Chapter 7

Summary and Conclusions

7.1 Summary

The goals of this research were to acquire the most comprehensive CPT-based field performance case history database to date, process this data consistently and to high standards, and then use the results to develop accurate and reliable predictive relationships for assessment of the likelihood of "triggering" or initiation of seismically induced soil liquefaction. Thin layer corrections required for interpretation of CPT for some cases were quantified using a refined thin layer correction which was developed based on an elastic solution, field data, and previous recommendations. Improved methods for normalization of tip and sleeve resistance measurements for effects of varying effective overburden stresses were defined using prior empirical work, new theoretical analyses, laboratory calibration chamber test data and field data.

A correlation is only as good as the quality of the data upon which it is based. One goal was to produce a database of the most highly scrutinized and consistently processed liquefaction/non-liquefaction sites available. To achieve this, strict protocols were established for processing and grading data according to the quality of information content. Data that did not meet a minimum level of quality were discarded. This database was then submitted for review to a panel of leading experts in the area of soil liquefaction engineering, and consensus views of key parameters for each case were developed iteratively.

Proper treatment of the data required a flexible statistical technique. A Bayesian-type analysis was chosen because this statistical technique can accommodate all forms of uncertainty associated with both the phenomena of seismic “triggering” of soil liquefaction and our attempts to quantify this phenomenon. Reliability methods were utilized to present the results in a formal probabilistic framework.

7.2 Conclusions

This work resulted in a new CPT-based soil liquefaction “triggering” correlation that provides greatly improved ability to assess the likelihood of initiation of soil liquefaction during earthquakes. Key elements that led to significant overall improvements relative to prior efforts included the following:

- A significantly larger number (more than 600) of CPT-based field performance case histories were assembled and analyzed.
- The quality and quantity of the field data, the careful and consistent processing of this data under the supervision and review of an expert panel, and the screening of the resultant processed data based on information content and reliability of each case, resulted in a processed case history database of high value.
- The methods used to quantify CPT data for liquefaction purposes were scrutinized by the authors and the review panel. The canonization of these methods should result in more consistency throughout the field of liquefaction engineering in both acquiring and processing future data.
- The new and improved procedures for normalization of CPT tip and sleeve resistances for effects of varying effective overburden stress represent an

improvement over previous empirical work, and will likely have value beyond the narrow application of liquefaction hazard assessment.

- Using higher order statistical methods to characterize and deal with the various forms of uncertainty associated with this problem resulted in a much improved basis for estimation of the likelihood of triggering of liquefaction during earthquakes. Moreover, the results are presented in a formal probabilistic framework, facilitating assessment of risk and uncertainty, as well as in a more simplified "deterministic" framework based on a selected and defined level of risk.

7.3 Future Research Recommendations

The results of this research represent a significant advance, but there is more that can be done. Recommendations for future work include the following:

- Cross correlation studies should be performed for SPT-, CPT-, and V_s-based triggering correlations (including correlations under development) to provide improved consistency between these index tests, and to draw on the advantages of each to better refine triggering assessments and to reduce overall variance uncertainty.
- Quantify the effects of "driving" static (gravity induced) shear stresses due to slopes, buildings, etc., on liquefaction initiation.

- Include pore pressure into the limit-state function as either an independent variable or in state-parameter (ψ) form to capture any effects this may have on the threshold of liquefaction.
- Perform liquefaction susceptibility studies using a combination of calibration chamber tests and triaxial or cyclic simple shear testing.
- Develop a theoretical (cavity expansion?) model for the CPT sleeve and also for the SPT.
- Improve the signal to noise ratio of CPT sleeve measurements.
- Quantify the effects of liquefaction on pre-to-post-earthquake index measurements.
- Develop an updated CPT-based soil "classification" chart using rigorous data processing techniques and higher order statistics.
- Acquire high quality field data from every seismic event that presents the opportunity.