CHAPTER 6 – SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

6.1 SUMMARY

In this study, a three-step approach was developed for integrity assessment of drilled shaft foundation that contains access tubes, according to:

1. *Anomaly Identification and Independent Verification* - The first step addressed how to correctly identify and independently verify anomalies in a drilled shaft. A dual testing approaches using crosshole sonic logging (CSL) and gamma-gamma density logging (GDL) methods was used. For proper imaging of shaft's interior, a three-dimensional crosshole sonic logging tomography (CSLT) inversion technique was utilized.
2. *Defect Definition* – Once a suspected "anomaly" zone was identified in a CSLT data, the second part of this study used a statistical analysis to separate velocity distribution of sound concrete from anomalous concrete. With this analysis, a cut-off velocity was obtained that separated the two velocity distributions. The cut-off velocity was used to volumetrically image (contour) a "defect".
3. *Defect Characterization and Imaging* - The third part of this study related changes in velocity values in the defect volume to changes in concrete strength and a 3-D strength image was developed for the integrity assessment by the engineer.

6.2 CONCLUSIONS

The report conclusions are as follows:

- *Anomaly Identification and Verification* – It was demonstrated that a dual CSL/GDL testing must be used to correctly identify anomalies. CSL did not record anomalies outside the rebar cage; GDL did not record anomalies in the interior portion of the shaft and did not distinguish between isolated anomalies located outside the cage from those that extend inside the cage but do not intercept the tubes. Dual testing approach also eliminated CSL and GDL false positives.
- *Shaft Velocity Imaging* – Two and three- dimensional crosshole sonic logging tomography (CSLT) was used for imaging the shaft's interior. It was found that for best results, a tomographic inversion package must be used that employs true 3-D inversion followed by 3-D display of the data. 2-D inversion of data followed by 3-D display sometimes created unacceptable velocity gradients between 2-D panels.
- *CSLT Pre-Processing (Velocity Equalization)* - CSLT requires the use of a true 3-D tomographic inversion package which entails the critical pre-processing step for velocity equalization. It was demonstrated that velocity equalization significantly reduced boundary artifacts and resolved anomalies better—especially for the 3-D inversion.
- *Defect Definition* - In this study, a statistical approach was used to determine cut-off velocities by fitting multiple Gaussian distribution curves to the CSLT velocity histogram. The curve fitting approach was applied separately for several levels of defects. For defective shafts, two to three Gaussian fit adequately resolved for a cut-

off velocity. For shafts without a defect, either a single Gaussian fit to the velocity histogram or a two Gaussian fit was obtained with a cut-off velocity close or higher than the median velocity. It was demonstrated that the cut-off velocity defines the defect volume in a velocity tomogram.

- *Defect Imaging (Velocity)* – Using the cut-off velocities, volumetric images of the defect was obtained (velocity contouring). It was demonstrated that tomography slightly over sizes defects but underestimates their velocities.
- *Defect Imaging (Strength)* – Finally, an empirical method was used to correlate velocity to strength and defect images were obtained in units of strength. A procedure was described for developing a shaft-specific velocity to strength correlation using laboratory concrete cylinders with the same design mix as the shaft and measuring their maturity. In developing the strength models, the edge artifacts present in tomograms were excluded; therefore, the strength tomograms represented the final interpretation for integrity assessment by the engineer. Strength tomograms sometimes resolved for small defects which were not readily observed in velocity tomograms using a separate cut-off velocity in that zone.
- *Shaft Monitoring Results* - It appeared that the strength of the concrete in a drilled shaft was not only a function of time but also a function of the physical properties of the surrounding soil/rock and the depth of the groundwater table (boundary condition). Two parameters from the soil profile were noted: the thermal conductivity and the permeability. Conductivity controls relative changes in temperature and permeability controls small relative changes in the moisture content. These parameters in turn control curing (age) and concrete strength—as it relates to incremental changes in velocity and density.

Therefore, in this study, a more compelling basis was created for the foundation engineer in deciding to accept, correct (remediate), or reject a given drilled shaft or a wall structure.

6.2.1 Benefits of Tomographic Imaging

For the anomalies that extend inside the rebar cage, the CSLT method is an indispensable tool for volumetric imaging of defects. CSLT also images horizontally elongated defects (such as cold joints) missed by both CSL and GDL methods. Therefore, three (3) main benefits of tomographic imaging can be identified:

1. Tomographic imaging provides better spatial resolution of defects for confirmation through coring followed by remedial action (if necessary);
2. Tomographic images provides a more accurate correlation between percentage drop in velocity with percentage drop in concrete strength for shaft acceptance criteria; and,
3. Two and three dimensional tomography, when performed routinely, will provide engineers in the owner agencies a tool for assessing the integrity of drilled shaft foundations without further costly delays to construction.

6.3 RECOMMENDATION FOR FUTURE STUDY

For future study, it is recommended to construct a test drilled shaft (preferably at a federal or state test site) of diameter of 1.8 m (6 ft) or larger containing both PVC and steel access tube with engineered defects. Accordingly, the following investigations are recommended:

- *Field Monitoring of The Shaft during Curing Cycle* – A second temperature monitoring study needs to be conducted at a larger diameter shaft of at least 1.8 m (6 ft)—as compared to the present study of 0.9 m (3 ft) diameter shaft—to better understand mass concrete behavior in drilled shafts. A continuous monitoring of temperature must be performed using both maturity meters and continuous geophysical temperature logging method. Along with temperature monitoring above, continuous crosshole sonic logging, gamma-gamma density, and neutron-moisture log measurements must be obtained on at least a 7-day period to examine changes in velocity, density, and moisture content versus time (or curing of the mass concrete).
- *Laboratory Testing and Monitoring* – Standard size concrete cylinders and beams must be placed using the same mix proportions used in the construction of the test drilled shaft. The specimens, equipped with thermocouples, must be connected to a maturity meter for a period of 28 days. Shortly before a specimen is subjected to strength test, ultrasonic pulse velocity measurement must be performed with 40 kHz frequency transducers. Standard compression or three point bending tests must be performed on at least 3 cylinders or beams at ages of 1, 4, 7, 14, 21, and 28 days. Next, a plot between the average compressive or flexural strengths and average maturity values at corresponding times must be made and a best-fit curve is drawn through the plot. The curve is then used for estimating the strength of concrete based on maturity. Similarly, a plot between the average compressive or flexural strengths and average velocity must be developed.
- *Permanent Test Site for the Calibration of Gamma-Gamma Density Probes* – The shaft must be constructed using three different concrete mixes (for instance, by changing water-cement ratio) at three different depth intervals. In this way, this shaft will serve as a much-desired permanent test site for GDL probe calibration under realistic field conditions with different tube types, and presence of the rebar cage. The three batches can be created using different densities; for example, at 1.6 g/cm^3 (100 lb/ft^3), 2.4 g/ cm^3 (150 lb/ft^3), and 3.2 g/cm^3 (200 lb/ft^3). In addition, velocity strength information must be obtained using each different concrete batch.
- *Defect Study* – The shaft must be constructed using engineered defects both inside and outside the rebar cage. The defects will be used in a defect study comparing the capabilities of all geophysical logging methods. In addition, defect definition by GDL method will be compared using PVC versus steel pipes. The carefully designed defects can be used for calibrating the radius of investigation of GDL probes. Special care must be taken in constructing the defects so that they do not collapse during construction.
- *Velocity to Strength Correction Factors* - Tomography tends to slightly over size defects and underestimates their velocities. Therefore, a corrective factor needs to be determined to apply to defect velocities for accurate correlation to strength. More extensive modeling study, similar to tomography modeling in Section 2.2.3, needs to be performed. Other correction factors include terms to correct for the effect of temperature, as

discussed above, and those discussed in Section 4.2. Using these correction factors, shaft-specific strength models must be developed.

- *Integrity Assessment* – The final goal of this study is to input strength models described in this study into a drilled shaft design modeling program (such as Florida Pier and PLAXIS finite element programs). Procedures for doing this task using commonly used shaft design programs needs to be described. These programs may also incorporate the soil profile as well as other drilled shafts in a shaft group. In this way, the effect of a defective shaft to the load capacity of the entire designed structure can be assessed and final evaluation of shaft integrity and serviceability can be analyzed by the engineer more quantitatively than the present practice.
- *Development of New Guidelines* – Finally, a new testing guideline needs to be written to address the steps required to identify, verify, image and assess the integrity of drilled shafts, as is described in the next section. This guideline must also include a detailed description of remediation methods and discuss each method's advantages and limitations.
- *Refine the Design Procedures* – Given the assumption that the drilled shafts are constructed properly without defects, the design procedures and factors of safety need to be refined for an improved cost efficiency and design life.

6.4 PROPOSED NEW GUIDELINES FOR NDE TESTING PROGRAM OF DRILLED SHAFT FOUNDATIONS

Ultimately, this focused effort will be directed by the FHWA-FLH in developing new guidelines and specifications for the foundation engineers in defining potentially defective concrete drilled shaft foundations and retaining walls. The guideline will close the decision making loop so that integrity evaluation are made within days of field testing rather than within weeks/months which is the current practice. A clear methodology or "road map" must be laid out for the engineers in the owner agencies as how to relate observed anomalies in CSL/CSLT data to possible defect definition, whether those defects are structurally significant, and what effective corrective measures are available for immediate remedial solutions. Ultimately, the new guidelines and specifications will eliminate uncertainty in integrity assessment of drilled shaft foundations, will result in project savings, and reduces costly project delays.

A brief example of the NDT testing guidelines are described herein. Based on the results of this study, it is recommended that the NDT testing program of the owner agencies to consist of the following three phases:

Phase I. Anomaly Identification (and Verification) – In this phase, the testing agency initially performs dual CSL and GDL testing at any time after 1.5-2 days after concrete placement to *screen*—as a whole—between sound and anomalous shafts and independently verify their existence. Dual testing is required to assess shaft integrity both inside ("core" of the shaft) and outside the rebar cage (cage "cover" and rebar's exposure to soil/moisture). Dual testing is also required to independently verify anomalies and discern false positives (or false negatives) of a particular test method (please refer to Appendix A case histories for examples).

Phase II. Strength Imaging of Defects **–** Only for the shafts suspected to be defective in the first phase, tomographic imaging is performed at least 7 days after the concrete placement. In this way, the sonic velocities in the tomogram will be similar to the laboratory measurements and a more realistic velocity-strength correlation is obtained in developing the final strength images.

Alternative Approach - Combined Phase I and II. CSLT testing is done at the same time as CSL/GDL testing and less than 7 days after the concrete placement. A total of 2-3 shafts must be instrumented with thermocouples at each soil, rock, and ground water boundary and continuously logged using maturity meters. In this way, CSLT velocities of the same maturity will be compared to the cylinder strength data. Otherwise, the less accurate fourth-power velocity to strength empirical relationships must be used.

In either approach, three-dimensional tomographic imaging software must be used and all CSL velocity curves must be equalized prior to the tomographic inversion. Statistical analysis must be used to analyze post-tomography images for determining cut-off velocity between sound and defective concrete.

Phase III. Shaft Integrity Evaluation and Remediation **–** In this phase, the strength image is input into the original shaft design program to determine if the shaft is still serviceable, can be repaired by remediation, or unacceptable. In this way, a final integrity (and pay-factor) is assessed by the engineer more quantitatively than the present practice.

Based on the results of modeling and the effects of size and location of a defect in relation to the load capacity of the designed structure, the engineer may recommend remediation. Some important criteria include the location of the maximum moment or the shaft's vulnerability to rebar corrosion when the cage cover is lost due to soil intrusion. For shallow defects, the shaft is usually excavated and patched in place. For deeper defects, the most common remediation method used is coring followed by pressure grouting using micro-fine cement. Other techniques used for deeper defects include compaction grouting (with about 2.5 cm (1" slump)) and jet grouting. CSLT tomography can be used post-remediation to check the effectiveness of remediation.

In the medical field, the first phase is analogous to the initial examination and diagnosis by the general practitioner. The second phase is analogous to the imaging of an unhealthy member. The third phase is analogous to conducting external or internal remedies by the specialist.

Laboratory and Field Support. In support of the NDE testing program above, standard size cylinders or beams must be placed using the same mix proportions used in the construction of the test drilled shaft. Shortly before a specimen is subjected to strength test, ultrasonic pulse velocity measurement (or equivalent test) must be performed using transducers with similar center frequency than the CSL system. Standard compression or three point bending tests must be performed on at least 3 cylinders or beams at ages of 1, 4, 7, 14, 21, and 28 days and a plot between the average compressive or flexural strengths and average velocity must be developed.

If the combined Phase I and II is used, the concrete cylinders must be equipped with thermocouples and be connected to a maturity meter for a period of 28 days. A plot between the average compressive or flexural strengths and average maturity values at corresponding times must be made and a best-fit curve is drawn through the plot. The curve is then used for estimating the strength of concrete based on maturity. Similarly, a plot between the average compressive or flexural strengths and average velocity must be developed. In the field, the temperature history of each drilled shaft must be recorded from placement to the time CSLT measurements are performed. Using the maturity index, the strength at that maturity is estimated by comparing to the laboratory measurements.

If a separate Phase I and Phase II approach is used, it is *recommended* to equip 1-2 test cylinders with thermocouples and connect to a maturity meter for a period of 28 days. In the field, one test drilled shaft must be embedded with thermocouples near the rebar cage and at the center of the shaft and be monitored for about 10 days. The purpose of this study is to: 1) assess the maximum temperature reached in the shaft; 2) examine maximum temperature differential between the center and the side of the shaft; and, 3) determine the required time for tomographic testing by comparing maturity indexes from the field to the laboratory samples.