an automated picker within the CSL software, and the pulse velocity can be calculated as:

$$PulseVelocity = \frac{PathLength}{TransitTime} \tag{1.7}$$

For accurate results, it is recommended that the path lengths and transit times be measured with a precision greater than 1%. Although pulse velocity varies with different concrete mixes, the average pulse velocity of a typical concrete is approximately 4,000 m/s. Knowing the linear distance between the transmitter and receiver (path length), and the pulse transit time (first arrival time of the P-wave), the pulse velocity can then be calculated. If the CSL access tubes are not installed in a near vertical position and the distance between them varies significantly along the length of the shaft, errors in velocity calculations may occur, and the results may be misleading.

The seismic wavelength can be calculated based on the known frequency of the transmitted signal and the calculated pulse velocity as shown in Table 1.1. Table 1.1 suggests that the higher the transmitted frequencies used during CSL testing, the shorter the wavelength, allowing for the detection of smaller defects. However, the tradeoff is that the higher the source signal frequency,

Table 1.1 Numerical Relationship between Path Length (PL), Transit Time (TT), Frequency (f), Period (T=1/f), Velocity (V=PL/TT), and Wavelength (λ=V/f)

PL, (m)	TT x10^{-4}, (s)	1/f, (kHz)	1/f x10^{-5}, (s)	V=(PL/TT), (m/s)	λ = (V/f), (m)
0.6	1.6	35	2.8	3,750	0.1
0.6	1.6	50	2.0	3,750	0.075
0.6	2.4	35	2.8	2,500	0.071
0.6	2.4	50	2.0	2,500	0.05

the greater the signal absorption[1] and the shorter the wavelength. This implies that if higher frequencies are used during the CSL testing, more accurate detection of small defects is permitted, but signal absorption will also be high, limiting the penetration range of the method. Although most CSL systems operate at 35 kHz, frequencies in the range between 30 kHz and 90 kHz are used for CSL tests. At frequencies of about 90 kHz, the wavelength is at about the size

[1] Absorption is the process responsible for the gradual and sometimes complete disappearance of wave motion. The elastic energy associated with wave motion passes through the medium, becoming slowly absorbed and transformed into heat (Robert E. Sheriff and Lloyd P. Geldart, 1995).

of the aggregate. At this scale, the concrete can no longer be considered a homogeneous material. Therefore very high frequencies are not recommended.

The energy of an ultrasonic wave is a measure of the motion of the medium as the wave passes through it. Energy per unit volume is called energy density (Robert E. Sheriff and Lloyd P. Geldart, 1995). A wave passing through a medium possesses both kinetic and potential energy. Because the medium oscillates as the wave passes through it, energy is converted back and forth from kinetic to potential forms, but the total energy remains fixed. When the particle has zero displacement, the kinetic energy is at a maximum and its potential energy is zero. Conversely, when maximum displacement of the particle occurs, the kinetic energy is zero, and the total energy is all potential energy. When the total energy equals the maximum value of the kinetic energy, the energy density for a harmonic wave is proportional to the first power of the density of the medium, and to the second power of the frequency and amplitude as shown in the following equation:

$$E=2\pi^2\rho f^2A^2 \tag{1.8}$$

where

E = total energy
ρ = density
f = transmitted frequency
A = wave amplitude

1.4 CSL Test Procedures and Results

CSL testing can be performed on either drilled shaft foundations or pre-cast concrete piles, provided that 50-mm-diameter steel or PVC access tubes capable of holding water are installed (50-mm-diameter holes can be cored, if necessary). These tubes must extend at least 1 m above the top of the shaft to compensate for water displaced by insertion and removal of the transmitter, receiver, and cable. To reduce the chances of tube debonding, steel access tubes are preferred (steel tubes are not suitable if SHUT is to be applied). If schedule 40 PVC tubes are used, the tests must be performed within 10 days after concrete placement to avoid debonding at the PVC/concrete interface. Other factors may also cause debonding:

1) Disturbance of tubes during or shortly after concrete placement.
2) Improperly tying the tubes firmly to the cage.
3) Delays in filling the tubes with water.

To perform CSL testing, two probes, a piezoelectric transmitter, and a receiver are lowered to the bottom of two access tubes. These probes are simultaneously pulled vertically at a constant interval while pulses are created and recorded. During testing, the transmitter and receiver are maintained at the same elevation to create a horizontal signal travel path between the transmitter and the receiver. The cables to the probes pass through a meter-wheel that is connected to the data acquisition control unit. The meter-wheel controls the ultrasonic wave pulse by triggering the pulse generator at predetermined vertical intervals, causing the transmitter probe to emit an ultrasonic pulse. The timer circuit measures the time between pulse emission and subsequent detection by the receiver. Since the number of pulses emitted is a function of meter-wheel rotation and the wheel circumference is known, the depth of the probes can be calculated. All records are automatically stored on the system hardware.

In general, the range of frequencies used for concrete testing is between 20 kHz and 250 kHz, with 35 kHz being most commonly used for field-testing of drilled shafts. Since concrete is a heterogeneous material, high-frequency pulses (short wavelengths of energy) are unsuitable for use because of the considerable amount of energy attenuation. The corresponding wavelength is approximately 200 mm for lower frequencies (20 kHz) and approximately 16 mm for the higher frequencies (250 kHz).

The waveform of the raw data is digitized and continuously displayed with the positive peak of the received pulse presented and the negative peak displayed as blank space. In some CSL systems, the full waveform traces are stacked and displayed in a format representing vertical profiles of the pulse propagation time through the concrete (dubbed "waterfall" profiles) as shown in Figure 1.2(a). Other logs depict the arrival times, apparent velocity, and energy amplitude versus depth, as shown in Figure 1.2(b).

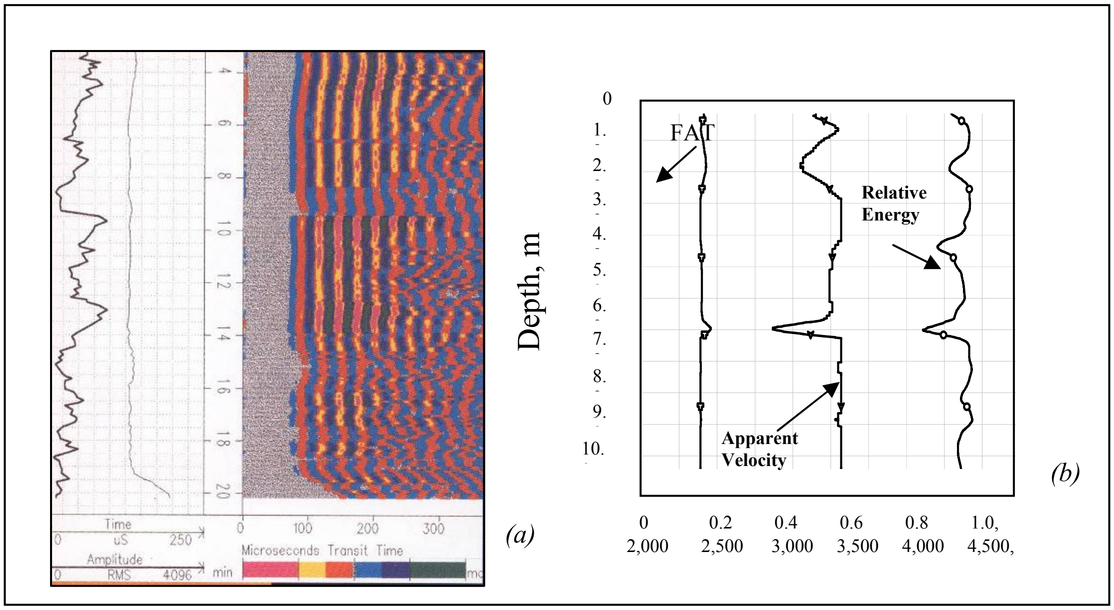

Figure 1.2. Plot. (a) Full Waveform Stacked Traces (InfraSeis, Inc.) and (b) CSL Log Plot – First Arrival Time (FAT), Apparent Velocity and Relative Energy Versus Depth (GRL & Assoc., Inc.)

CSL results can be evaluated on-site immediately following testing. Concrete integrity can be preliminary assessed based on first arrivals and signal amplitude. Good quality concrete is indicated by constant travel time per unit distance and good signal amplitude. Where the pulse velocity is reduced by defects or low modulus material, the propagation time will be longer, and the amplitude will decrease. Several irregularities can be identified at different locations within the same-drilled shaft as shown in Figure 1.3. In some cases, defects can significantly reduce pulse amplitude, causing the signal to be lost completely. Poor bonding between access tubes and the concrete, or de-lamination, can also cause complete signal loss. Steel tubes provide improved bonding with concrete, but the high mechanical impedance of steel may cause attenuation of the signal transmission and the signal may not be as well defined when PVC tubes are used. Since the tubes must be oversized to permit free passage of the probes and to allow for minor bending of the tubes during placement, the probes are somewhat free to move laterally.

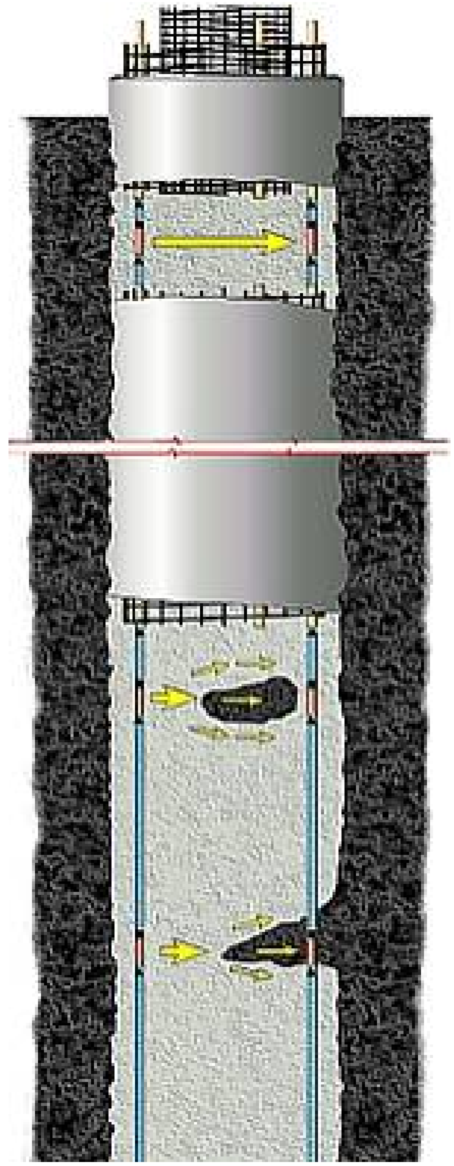

Figure 1.3. Plot. Drilled Shaft with Defects

Consequently, this may cause variation in transmitted pulse strength and received signal amplitude.

The received amplitude of an ultrasonic pulse can also vary depending on aggregate shape, orientation, and local changes in aggregate distribution. Concrete defects such as gravel zones, soil inclusions, bentonite inclusions, or honeycombing have a much lower propagation velocity, and their presence can usually be detected.

Current CSL tests only indicate that an anomaly may exist somewhere between two access tubes. It is, however, difficult to determine the geometry and exact location of the anomaly with the respect to tube location. To better characterize defects in terms of size, geometry, and location, additional CSL tests are performed. Data are collected with several offsets between transmitter and receiver in adjacent boreholes and used for detailed analysis and cross-hole tomography. A 2-D color tomogram is then plotted to better identify anomaly geometry and location.

1.5 CSL Data Processing and 3-D Tomography

The basic principles of tomography are borrowed from the medical field where imaging of a body is done by multidirectional CAT-scans. Tomography for medical purposes is used to display the loss in intensity of x-rays due to absorptive properties of different body parts. Because x-ray imaging depends entirely on variations in absorption with no refraction or diffraction, medical and seismic tomography are not perfectly analogous. In CAT-scanning, the x-rays travel mostly in straight lines in many directions, whereas in seismic tomography, the ray paths can bend appreciably depending on the velocity contrast within the medium.

The main concept of 3-D seismic tomographic imaging is the creation of color-coded images that provide a clear and detailed representation of property variations within a medium from seismic rays projected through the medium. Travel time tomography involves imaging the seismic properties from the observation of the transmitted compressional first arrival energy (Dines and Lytle, 1979). The relationship between the travel time t_i and the velocity field $v_{(x,y)}$ is given by the line integral for a ray "*i*":

$$t_i = \int_{R_i} \frac{ds}{v_{(x,y)}} \tag{2.1}$$

where
ds is the path length,
R_i denotes the curve connecting a source receiver pair that yields the least possible travel time according to Fermat's principle.

Tomography is an attempt to match calculated travel times from model responses to the observed data by inversion of these line integrals. Initially, the region of interest is divided into grids of uniform cells "*j*" of constant velocity cells and a discrete approximation of the line integral is assumed as:

$$t_i = \sum_j \Delta S_{ij} . n_j \tag{2.2}$$

where
ΔS_{ij} is the distance traveled by ray "*i*" in cell "*j*"
n_j is the slowness (inverse of velocity) within cell "*j*".
Using a first order Taylor expansion and neglecting residual error, from equations (2.1) and (2.2), the following equation can be written in matrix form as:

$$\bar{y} = A\bar{x} \tag{2.3}$$

where
$\bar{y}$ is the difference between computed travel times obtained from the model and the observed travel times obtained from the field
$\bar{x}$ is the difference between the true and the modeled slowness
A is the Jacobian matrix.

In travel time tomography, Equation 2.3 is usually solved by two methods: 1)- the matrix inversion approach (e.g. conjugate gradient (CG) matrix inversion technique) (Nolet, 1987; Scales, 1987); and 2)- the "back-projection" inversion technique, adapted from medical tomography (e.g. simultaneous iterative reconstruction technique (SIRT)) (Herman, 1980; Ivanson, 1986).

In both techniques, the acoustic wave-field is initially propagated through a presumed theoretical model, and a set of travel times are obtained by ray tracing through the cells (forward modeling step). The travel time equations are then inverted iteratively to solve for the changes in slowness that produces a best-fit solution with the lowest root mean square (RMS) error between the observed and computed travel times (inversion step). The model is then modified, new ray paths traced, and the process repeated until the slowness distribution matches observations within acceptable tolerances. In practice, an adequate tomographic solution can be obtained if enough ray paths penetrate the medium in multiple directions. To reach this, the recording procedure uses large number of source/receiver locations. Color-coded tomograms of the velocity distribution within the medium are then generated from inversion results as the final step in the tomography data processing. Tomogram interpretation is the next step for defining areas of defects by evaluating velocity changes through the medium (Robert E. Sheriff and Lloyd P. Geldart, 1995).

In velocity tomography, only the first arrival pulses are considered. Therefore, only the signal component that travels through the fastest path is used in the analysis. As the velocity changes through the medium due to energy absorption, the slowness (1/velocity) of any uniform cell of the medium may change not only the travel time, but also the ray path.

A number of software algorithms for performing travel time tomography exist. These algorithms use straight or curved rays, 2-D or 3-D matrix inversion, and 2-D or 3-D graphic packages to display the results. For accurate volumetric imaging of anomalies in drilled shafts, it is critical to use a software package with the following characteristics: a)- curved ray tracing or wave propagation; b)- true 3-D tomographic inversion; c)- 3-D display of data. Two-dimensional tomographic inversion produces defect images in 2-D planes (panels), which is inadequate for reconstructing the size and shape of anomalies in some cases.

The CSL data measured between the three access tubes of abutment 1 shaft 2 were processed for P-wave first arrival times. The data were then processed using the RockVision3D software for generating 3-D velocity tomograms of the shaft interior. The input information for the tomogram generation was; 1) depth of the shaft where the first arrived component of the signal was measured, 2) the first picked arrived time at each depth, and 3) tube separation distance.

The program code is designed to provide multiple iterative reconstructions of path length for calculated seismic velocity determined from measured travel times. Ray paths are calculated by propagating a finite-difference wave front across the surveyed shaft from a known source location. For low velocity contrast, straight rays are often assumed. In higher velocity contrast, the rays bend (refract) resulting in longer ray paths.

A 3-D representation of the shaft interior was constructed and imaged to produce 3-D contours velocities (green areas in the figure) to emphasize areas of "questionable" integrity and 2-D cross-sections between access tubes in Figure 2.2. From these images, three distinct velocity contrast zones are seen: z*one1* with maximum measured velocity (red), which indicates that the concrete is in "good" condition; z*one 2* with middle range velocity (green), indicating velocities 10%-20% lower than the maximum measured velocity, and z*one 3* upper zone (purple) showing the extent of the shaft with the velocities down to 2,000 m/s. This zone shows the top of the shaft where the tubes are outside the concrete and is not an indication of any defects in the upper area of the shaft. The locations, size, and orientation of the anomalies are clearly depicted in these images.

Horizontal cross-sections looking from the top of the shaft at 0.5-m intervals are also plotted and shown in Appendix A. The first image at 5.5 m from the bottom of the shaft shows the portion of the shaft with the velocities down to 2,000 m/s. Going deeper into the shaft, the location of an anomalous zone with the velocities of the concrete showing "questionable" structure condition can be clearly seen. Images were produced to compare the results of the CSL x,y plots with the tomographic imaging maps. By plotting color-coded 3-D tomographic images of the ultrasonic data (CSL), accurate location of anomalous/questionable zones and their geometries can result in more reliable information about the shaft concrete integrity.

1.6 Defect Definition and Drilled Shaft Integrity

Defects, or anomalies that critically affect shaft performance, are difficult to define using results from CSL. This limitation has resulted in serious disputes and litigation. The effect of the size, location, and distribution of anomalies on shaft performance and structural integrity are difficult to quantify apart from numerical analysis. Without advanced numerical analysis tools, defect definition is often arbitrary, exaggerated, and overrated. Certain guidelines have been proposed to constitute a defective shaft, such as a 20% reduction in overall concrete velocity. Errors in tube separation distances could easily result in an invalid shaft rejection. A defective shaft could easily be adjusted to pass acceptance by "correcting" the picks or tube separation distance. This problem will be analyzed in greater depth in the following chapters, to define the relationship between defects and shaft integrity, using numerical analysis tools and techniques.