

Table of Contents

Abstract.....	ii
Grant Information.....	iv
Dedication.....	v
Acknowledgements.....	vi
Table of Contents.....	viii
List of Tables.....	xiv
List of Figures.....	xvi
Chapter 1. Introduction.....	1
1.1 Objective of Research.....	1
1.2 Background and Approach to Solution.....	1
1.3 Organization of the Thesis.....	5
Chapter 2. Review of Liquefaction Evaluation Procedures.....	9
2.1 Introduction.....	9
2.2 Overview of the Procedures.....	10
2.2.1 Stress-based procedure.....	10
2.2.2 Strain-based procedure.....	17
2.2.3 Energy-based procedures.....	23
2.2.3.1 Procedures developed from earthquake case histories.....	26
2.2.3.1.1 Gutenberg-Richter approaches.....	26
2.2.3.1.1a Davis and Berrill (1982).....	26
2.2.3.1.1b Berrill and Davis (1985).....	28
2.2.3.1.1c Law, Cao, and He (1990).....	31
2.2.3.1.1d Trifunac (1995).....	33
2.2.3.1.2 Arias intensity approaches.....	40
2.2.3.1.2a Kayen and Mitchell (1997).....	40
2.2.3.1.2b Running (1996).....	45
2.2.3.2 Procedures developed from laboratory data.....	47
2.2.3.2.1 Alkhatib (1994).....	47

2.2.3.2.2 Liang (1995).....	49
2.2.3.3 Other Approaches.....	50
2.2.3.3.1 Mostaghel and Habibaghi (1978, 1979).....	50
2.2.3.3.2 Moroto and Tanoue (1989).....	50
2.2.3.3.3 Ostadan, Deng, and Arango (1996, 1998).....	50
2.3 Overview of the Parameter Study.....	50
2.3.1 Objective.....	50
2.3.2 Discussion of expected trends.....	52
2.3.3 Results of parameter study and summary of observed trends.....	56
2.3.4 Commentary on procedures.....	67
2.3.4.1 Gutenberg-Richter approaches.....	67
2.3.4.2 Arias intensity approaches.....	68
2.4 Conclusions.....	75
Appendix 2a: Normalization of measured SPT <i>N</i> -values.....	76
Chapter 3. Mechanism and Mathematical Representation of Energy Dissipation.....	78
3.1 Introduction.....	78
3.2 Mechanisms of Energy Dissipation in Sands.....	78
3.2.1 Frictional Dissipation Mechanism.....	79
3.2.2 Viscous Dissipation Mechanism.....	85
3.3 Modeling of Energy Dissipation.....	87
3.3.1 Hysteresis loops.....	87
3.3.2 Equivalent Linearization and Damping Ratios.....	89
3.3.3 Final Comments on <i>D</i>	95
3.4 Use of Dissipated Energy to Quantify Capacity.....	96
3.5 Computing Dissipated Energy from Laboratory Tests.....	97
3.5.1 Cyclic Triaxial Test.....	100
3.5.2 Cyclic Simple Shear Test.....	101
3.5.3 Hollow Cylinder Triaxial - Torsional Shear Test.....	102
3.5.4 Use of the Derived Equations.....	104

Chapter 4. Energy-Based Excess Pore Pressure Generation Models.....	105
4.1 Introduction.....	105
4.2 Energy-Based Pore Pressure Models from Published Literature.....	106
4.2.1 <i>N-NS</i> Model.....	107
4.2.2 <i>MH</i> Model.....	108
4.2.3 <i>DBI</i> Model.....	108
4.2.4 <i>BD</i> Model.....	109
4.2.5 <i>DB2</i> Model.....	109
4.2.6 <i>YTI</i> Model.....	110
4.2.7 <i>LCH</i> Model.....	112
4.2.8 <i>YS</i> Model.....	113
4.2.9 <i>Hsu</i> Model.....	114
4.2.10 <i>Liang</i> Model.....	115
4.2.11 <i>OAY</i> Model.....	116
4.2.12 <i>FSKL</i> Model.....	117
4.2.13 <i>WTK</i> Model.....	118
4.3 Commentaries on the Models.....	119
4.4 <i>GMP</i> Model.....	120
4.5 Load Dependency of Calibration Parameters.....	126
4.6 Summary.....	128
 Chapter 5. Proposed Energy-Based Liquefaction Evaluation Procedure.....	 129
5.1 Introduction.....	129
5.2 Mathematical Expression for Computing Dissipated Energy.....	129
5.2.1 Determination of τ	131
5.2.2 Determination of G and D	131
5.2.3 Determination of N_{eqv}	134
5.3 <i>Capacity</i> Curve.....	142
5.4 Liquefaction Evaluation.....	151
5.5 Parameter Study.....	151

5.6 Comparison of Energy-Based Capacity Curve Derived from Field Data with Laboratory Test Data.....	156
Appendix 5a: Earthquake time histories used in the parameter study to develop the correlation relating Richter magnitude (M), epicentral distance (ED) from the site to the source, and number of equivalent cycles (N_{eqv}).....	178
Appendix 5b: Profiles used in the parametric study to develop the correlation relating Richter magnitude (M), epicentral distance from the site to the source (ED), and number of equivalent cycles (N_{eqv}).....	181
Appendix 5c: Energy-based magnitude scaling factors (MSF).....	186
Chapter 6: Determination of Seismologic Parameters for Proposed Liquefaction Evaluation Procedure.....	195
6.1 Introduction.....	195
6.2 Procedure for determining epicentral distance (ED) and magnitude (M) of the design earthquake.....	196
6.3 Currently Used Procedures for Determining a_{max}	200
6.4 Proposed Procedure for Determining a_{max}	206
6.4.1 Approximate Spectral Shapes of USGS Rock Outcrop Motions.....	210
6.4.2 Response of Uniform Soil Profiles.....	216
6.5 Comparison of proposed procedure with currently used amplification curves.....	222
Appendix 6a: Procedure for computing an equivalent uniform profile.....	230
Chapter 7. Remedial Ground Densification Techniques.....	234
7.1 Introduction.....	234
7.2 Vibro-Compaction.....	239
7.2.1 Vibrocompaction.....	241
7.2.2 The Vibratory Probe Method.....	249
7.2.2.1 Terra-Probe.....	251
7.2.2.2 Double Tube Rod and Rod with Projectives.....	252
7.2.2.3 Vibro Wing.....	254

7.2.2.4 Franki TriStar Probe (or Y-Probe).....	255
7.2.2.5 Double-Y or Flexi Probes.....	256
7.2.2.6 Frequency of Vibration.....	260
7.3 Deep Dynamic Compaction.....	267
7.4 Explosive Compaction.....	279
7.4.1 Mechanisms of Densification.....	282
7.4.2 Procedures for Selecting Charge Size and Spacing.....	290
7.4.2.1 Kok Approach.....	290
7.4.2.2 Gohl et al. Approach.....	296
7.4.2.3 Narin van Court and Mitchell Approach.....	298
7.5 Comparison of the Mechanical Energy Input by the Densification Techniques.....	300
7.5.1 Vibro-Compaction.....	300
7.5.2 Deep Dynamic Compaction.....	302
7.5.3 Explosive Compaction.....	302
7.5.4 Discussion.....	303
7.6 Summary.....	304
 Chapter 8. First Order Numerical Models of Remedial Ground Densification Techniques.....	306
8.1 Introduction.....	306
8.2 Numerical Model Verification and Validation.....	307
8.3 Numerical Modeling of Vibro-Compaction.....	308
8.3.1 Proposed Model.....	308
8.3.2 Attenuation Relationships.....	313
8.3.3 Comparison of Proposed First Order Model Predictions with Empirical Guidelines.....	324
8.4 Numerical Modeling of Deep Dynamic Compaction.....	329
8.4.1 Approximate Input Motion for Deep Dynamic Compaction.....	329
8.4.2 Response of the Soil at Depth for Deep Dynamic Compaction.....	341
8.5 Numerical Modeling of Explosive Compaction.....	351
8.6 Higher Order Numerical Modeling for Remedial Ground Densification.....	361

8.7 Summary and Conclusions.....	362
Chapter 9. Summary and Conclusions.....	365
9.1 Restatement of Research Objective.....	365
9.2 Overview of Research.....	365
9.3 Summary of Major Findings.....	366
9.4 Recommendations for Future Work.....	369
References.....	370
Vita.....	393