

EVALUATION OF LIQUEFACTION POTENTIAL
OF SILTY SAND
BASED ON CONE PENETRATION TEST



Paulus P. Rahardjo

46400 / T
16
10 - 89

1989

Pembastakaan
Universitas Padjadjaran
Jl. Sekeloa No. 19
BANDUNG

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

EVALUATION OF LIQUEFACTION POTENTIAL OF SILTY SAND BASED ON CONE
PENETRATION TEST

by

Paulus P. Rahardjo

Dissertation submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of
Doctor of Philosophy
in
CIVIL ENGINEERING

APPROVED:



T.L. Brandon, Co-chairman



G.W. Clough, Co-chairman



J.M. Duncan



T. Kuppusamy



C.W. Smith

Perpustakaan
Universitas Padjadjaran
Jl. Raya Bandung 29
BANDUNG

September, 1989

Blacksburg, Virginia

EVALUATION OF LIQUEFACTION POTENTIAL OF SILTY SAND BASED ON CONE PENETRATION TEST

by

Paulus P. Rahardjo

T.L. Brandon, Co-chairman

G.W. Clough, Co-chairman

CIVIL ENGINEERING

(ABSTRACT)

Liquefaction is a phenomenon where a saturated soil can temporarily lose its shear strength during an earthquake as a result of the development of excess pore pressures. For the past 25 years since liquefaction phenomenon was first explained, it was thought to be mainly a problem with clean sand, and most of the research has focused on these soils. However, as case history information has come to light, it has become apparent that silty sands are commonly involved, and in some cases even silts. This has generated a need for knowledge about the response of silty sands and silts under seismic loading. Related to this issue is the question of how best to determine the liquefaction resistance of these soils in a practical setting.

This research has the objectives of providing an understanding of the behavior of saturated silty sands under seismic loading, and developing a rational basis for the use of the Cone Penetration Test (CPT) to predict liquefaction resistance in these materials. The study is primarily experimental, relying on laboratory and field testing and the use of a unique, large scale calibration chamber. The calibration chamber allows the field environment to be duplicated in the laboratory where conditions can be closely controlled and accurately defined.

One of the first problems to be overcome in the research was to determine how to prepare specimens of silty sands that would reasonably duplicate field conditions in both the small

scale of the conventional laboratory tests, and the large scale of the calibration chamber. Out of four different methods explored, consolidation from a slurry proved to be best. Two silty sands were located which had the desired characteristics for the study. Field work, involving both the Standard Penetration Test (SPT) and CPT was done as part of this investigation. The behavior of the silty sands were determined in the laboratory from monotonic and cyclic loading tests.

The test results show that the effect of fines is to reduce the cone penetration resistance, but not to affect the liquefaction resistance. The steady state shear strength of the soils seems to be correlated to the cone tip resistance, however, this correlation shows a higher steady state shear strength than those back figured from case history data. The results were also used to define state parameters for both of the soils tested. The state parameter was found to be a reliable index to the liquefaction potential and further study in this area is recommended.

Acknowledgements

This work has been brought to completion by the assistance and advice of many people. The author is extremely grateful to his advisors, Prof. G.W. Clough and Prof. T.L. Brandon for their continuous support, patience and insights in the course of this research. The author would like to thank also Prof. J.M. Duncan, Prof. T. Kuppusamy and Prof. C.W. Smith to serve in his committee. All of them have contributed and imparted generously their wisdom and knowledge in the author's education.

This research project would not be possible without the support from the National Science Foundation. Special thanks are also due to all the geotechnical graduate fellows whose friendship has made the life in Blacksburg more alive. To all the personnel and staff in the Civil Engineering Department who help with mechanical and electronic facilities and the paper work, the author would like to express his sincere thanks.

The author owed the greatest debt to his family. Through it all, they have been at the author's side with all their love, patience and continuous support. For them, this work is dedicated to my wife, Linda, and my children, Grace, Adrian and Aditya.

Table of Contents

INTRODUCTION	1
REVIEW OF PREVIOUS STUDIES	7
2.1. INTRODUCTION	7
2.2. LIQUEFACTION MECHANISM AND THE CORRESPONDING EVALUATION METHODS	8
2.2.1. Concept of Pore Pressure Generation	8
2.2.2. Concept based on Undrained Steady State Shear Strength	14
2.2.3. State Parameter Approach	22
2.3. LIQUEFACTION POTENTIAL EVALUATION WITH EMPHASIS ON SILTY SAND	25
2.3.1. Soil Conditions Susceptible to Liquefaction.	25
2.3.2. Laboratory studies	29
2.3.3. Use of In situ Tests for Liquefaction Potential Assessment.	35
2.3.4. Liquefaction Potential Evaluation based on SPT.	37
2.3.5. Evaluation of Residual Shear Strength by SPT.	46
2.3.6. Liquefaction Potential Evaluation based on CPT.	52
2.3.7. Example of Analysis : Imperial Valley Earthquake, A Case History	62
2.4. SUMMARY.	71

EXPERIMENTAL PROGRAM AND MATERIALS	76
3.1. INTRODUCTION	76
3.2. LABORATORY TESTING PROGRAM	76
3.2.1. Sample Fabrication Techniques	77
3.2.2. Laboratory Tests for Property Evaluation	78
3.3. CONE PENETRATION TESTS IN THE CALIBRATION CHAMBER	78
3.4. CONE PENETRATION TESTS IN THE FIELD	79
3.5. SOILS	79
3.5.1. Yatesville Silty Sand	79
3.5.2. Pepper's Ferry Silty Sand	80
INVESTIGATION OF SAMPLE FABRICATION OF SILTY SANDS	83
4.1. INTRODUCTION	83
4.2. PLUVIATION TECHNIQUES	84
4.2.1. Previous Studies	84
4.2.2. Pluviation of Silty Sand through Air	87
4.2.3. Pluviation of Silty Sand through Vacuum	92
4.3. COMPACTION METHOD	98
4.4. CONSOLIDATION OF SILTY SAND FROM A SLURRY	99
4.5. SUMMARY	105
LABORATORY STUDY OF THE UNDRAINED BEHAVIOR OF SILTY SAND	109
5.1. INTRODUCTION	109
5.2. GENERAL STRESS-STRAIN BEHAVIOR OF COHESIONLESS SOIL	110
5.2.1. Behavior of Cohesionless Soil Under Monotonic Loading.	110
5.2.2. Behavior of Cohesionless Soil under Cyclic Loading	111
5.3. CONSOLIDATED UNDRAINED TESTS ON SILTY SAND	113
5.4. DISCUSSION AND INTERPRETATION OF TEST RESULTS	120

5.4.1. The Steady State Line (SSL)	123
5.4.2. The Envelope and the Mobilized Friction Angle at Steady State	127
5.4.3. Mobilized Friction Angle at Phase of Transformation	137
5.4.4. Observation of the stress-strain behavior	139
5.4.5. Behavior of Silty Sand as a function of State Parameter	140
5.5. CYCLIC TRIAXIAL TESTS ON SILTY SANDS	164
5.5.1. Test Procedures	164
5.5.2. Test Results and Discussions	165

STUDY OF CONE PENETRATION RESISTANCE OF SILTY SAND IN THE CALIBRATION

CHAMBER.	172
6.1. INTRODUCTION	172
6.2. DEVELOPMENT OF CALIBRATION CHAMBERS	173
6.3. FEATURES OF VIRGINIA TECH CALIBRATION CHAMBER	175
6.4. THE CONE PENETROMETERS	179
6.5. SAMPLE FABRICATION AND TESTING PROCEDURES	181
6.6. THE CALIBRATION CHAMBER SPECIMEN	186
6.6.1. Consolidation Data	186
6.6.2. Specimen compressibility	189
6.6.3. Void Ratio, Density and Water Content Profiles	189
6.7. CONE PENETRATION TEST RESULTS	190
6.7.1. Cone Tip Resistances	190
6.7.2. Use of Cone Tip Resistance to Characterize Sand Behavior under Load	197
6.7.3. Interpretation of the Sleeve Friction	199
6.7.3. Interpretation of the Generated Pore Pressure During Penetration	203
6.7.4. Prediction of void ratio by CPT.	207
6.7.5. Comparison to Field Penetration Resistance at Yatesville Dam site	210

FIELD CONE PENETRATION TEST STUDY	212
7.1. TEST SITE	212
7.2. TEST PROCEDURE	217
7.3. TEST RESULTS	219
7.4. ANALYSIS AND DISCUSSION	219
7.4.1. Soil type and soil profile.	224
7.4.2. SPT vs. CPT Results	224
7.4.4. Scale effect	226
EVALUATION OF LIQUEFACTION POTENTIAL OF SILTY SANDS BASED ON THE CONE PENETRATION TEST	231
8.1. INTRODUCTION	231
8.2. EVALUATION BASED ON CYCLIC STRESS RATIO	232
8.2.1. Correlation of Cyclic Strength of Yatesville Silty Sand and the CPT.	232
8.2.2. Comparison of The Tip Resistance of Silty Sand to Clean Sand at a Similar Cyclic Stress Ratio.	233
8.2.3. Analysis of Liquefaction Potential at Pepper's Ferry site	238
8.3. EVALUATION BASED ON THE STATE PARAMETER	243
8.4. EVALUATION BASED ON THE STEADY STATE SHEAR STRENGTH	247
SUMMARY AND CONCLUSIONS	253
9.1. SUMMARY	253
9.2. CONCLUSIONS	256
Bibliography	260
Appendix A. ICU TRIAXIAL TESTS	272

Appendix B. CPT IN THE CALIBRATION CHAMBER	273
Appendix C. CPT AT PEPPER'S FERRY	274
Appendix D. STATE PARAMETER AND THE OCCURENCE OF LIQUEFACTION	275

List of Illustrations

Fig. 1.1.	THE CONE PENETROMETER	5
Fig. 2.1.	IDEALIZATION OF THE EARTHQUAKE LOAD ON SOIL ELEMENT (Seed, 1979) .	9
Fig. 2.2.	TYPICAL CYCLIC TRIAXIAL TEST RESULTS (Seed, 1982)	12
Fig. 2.3.	PORE PRESSURE RATIO AS A FUNCTION OF CYCLIC SHEAR STRAIN (Dobry, 1982)	15
Fig. 2.4.	VOLUME CHANGES OF SANDS AND SILTS DUE TO RECONSOLIDATION AFTER CYCLIC LOADING (Castro, 1987).	16
Fig. 2.5.	UNDRAINED BEHAVIOR OF SATURATED COHESIONLESS SOIL (Castro, 1977)	19
Fig. 2.6.	STRESS STRAIN BEHAVIOR OF SATURATED SAND UNDER MONOTONIC AND CYCLIC LOADING (Castro, 1987)	21
Fig. 2.7.	STEADY STATE DIAGRAM SHOWING THE USE OF SSL FOR ESTIMATING THE STEADY STATE UNDRAINED SHEAR STRENGTH IN SITU (Castro, 1987)	23
Fig. 2.8.	DEFINITION OF STATE PARAMETER (Been et al., 1985)	24
Fig. 2.9.	RELATIONSHIPS OF DRAINED FRICTION ANGLE AND DILATION RATE TO STATE PARAMETER (Been et al., 1987).	26
Fig. 2.10.	GRAIN SIZES OF SOILS SUSCEPTIBLE TO LIQUEFACTION (Tsuchida, 1970) ..	28
Fig. 2.11.	SOIL CLASSIFICATION CHART FOR ELECTRIC CONE (Robertson and Campanella, 1985)	30
Fig. 2.12.	CYCLIC STRENGTH OF SILTY SANDS VS. FINES CONTENT	33
Fig. 2.13.	CYCLIC STRENGTH OF SILTY SANDS VS. MEAN GRAIN SIZE.	34
Fig. 2.14.	RELATIONSHIPS BETWEEN STRESS RATIO CAUSING LIQUEFACTION AND NORMALIZED N-SPT (Seed et al., 1984).	39
Fig. 2.15.	CORRELATION OF FIELD STRESS RATIO AND SPT-N1 FOR CLEAN SANDS AND SILTY SAND (Tokimatsu and Yoshimi, 1983)	41

Fig. 2.16.	RELATIONSHIPS OF NORMALIZED SPT-N VALUE FOR LIQUEFIED SOILS BASED ON MEAN GRAIN SIZE AND FINES CONTENTS	42
Fig. 2.17.	RELATIONSHIPS OF UNDRAINED RESIDUAL STRENGTH AND EQUIVALENT CLEAN SAND VALUES OF N-SPT (de Alba Seed, 1987)	47
Fig. 2.18.	RELATIONSHIPS OF UNDRAINED STEADY STATE SHEAR STRENGTH FROM FIELD AND LABORATORY DATA WITH SPT-N VALUES (Poulos, 1988).	51
Fig. 2.19.	CORRELATION OF CYCLIC STRESS RATIO AND NORMALIZED TIP RESISTANCE OF CPT (Robertson & Campanella, 1985)	54
Fig. 2.20.	CPT-BASED METHOD FOR LIQUEFACTION POTENTIAL EVALUATION WITH CORRECTION OF FINES CONTENTS (Ishihara, 1985).	56
Fig. 2.21.	SPT BASED CONVERSION TO CPT FOR LIQUEFACTION ASSESSMENT (Seed and de Alba, 1986).	57
Fig. 2.22.	PROPOSED CORRELATION OF CYCLIC STRESS RATIO FOR CLEAN SANDS AND SILTY SANDS (Shibata and Terapaksa, 1988).	58
Fig. 2.23.	RELATIONSHIP OF NORMALIZED CPT DATA TO STATE PARAMETER (Been and Jefferies, 1987).	61
Fig. 2.24.	SUMMARY OF METHODOLOGY TO DETERMINE VOID RATIO IN SITU (Jefferies, 1988)	63
Fig. 2.25.	MAP OF IMPERIAL VALLEY (Youd and Bennett, 1979)	65
Fig. 2.26.	SOIL PROFILE AT HEBER ROAD SITE (Castro, 1987)	66
Fig. 2.27.	LIQUEFACTION ANALYSIS AT IMPERIAL VALLEY BASED ON CYCLIC STRESS RATIO	67
Fig. 2.28.	LIQUEFACTION ANALYSIS BASED ON FLOW FEATURE MECHANISM (CASTRO, 1987).	69
Fig. 3.1.	GRAIN-SIZE DISTRIBUTION OF YATESVILLE SILTY SAND	81
Fig. 3.2.	GRAIN-SIZE DISTRIBUTION OF PEPPER'S FERRY	82
Fig. 4.1.	ALTERNATIVE PLUVIATION TECHNIQUES FOR SAMPLE FABRICATION	86
Fig. 4.2.	EFFECT OF DROP HEIGHT ON DENSITIES OF PLUVIATED SAMPLES.	90
Fig. 4.3.	EFFECT DEPOSITION RATE ON DENSITIES OF PLUVIATED SAMPLES.	91
Fig. 4.4.	COMPARISON OF EFFECT OF DROP HEIGHT ON DENSITIES OF SILTY SAND AND CLEANSAND	93
Fig. 4.5.	IMPACT VELOCITY AND ENERGY FOR PLUVIATION THROUGH VACUUM.	95
Fig. 4.6.	THE VACUUM PLUVIATOR	96
Fig. 4.7.	RESULTS OF COMPACTION TESTS ON YATESVILLE SILTY SAND	100

Fig. 4.8.	VOID RATIO OF THE COMPACTED SAMPLES.	101
Fig. 4.9.	RESULTS ON CONSOLIDATION TEST ON SLURRY	103
Fig. 4.10.	RESULTS ON CONSOLIDATION TEST ON SLURRY	104
Fig. 5.1.	BEHAVIOR OF SANDS UNDER MONOTONIC LOADING	112
Fig. 5.2.	BEHAVIOR OF SANDS UNDER CYCLIC LOADING (Vaid & Chern, 1985)	114
Fig. 5.3.	SPECIMEN CONDITION AT VERY LARGE STRAIN	118
Fig. 5.4.	AREA CORRECTION	119
Fig. 5.5.	SSL FOR YATESVILLE SILTY SAND IN TERMS OF MINOR PRINCIPAL EFFEC- TIVE STRESS	124
Fig. 5.6.	SSL FOR YATESVILLE SILTY SAND IN TERMS OF STEADY STATE SHEAR STRENGTH	125
Fig. 5.7.	SSL FOR YATESVILLE SILTY SAND IN TERMS OF MEAN EFFECTIVE STRESS	126
Fig. 5.8.	SSL FOR PEPPER'S FERRY SILTY SAND IN TERMS OF MINOR PRINCIPAL EF- FECTIVE STRESS	128
Fig. 5.9.	SSL FOR PEPPER'S FERRY SILTY SAND IN TERMS OF STEADY STATE SHEAR STRENGTH	129
Fig. 5.10.	SSL FOR PEPPER'S FERRY SILTY SAND IN TERMS OF MEAN EFFECTIVE STRESS	130
Fig. 5.11.	SSL FOR SIX SANDS	131
Fig. 5.12.	STEADY STATE ENVELOPE FOR YATESVILLE SILTY SAND	132
Fig. 5.13.	STEADY STATE ENVELOPE FOR PEPPER'S FERRY SILTY SAND	133
Fig. 5.14.	CORRELATION OF RESIDUAL EFFECTIVE STRESS AND STEADY STATE SHEAR STRENGTH FOR SILTY SANDS	135
Fig. 5.15.	CORRELATION OF RESIDUAL EFFECTIVE STRESS AND STEADY STATE SHEAR STRENGTH FOR CLEAN SANDS	136
Fig. 5.16.	TAN α_{ss} VS. VOID RATIO	138
Fig. 5.17.	CHANGES OF STATE PARAMETER UPON SHEARING	144
Fig. 5.18.	STATE PARAMETER AT PHASE OF TRANSFORMATION VS INITIAL STATE PA- RAMETER	145
Fig. 5.19.	NORMALIZED STRESS PATH OF SILTY SAND WITH VARIOUS INITIAL STATE	147
Fig. 5.20.	PROPOSED BOUNDARY OF DILATIVE-CONTRACTIVE BEHAVIOR	148
Fig. 5.21.	PEAK AND STEADY STATE FRICTION ANGLE VS. STATE PARAMETER	150

Fig. 5.22.	NORMALIZED STEADY STATE SHEAR STRENGTH VS. STATE PARAMETER FOR SILTY SAND	151
Fig. 5.23.	NORMALIZED STEADY STATE SHEAR STRENGTH VS. STATE PARAMETER FOR CLEAN SAND	152
Fig. 5.24.	NORMALIZED PEAK DEVIATOR STRESS VS. STATE PARAMETER FOR SILTY SAND	154
Fig. 5.25.	NORMALIZED PEAK DEVIATOR STRESS VS. STATE PARAMETER FOR CLEAN SAND	155
Fig. 5.26.	PORE PRESSURE GENERATED DURING UNDRAINED SHEAR VS STATE PARAMETER	156
Fig. 5.27.	DEFINITION OF BRITTLINESS INDEX	158
Fig. 5.28.	LIQUEFACTION SEVERITY VS. STATE PARAMETER	160
Fig. 5.29.	SEVERITY OF LIQUEFACTION IN TERMS OF MEAN EFFECTIVE STRESS	161
Fig. 5.30.	DUCTILITY INDEX FOR SILTY SANDS	162
Fig. 5.31.	DUCTILITY INDEX FOR BANDING #6 SAND AND SACRAMENTO RIVER SAND	163
Fig. 5.32.	CYCLIC TRIAXIAL TEST RESULTS FOR YATESVILLE SILTY SAND	166
Fig. 5.33.	CYCLIC TRIAXIAL TEST RESULTS FOR PEPPER'S FERRY SILTY SAND	167
Fig. 5.34.	CYCLIC TRIAXIAL TEST RESULTS FOR UNDISTURBED SAMPLES FROM THE LOWER SAN FERNANDO DAM (Hsing and Seed, 1988)	169
Fig. 5.35.	CYCLIC TRIAXIAL TEST RESULTS FOR MONTEREY #0/30 SAND (Sweeney, 1987)	170
Fig. 5.36.	COMPARABLE CYCLIC TRIAXIAL TEST RESULTS OF SILTY AND CLEAN SANDS	171
Fig. 6.1.	VIRGINIA TECH CALIBRATION CHAMBER	176
Fig. 6.2.	PLAN VIEW OF THE TEST HOLES IN THE CALIBRATION CHAMBER	178
Fig. 6.3.	SCHEMATIC CROSS SECTION OF THE CONE PENETROMETERS (Schaap and Zuidberg, 1982)	180
Fig. 6.4.	THE VACUUM VESSEL TO DE-AIR THE TIP OF PIEZOCONE	182
Fig. 6.5.	CONSOLIDATION OF THE SLURRY	184
Fig. 6.6.	TYPICAL CONSOLIDATION DATA FROM SPECIMEN CC-5	185
Fig. 6.7.	SET UP OF CONE PENETRATION TESTING IN THE CALIBRATION CHAMBER	187
Fig. 6.8.	TYPICAL PIEZOCONE TEST RESULTS IN CALIBRATION CHAMBER SPECIMEN	192
Fig. 6.9.	TIP RESISTANCE FROM MULTI PENETRATION TESTS IN SPECIMEN CC-5	193

Fig. 6.10.	TIP RESISTANCE VS. VOID RATIO IN THE CALIBRATION CHAMBER	195
Fig. 6.11.	COMPARISON OF TIP RESISTANCE OF SILTY SAND AND CLEAN SAND	196
Fig. 6.12.	CORRELATION OF NORMALIZED TIP RESISTANCE AND STATE PARAMETER BASED ON JEFFERIES EQUATION	200
Fig. 6.13.	NORMALIZED TIP RESISTANCE VS. STATE PARAMETER (LINEAR SCALE)	201
Fig. 6.14.	NORMALIZED TIP RESISTANCE VS. STATE PARAMETER (SEMI LOG SCALE)	202
Fig. 6.15.	TENTATIVE CLASSIFICATION CHART BASED ON	205
Fig. 6.16.	COMPARISON OF PORE PRESSURE GENERATED IN CPT AND IN TRIAXIAL TEST	206
Fig. 6.17.	PREDICTED VS. MEASURED VOID RATIO IN THE CALIBRATION CHAMBER	209
Fig. 6.18.	TYPICAL BORING LOG AT THE YATESVILLE DAM EXCAVATION, KENTUCKY	211
Fig. 7.1.	LOCATION AND THE GEOLOGY OF PEPPER'S FERRY SITE	214
Fig. 7.2.	BORING LOCATION PLAN AT PEPPER'S FERRY SITE	215
Fig. 7.3.	SPT DATA FROM BORING A1 AND C1	216
Fig. 7.4.	PHOTOGRAPH OF THE CONE PENETROMETERS	218
Fig. 7.5.	TYPICAL MINICONE TEST RESULT FOR PEPPER'S FERRY CPT NO. MIN-2	220
Fig. 7.6.	TYPICAL STANDARD CONE TEST RESULT FOR PEPPER'S FERRY CPT NO. STD-2	221
Fig. 7.7.	DATA OF 3 STANDARD CONE TIP RESISTANCE	222
Fig. 7.8.	DATA OF 3 MINI CONE TIP RESISTANCE	223
Fig. 7.9.	EXAMPLE OF PLOT OF CPT RESULTS FOR CLASSIFICATION PURPOSES	225
Fig. 7.10.	q_c/N VARIATION WITH DEPTH AT PEPPER'S FERRY	227
Fig. 7.11.	AVG. OF TIP RESISTANCE OF STANDARD CONE, MINICONE AND LARGE CONE	229
Fig. 7.12.	AVG. OF FRICTION RATIO OF STANDARD CONE, MINICONE AND LARGE CONE	230
Fig. 8.1.	COMPARISON OF BOUNDARY CURVES FOR LIQUEFACTION ANALYSIS	234
Fig. 8.2.	CORRELATION OF RELATIVE DENSITY VS STRESS RATIO FOR MONTEREY 0/30	236
Fig. 8.3.	CORRELATION OF RELATIVE DENSITY VS TIP RESISTANCE FOR MONTEREY 0/30	237
Fig. 8.4.	RANGE OF SOIL GRADATION OF PEPPER'S FERRY SITE	239

Fig. 8.5.	CORRECTION FOR DIFFERENT EARTHQUAKE MAGNITUDE	241
Fig. 8.6.	LIQUEFACTION POTENTIAL OF PEPPER'S FERRY SITE FOR DIFFERENT EARTHQUAKE MAGNITUDE	242
Fig. 8.7.	STATE PARAMETER AND THE OCCURENCE OF LIQUEFACTION (Farrar, 1986)	244
Fig. 8.8.	CHART FOR LIQUEFACTION EVALUATION BASED ON STATE PARAMETER	246
Fig. 8.9.	UNDRAINED STEADY STATE SHEAR STRENGTH VS NORMALIZED TIP RE- SISTANCE	249
Fig. 8.10.	UNDRAINED STEADY STATE SHEAR STRENGTH VS NORMALIZED TIP RE- SISTANCE	250
Fig. 8.11.	NORMALIZED UNDRAINED STEADY STATE SHEAR STRENGTH VS NORMAL- IZED TIP RESISTANCE	251
Fig. 8.12.	NORMALIZED UNDRAINED STEADY STATE SHEAR STRENGTH VS NORMAL- IZED TIP RESISTANCE	252

List of Tables

Tbl. 2.1.	SUMMARY OF LABORATORY STUDIES ON CYCLIC STRENGTH OF SILTY SANDS	32
Tbl. 2.2.	MEAN SPT-N1 VALUES FOR LIQUEFIED SOILS (Tokimatsu & Yoshimi, 1983)	43
Tbl. 2.3.	APPROXIMATE VALUES OF N1 (Seed, 1987).	49
Tbl. 2.4.	SUMMARY OF CHARACTERISTICS OF EARTHQUAKE INDUCED PHENOMENA (Castro, 1987)	73
Tbl. 2.5.	SUMMARY OF LIQUEFACTION POTENTIAL EVALUATION OF SILTY SAND USING CPT	75
Tbl. 4.1.	RECORD OF DEPOSITION RATE VS. DIAMETER OF APERTURE.	89
Tbl. 4.2.	SUMMARY OF THE RANGE OF VOID RATIO OF SILTY SAND SAMPLES	107
Tbl. 4.3.	SUMMARY ON THE ADVANGES AND DISADVANTAGES SAMPLE FABRICATED	108
Tbl. 5.1.	RESULTS OF ICU TRIAXIAL TESTS OF YATESVILLE SILTY SAND	121
Tbl. 5.2.	RESULTS OF ICU TRIAXIAL TESTS OF PEPPER'S FERRY SAND	122
Tbl. 5.3.	STEADY STATE PARAMETERS FOR SIX SANDS	142
Tbl. 6.1.	RESULTS OF CPT IN THE CALIBRATION CHAMBER	194
Tbl. 6.2.	PREDICTED VS. MEASURED VOID RATIO IN THE CALIBRATION CHAMBER	208

INTRODUCTION

During the past twenty years, research in geotechnical engineering has amply demonstrated that seismic shaking can induce excess pore pressures in saturated sands. This pore pressure development leads to a reduction of the stiffness and strength of the sand, and in extreme, it can cause the soil to liquefy. Liquefaction is a condition where the soil can flow in the presence of shear stresses such as those induced by a slope, a building foundation, or an embankment. Where the subsurface conditions are optimal for liquefaction, this phenomenon can account for a significant percentage of the life and property loss that occurs in an earthquake.

To this date (1989), most investigations into liquefaction have focussed on clean sandy soils. In part, this was due to a natural tendency to work with the simplest materials to avoid complications in testing. This trend also reflected the fact that few field studies were available to document the kinds of soils involved in liquefaction events. With time, evidence has grown that liquefaction is often associated with silty sands, and in some cases silts (Andresen and Bjerrum, 1967; Dobry et al., 1967; Lee et al., 1975; Youd and Bennett, 1983; Zhou, 1981; Ishihara et al., 1984; Hsing and Seed, 1988). As a result more interest has developed in the response of saturated silty sand during seismic loading (Ishihara et al., 1978; Chang et al., 1982; Dezfulian, 1984; and Kuerbis et al., 1988). In the 1985 National Research Council workshop

on liquefaction, one of the priority research needs was identified as understanding the behavior of silty sands and silts (National Research Council, 1985).

In addition to the change in attitudes about silty soils, the past decade has seen a shift in views about the methods of testing that should be used to identify liquefaction resistance of soils. The general conclusion has been that while laboratory tests are useful in research studies, it is not possible to reproduce the vagaries of soil structure and stress history in the laboratory that exist in the field. Thus, there has been a move towards field testing as the preferred method to evaluate the resistance of soil to seismic loading. In this process, the early emphasis was placed on use of the Standard Penetration Test (SPT) to provide the data base to characterize the soil (Seed, 1979; Tokimatsu and Yoshimi, 1983). The SPT is a simple procedure, and is commonly done as a matter of course in most geotechnical investigations. Also, because the SPT has been around for a long time, data were often available for sites where behavior was documented under earthquake shaking (Ishihara, 1977; Seed and Idriss, 1981; Seed et al., 1983). Recently, it has been recognized that the cone penetration test (CPT) offers a number of advantages over the SPT for soil characterization and for help in quantifying liquefaction resistance (Zhou, 1980, 1981; Robertson and Campanella, 1985; Ishihara, 1985; Seed and de Alba, 1986; Shibata and Terapaksa, 1987). However, the data base supporting the CPT is limited, and few, if any, formal calibration studies have been conducted in silty sands.

The purpose of this investigation is to improve our knowledge about the undrained behavior of silty sands under cyclic loading, and to help formulate a technology for use of the cone penetrometer in quantifying the liquefaction resistance of silty sands. The basis of the study is experimental, relying on laboratory and field testing, and full-scale cone penetration tests in a unique large calibration chamber.

The first cone penetrometers were developed in the Netherlands to determine the soil parameters needed to define the resistance of piles in clays. Since then, this device has been

extended to a wide range of applications. A modern cone operates electrically (Figure 1.1), and records the resistance at the tip, and friction acting on the sleeve of the cone. According to ASTM standards, the cone is 35.7 mm in diameter, with a cone tip angle of 60°, a projected tip area of 10 cm², and a friction sleeve surface area of 150 cm². Recently smaller and larger cones than the standard have been proposed and are used in practice.

The use of the cone penetrometer in liquefaction studies has taken a number of different paths, most of which are based on empirical correlations related to past site performance in earthquakes (Zhou, 1980, 1981; Shibata and Terapaksa, 1987, 1988). In these methods, the cone information is often supplemented by SPT data converted to equivalent cone tip resistances using empirical factors. Such data are useful, but ultimately are questionable because of the scatter in the conversion relations. A recent development is the introduction of concept using a soil resistance known as the "undrained steady state shear strength," and a "state parameter". The undrained steady state shear strength is the resistance of the soil when it reaches what is known as the critical state, following failure and application of large strains (Poulos et al., 1985). The state parameter defines the degree by which the initial conditions of the soil deviates from the critical state, and it has been correlated with cone tip resistance (Been et al., 1987a; Jefferies, 1988). In this research, the state parameter is used to characterize the behavior of silty sands under seismic loading.

In addressing the issues related to the use of the cone penetrometer to identify liquefaction resistance, the objectives were to :

- 1.) determine a reliable and repeatable method to produce samples of silty sand for both small samples in laboratory tests and the large samples used in the Virginia Tech large scale calibration chamber that are as representative as possible of field conditions.
- 2.) perform static and cyclic laboratory tests to define parameters and behavior of the silty sands that relate to development of excess pore pressure in an earthquake.
- 3.) conduct cone penetration tests in silty sands in both the field and in the large scale calibration chamber to provide well documented data base for cone resistance in these

materials.

- 4.) Using the data from this investigation, improve the methods for predicting liquefaction resistance of silty sands both from a conceptual and practical standpoint.

Two silty sands were used for the test program, the first of which was obtained from the location of the old Pepper's Ferry on the New River near Blacksburg. A field investigation using CPT and SPT procedures was performed at this site. The second soil came from the excavation for Yatesville Dam in Kentucky, and was provided by the U.S. Corps of Engineers. This material was used in the calibration chamber tests. In the course of this research, four procedures were examined to assess the sample formation issue. This work involved both small scale tests in the laboratory and full scale tests in the calibration chamber. To define the pore pressure and strength response of the silty sands, a total of 15 monotonic triaxial tests and 42 cyclic triaxial tests were conducted.

The calibration chamber tests involved excavating and replacing 6000 kg of the Yatesville soil for each test. To prepare the Yatesville sand for testing, it had to be processed to eliminate oversize particles and detritus. After processing, the soil was placed in the chamber in a slurry form, and consolidated for two to three weeks under stresses similar to those in the field conditions and also used in the small scale laboratory tests. A total of five calibration chamber specimens were created and 23 CPT's were performed.

The results of the investigation are provided in the following chapters. Chapter 2 gives a background review of previous work on liquefaction evaluation and cone penetration testing related to this study. At the end of this chapter the justifications for this work are presented. The scope and general methods used in the investigation are given in Chapter 3, along with a description of the two field site and testing programs at the sites. Chapter 4 covers the studies performed concerning sample fabrication techniques. This effort turned out to be more difficult than originally thought in that well developed procedures for clean sands did not work for silty sands. It is believed that the results have implications important for a variety

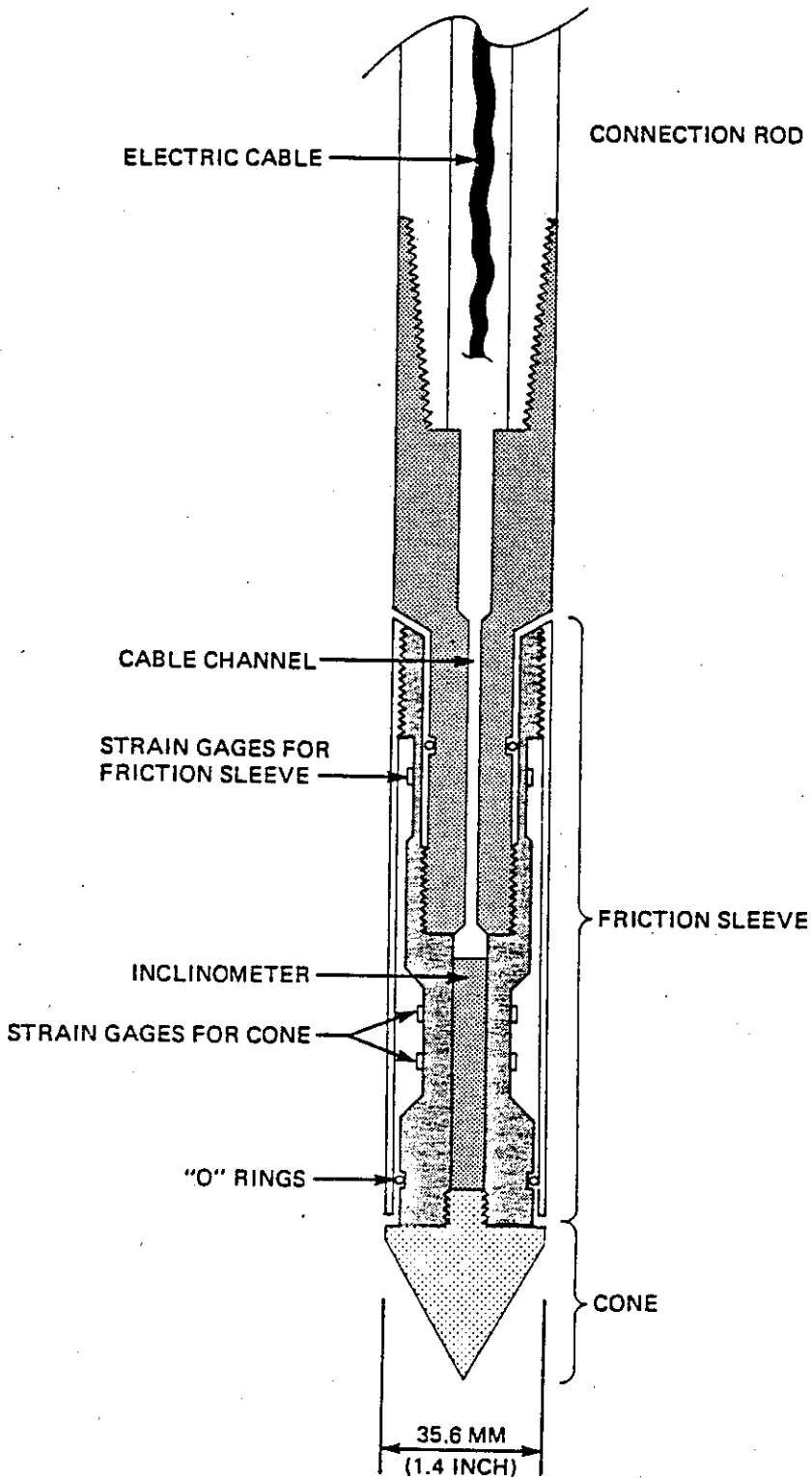


FIG.1.1. ELECTRICAL CONE PENETROMETER

of laboratory studies using silty sands. The findings obtained in the laboratory triaxial tests are presented in Chapter 5. Basic data for defining the state parameter for the two test sands is given, and compared to those for similar soils reported in the literature. Chapter 6 presents the results of the cone penetration testing in the calibration chamber. These data are unique in that the cone results can be interpreted in terms of well defined soil densities and stress conditions. The test results in the calibration chamber will be compared to the penetration characteristic in the field where the soil was derived. The field testing effort at the Pepper's Ferry site is covered in chapter 7, and the results are related to those obtained on the Pepper's Ferry soil in the other types of tests. Chapter 8 links the findings of the entire experimental program, and presents a new procedure for evaluating the liquefaction resistance of silty sands using a cone penetrometer. Finally Chapter 9 gives the summary and conclusions.