CHAPTER 7. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS FOR FUTURE STUDY

Several conclusions may be explicitly or implicitly inferred from this study. The modeling technique used here identifies the discrete sources that can influence the variation of measured CSL velocities. Where CSL data are shown as a cumulative result of the various factors that effect velocities over the cross-section of the drilled shaft, this method provides insight into how each one contributes to the final estimate of concrete quality. It also offers a basis for quality control engineers to use in refining and improving CSL data collection methods such that one-by-one sources of velocity variations can be eliminated, and a truer estimate of the concrete quality can be obtained.

This study suggests that current techniques for generating CSL data plots of velocity and energy are fairly reliable for estimating concrete consistency, as CSL data processing techniques have potential to detect voids and honeycomb regions. It does however, have difficulty in detecting cracking and estimating strength.

Current methods employed for first arrival determination are arbitrary and open to manipulation. Manipulation of arrival picks can result in velocity artifacts, or can eliminate existing defects. Lack of tolerances in CSL data collection equipment is also a problem, which may result in arrival pick variations. Poor quality CSL data collection equipment results in poor quality, noisy, and unreliable data. For tomography purposes, failure to account for tube bending results in velocity artifacts. Failure to account for sensor position and orientation in access tubes can result in velocity artifacts. PVC access tubes transmit higher amplitude signals than steel. Steel access tubes are more resistant to breaking and bending during concrete placement and curing. Steel access tubes reduce tube de-bonding due to lower thermal expansion. The thermal expansion of PVC is 10 times higher than steel. Thermal expansion of access tubes results in tube de-bonding in the upper portions of the shaft, further complicating data interpretation. Access tubes transport heat from the shaft, and can result in concrete cracking. The resulting CSL data can be misinterpreted as tube de-bonding, but it can be accurately noted as cracking as it also is more likely to occur in the upper portions of the shaft where tubes are exposed to the surface. Filling tubes with water prior to concrete placement reduces this effect.

Concrete cures as a result of chemical hydration processes, and does not dry by loss of moisture. Surrounding ground conditions affect curing rates and temperature gradients. Temperature gradients above a certain level result in cracking. Stress in the drilled shaft is not uniformly distributed throughout the depth of the shaft. Soil density, friction angles of geo-materials, defects in the shaft, and consolidation levels are the major control factors for stress concentration. Failure to account for variations in curing rates, shaft temperatures, heat transfer, stress, cracking, and the surrounding environment will likely result in velocity artifacts. This may be an issue if the CSL data is collected too soon, that is before the conventional 48-hour cure time.

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Full shaft tomography should not be done unless all the deviations have been identified. Quantitative processing techniques, such as tomography, should not be used on CSL data that has not been quantitatively acquired or processed. With quantitative data collection, numerical inversion and analysis has potential to improve data processing and interpretation for CSL, providing objective, automated techniques for evaluating the data. This includes in situ measurement of concrete properties, shaft evaluation outside of the reinforcement cage, shaft cohesion with the surrounding ground, shaft bulging or necking, and cracking defects. Numerical analysis can evaluate effects of shaft defects, estimate load capacity, account for variations in curing rates, and estimate cracking. Numerical analysis can also estimate long term effects such as corrosion and scouring, with further study.

RECOMMENDATIONS FOR THE FUTURE

Recommendations for future improvement are to supplement CSL with a more quantitative NDE and emerging technique. We propose the installation of embedded sensors as opposed to access tubes. These sensors should be distributed throughout the shaft, connected serially by a single cable for power and data communication. This cable may be connected to a power source and computer at the surface, and be accessible for the life of the shaft. Each sensor should be capable of generating a seismic source. The sensors should measure three-component particle acceleration within the concrete, of sources generated by other embedded sensors within the same shaft, from adjacent shafts, from vertical or horizontal impacts at the top of the shaft, or impacts at the surface on surrounding ground. Each sensor should measure the temperature of the concrete. The sensors should be capable of accurate and automatic self location and orientation. Data from the sensors should be processed and analyzed to reconstruct an image of the entire shaft, inside and outside the rebar cage, as well as the surrounding ground. The bearing capacity of the entire support structure, including adjacent shafts and surround ground, should be evaluated by numerical analysis.

The system could be fully automated, and accommodate additional manual surveys if desired. Automated surveys should be conducted monthly for the first half year, and annually after that, to show changes in the shafts or surrounding ground over time. This system would be effective for on-demand monitoring to determine the drilled shafts condition for instance after catastrophic events of scour events or earthquakes. Until this proposed embedded sensor system is developed and validated, the CSL systems should still be employed.