EFFECTS OF PARTICLE SIZE AND GRADING CHARACTERISTICS ON SAND MATRIX SOILS UNDER MONOTONIC AND CYCLIC LOADINGS

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DEDICATION

Alhamdulillah, thank you Allah. This thesis is dedicated to my lovely father and mother, my lovely wife and my kids who always give full support in difficulties and happy times. To all who pray and give us help, thank you. May Allah bless you.

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ABSTRACT

Since 1964, liquefaction resistance of sand matrix soils or sand-fine mixtures has been extensively studied by researchers. These extensive studies were done/conducted following dramatic damages due to liquefaction caused by earthquakes in Niigata and Alaska. However, until the end of the 2010s and the latest major liquefaction occurrence in September 2018 at Palu, Indonesia, little research effort had been made to focus on the effects of particle shape and size, grading characteristics, particle arrangement and fines content of sand matrix soils. Although sand is the dominant material in sand matrix soils, there have not been enough efforts to elucidate the effects of particle size and grading characteristics of sand as the main factor in altering liquefaction resistance. Moreover, some results previously reported are still contradictory. This research aims to determine the effects of particle size and grading characteristics of sand on liquefaction resistance of sand matrix soils. To achieve the aim, three (3) objectives have been identified; (1) to evaluate the particle size, the grading characteristics and the physical properties of sand matrix soils at various compositions of sand and fines, (2) to establish the critical state line as the failure envelope of sand matrix soils from the results of monotonic undrained triaxial tests, and (3) to characterize the liquefaction susceptibility of sand matrix soils from the cyclic triaxial tests and validate through the centrifuge tests. The material used in the research was selected clean sand, which was sieved into three ranges of grain size that were coarse, medium and fine. Sand matrix soils were reconstituted by mixing these three-grain sizes of sand with low plasticity fines (kaolin) at 0% to 40% by weight. The results showed that the threshold fine content for coarse sand matrix soil and medium sand matrix soils were 30%, while for fine sand matrix soil, the percentage was 10%. From cyclic triaxial tests, it also indicated that the liquefaction resistance of sand matrix soils decreases with increases in fine content and showed a reverse trend after reaching threshold fine content. The threshold fines content (f_{th}) for coarse sand matrix soils and medium sand matrix soils was 30%, whereas, for fine sand matrix soils, it was 10%. Threshold fines (f_{th}) were observed to change the transition behaviour of sand dominates to fines dominates which occurred at different percentages of fines content depending on the grain size of sand. Less number of cycles was required to initiate soil liquefaction of sand matrix soils with a higher value of the coefficient of curvature and coefficient of uniformity. In general, the sand matrix soil has higher liquefaction resistance at larger sand particles. By using the centrifuge test, similar trends were observed as a result of the cyclic triaxial test. Some of the equations were generated to provide a new outcome for this research.

ABSTRAK

Sejak 1964, rintangan terhadap pencecairan bagi tanah matriks pasir atau campuran pasir butiran halus telah dikaji secara meluas oleh penyelidik-penyelidik. Kajian secara meluas ini telah dilaksanakan mengikuti kerosakan yang dramatik akibat pencecairan disebabkan oleh gempa bumi di Niigata dan Alaska. Namun, sehingga akhir tahun 2010 dan insiden terkini pencecairan berlaku pada bulan September 2018 di Palu, Indonesia, sedikit usaha penyelidikan yang dilakukan fokus kepada kesan bentuk butiran dan saiz pasir, ciri-ciri penggredan, susunan butiran dan kandungan butiran halus bagi tanah matriks pasir. Walaupun pasir adalah bahan yang dominan bagi tanah matriks pasir, belum ada usaha yang mencukupi untuk menjelaskan kesan saiz butiran dan ciri-ciri pengredan pasir sebagai faktor utama dalam mengubah rintangan pencecairan. Lebih-lebih lagi,beberapa hasil yang dilaporkan sebelum ini masih bercanggah. Kajian ini bertujuan untuk menentukan kesan saiz butiran dan ciri-ciri penggredan pasir terhadap rintangan pencecairan tanah matriks pasir. Untuk mencapai tujuan tersebut, tiga (3) objektif telah dikenal pasti; (1) untuk menilai saiz butiran, ciri-ciri penggredan dan ciri-ciri fizikal bagi tanah matriks pasir pada pelbagai komposisi pasir dan butiran halus, (2) untuk menubuhkan garis keadaan kritikal sebagai sampul kegagalan bagi tanah matriks pasir hasil keputusan ujikaji tiga paksi monotonik di bawah keadaan tidak tersalir, dan (3) untuk mencirikan kerentanan pencecairan bagi tanah matriks pasir daripada ujikaji tiga paksi berkitar dan pengesahan melalui ujian empar. Bahan yang digunakan dalam penyelidikan ini adalah pasir bersih yang terpilih, dimana telah diayak ke dalam tiga saiz julat butiran iaitu kasar, pertengahan dan halus. Tanah matriks pasir disusun semula dengan mencampurkan tiga saiz julat butiran pasir indengan butiran halus berkeplastikan rendah (kaolin) pada 0% to 40% daripada berat. Keputusan menunjukkan bahawa kandungan butiran halus ambang untuk tanah matriks pasir kasar dan pertengahan adalah 30% manakala untuk tanah matriks pasir halus adalah 10%. Daripada ujian tiga paksi berkitar, ia juga menunjukkan bahawa rintangan pencecairan tanah matriks pasir berkurang dengan peningkatan butiran halus dan telah menunjukkan arah aliran sebaliknya selepas mencapai kandungan butiran halus ambang. Nilai butiran halus ambang (f_{th}) bagi tanah matriks pasir kasar dan juga tanah matriks pasir sederhana adalah 30% manakala untuk tanah matriks pasir halus adalah 10%. Butiran halus ambang (f_{th}) diperhatikan telah mengubah sifat arah aliran daripada dominasi pasir kepada butiran halus yang mana berlaku pada peratusan butiran halus berbeza berdasarkan kepada saiz butiran pasir. Kurang bilangan kitaran yang diperlukan untuk memulakan pencecairan tanah bagi tanah matriks pasir dengan nilai yang lebih tinggi bagi pekali kelengkungan dan pekali keseragaman. Secara umumnya, tanah matriks pasir mempunyai rintangan pencecairan yang tinggi pada butiran yang lebih besar. Dengan menggunakan ujian empar, arah aliran serupa diperhatikan sebagaimana keputusan daripada ujian tiga paksi berkitar. Sebilangan persamaan dihasilkan untuk menyediakan hasil baru dari penyelidikan ini.

TABLE OF CONTENTS

	TITLE	PAGE
	DECLARATION	**iii**
	DEDICATION	**iv**
	ACKNOWLEDGEMENT	**v**
	ABSTRACT	**vi**
	ABSTRAK	**vii**
	TABLE OF CONTENTS	**ix**
	LIST OF TABLES	**xiii**
	LIST OF FIGURES	**xv**
	LIST OF ABBREVIATIONS	**xxii**
	LIST OF SYMBOLS	**xxiv**
	LIST OF APPENDICES	**xxvi**
CHAPTER 1	**INTRODUCTION**	**1**
1.1	Background	1
1.2	Problem Statement	6
1.3	Research Objectives	7
1.4	Scope and Limitation	8
1.5	Significance of the Research	10
1.6	Thesis Outline	10
CHAPTER 2	**LITERATURE REVIEW**	**13**
2.1	Introduction	13
2.2	Liquefaction of Soil	13
2.3	Loading on Soil	15
2.4	Factors Effecting Liquefaction Susceptibility	18
	2.4.1 Particle Size Distribution and Soil Types	18
	2.4.2 Fines Content	21

	2.4.3	Particle Shape	24
	2.4.4	Relative Density	26
	2.4.5	Particle Size and Grading Characteristics of Soil	27
	2.4.6	Cyclic Loading	30
2.5		Critical State Soil Mechanic	37
	2.5.1	Critical State	37
	2.5.2	Relationship Between Critical State Parameter on Liquefaction Resistance	41
2.6		Centrifuge	44
2.7		Seismic Hazard Research in Malaysia	45
2.8		Summary	54
CHAPTER 3		**RESEARCH METHODOLOGY**	**59**
3.1		Introduction	59
3.2		Research Materials	61
3.3		Laboratory Testing Program	62
3.4		Index Test	65
	3.4.1	Sieve and Hydrometer Test	66
	3.4.2	Particle Density Test of Sand Matrix Soil	67
	3.4.3	Maximum and Minimum Density	67
	3.4.4	Microstructure Test	68
3.5		Triaxial Test	71
	3.5.1	Triaxial System	73
	3.5.2	Sample Preparation	75
	3.5.3	Triaxial Cell Setup	78
	3.5.4	Saturation Stage	79
	3.5.5	Consolidation Stage	81
	3.5.6	Monotonic Compression Triaxial Test of Sand Matrix Soils	82
	3.5.7	Cyclic Triaxial Test of Sand Matrix Soils	82
	3.5.8	Analysis of Triaxial Test Results	85
		3.5.8.1 Monotonic Triaxial Compression Test	85

3.5.8.2 Two-way Cyclic Undrained Triaxial Test 86

3.6 Centrifuge Test 86

3.6.1 Centrifuge Facilities at DPRI 86

3.6.2 Scaling Law in Centrifuge 88

3.6.3 Soil Material and Model Box 89

3.6.4 Transducers Setup and Data Acquisition 91

3.6.5 Saturation 92

3.6.6 Input Motion for Centrifuge Test 95

CHAPTER 4 SOIL CHARACTERISTICS AND CRITICAL STATE PARAMETERS 97

4.1 Introduction 97

4.2 Classification Test 98

4.2.1 Particle Size Distribution 98

4.2.2 Minimum and Maximum Void Ratio 106

4.2.3 Particle Density 109

4.2.4 Classification of Sand Matrix Soils 110

4.3 Microstructure Analysis of Sand Matrix Soils 113

4.3.1 X-Ray Diffraction 113

4.3.2 Scanning Electron Microscope (SEM) 114

4.3.3 Digital Microscope Scanner 116

4.3.4 Grain Shape of Sand Particles 121

4.4 Monotonic Triaxial Test Results 125

4.4.1 Stress-Strain Relationship 126

4.4.2 Pore Water Pressure-Strain Relationship 128

4.4.3 Peak Deviator Stress 128

4.4.4 Effect of Particle Sizes and Grading Characteristics on Peak Deviator Stress 132

4.4.5 Mohr-Coulomb Failure Envelope 137

4.4.6 Critical State from CU Triaxial Tests 143

4.4.6.1 Critical State Parameter in q – p' Stress Space 144

4.4.6.2 Critical State Line in Compression Space 146

4.4.6.3 Effect of Particle Size from Critical State Line 152

4.4.6.4 Effect of Grading Characteristics on Critical State Parameter 158

4.5 Chapter Summary 163

CHAPTER 5 LIQUEFACTION RESISTANCE OF SAND MATRIX SOILS 165

5.1 Introduction 165

5.2 Cyclic Triaxial Test Results 166

5.2.1 Effects of Particle Size 172

5.2.2 Effect of Grading Characteristics 176

5.3 Centrifuge Test Results 180

5.3.1 Acceleration Behaviours 180

5.3.2 Pore Water Pressure Development 183

5.4 Chapter Summary 188

CHAPTER 6 CONCLUSION AND RECOMMENDATIONS 191

6.1 Introduction 191

6.2 Conclusions 191

6.3 Contributions to Knowledge 193

6.4 Recommendations for Future Works 194

REFERENCES 195

LIST OF PUBLICATIONS 223

LIST OF TABLES

TABLE NO.	TITLE	PAGE
Table 2.1	Summary grain sizes of liquefied soils or large potential to liquefy (Sumer, 2014)	28
Table 2.2	Selected scaling laws (Madabushi, 2014)	45
Table 2.3	Scale of earthquake based on Magnitude, Mw (modified from MMD, 2019)	46
Table 2.4	Earthquake events recorded in 2007 and 2008 at Bukit Tinggi, Pahang (modified from Shuib, 2009)	46
Table 2.5	Summary of some related studies on grading characteristics and particle size distribution in sand-fine mixtures	56
Table 3.1	The composition of reconstituted sand matrix soils	62
Table 3.2	Number of tests conducted on soil classification test of sand matrix soils	63
Table 3.3	Number of tests conducted on triaxial and centrifuge test of sand matrix soils	64
Table 3.4	Test summary for soil classification test	65
Table 3.5	Testing programs for monotonic undrained triaxial test at loose state	72
Table 3.6	Testing programs for two-way cyclic undrained triaxial test at loose state	72
Table 3.7	Summary of the technique applied for preparation sample for triaxial test	76
Table 3.8	Material properties of sand matrix soils used in centrifuge test	90
Table 3.9	List of transducers installed for centrifuge test	91
Table 4.1	Summary of grading characterizations of sand matrix soils	103
Table 4.2	Summary of index properties of sand matrix soils	112
Table 4.3	The microscopic view of the sand particle at different percentage of kaolin	120
Table 4.4	Summary of angularity for coarse sand particles	123
Table 4.5	Summary of angularity for medium sand particles	124
Table 4.6	Summary of angularity for fine sand particles	124

Table 4.7 Summary of peak deviator stress at different effective consolidation pressure of sand matrix soils 129

Table 4.8 Summary of peak deviator stress and grading characteristics equation of sand matrix soils 136

Table 4.9 Summary of results at peak deviator stress from monotonic triaxial test at 50kPa effective consolidation pressure of sand matrix soils 138

Table 4.10 Summary of results from monotonic triaxial test at 100kPa effective consolidation pressure of sand matrix soils 139

Table 4.11 Summary of results from monotonic triaxial test at 200kPa effective consolidation pressure of sand matrix soils 140

Table 4.12 Summary of shear strength parameter for each sand matrix soils 142

Table 4.13 Critical state parameter of sand matrix soils sample 145

Table 4.14 Stress parameter at for coarse sand matrix soils at critical state 147

Table 4.15 Stress parameter at for coarse sand matrix soils at critical state 147

Table 4.16 Stress parameter at for fine sand matrix soils at critical state 148

Table 4.17 Summary of critical state parameter and critical state lines equation of sand matrix soils 152

Table 5.1 Summary of liquefaction resistance in term of Nc on loose sand matrix soils at CSR = 0.1 170

Table 5.2 Summary of liquefaction resistance in term of Nc on sand matrix soils at CSR = 0.2 171

Table 5.3 Summary of liquefaction resistance in term of Nc on sand matrix soils at CSR = 0.3 172

Table 5.4 Summary equations for Nc and FC of each sand matrix soils with the inclusion of CSR between 0.1 to 0.3 173

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
Figure 1.1	Seismic activities map of the world (Dowrick, 2009 after Barazangi and Dorman, 1969)	2
Figure 1.2	Ring of Fire (U.S. Geological Survey, 2019)	2
Figure 2.1	Static Liquefaction at Fort Peck Dam on 1938 (Davies *et al.,* 2016)	16
Figure 2.2	Four types of behaviour on loose silty sand (Lade and Yamamuro, 1997)	17
Figure 2.3	Particle size distribution curve to assess the liquefaction potential of soil (Tsuchida, 1970)	19
Figure 2.4	Chart for liquefaction potential assessment at different percentage of fines (Seed *et al*., 1985)	22
Figure 2.5	SEM micrograph of different percentage of fines content in sand-fine mixtures (Bahadori *et al*., 2008)	24
Figure 2.6	Angularity classification in Convexity-Sphericity chart proposed by Altuhafi *et al.* (2013)	25
Figure 2.7	The effect of different relative density of soil on cyclic stress ratio against number of cycle plot (Hakam, 2016)	27
Figure 2.8	Mean grain sizes (D_{50}) for liquefied soils (Hakam *et al.,* 2016)	29
Figure 2.9	Typical illustration on stress reversal of one-way loading and two-way loading (Rees, 2013)	30
Figure 2.10	Number of cycles to liquefaction for different types of samples on cyclic triaxial test (Singh, 1994)	32
Figure 2.11	Effective stress path of loose and dense sand under cyclic loading (Marto *et al*., 2016a)	32
Figure 2.12	Effective stress path and cyclic behaviour of silty sand soil (Hussain and Sachan, 2019)	33
Figure 2.13	Cyclic loading results on deviator stress of sand fine mixtures (Balreddy *et al*., 2016)	34
Figure 2.14	Pore pressure generation from cyclic loading test (Balreddy *et al.*, 2016)	34
Figure 2.15	Axial strain generation with number of cycles (Balreddy *et al*., 2016)	35

Figure 2.16 Effective stress path on sand fine mixtures at 10% of fines content (Balreddy et al., 2016) 35

Figure 2.17 Undrained cyclic test results on uniform JCA sand (Yoshimine and Koike, 2005) 36

Figure 2.18 Undrained cyclic test results on stratified JCA sand (Yoshimine and Koike, 2005) 37

Figure 2.19 Critical state concept definition (redraw by Hosseini *et al.,* 2005) 38

Figure 2.20 Contraction and dilation of sand (University of Cambridge, 2020) 39

Figure 2.21 Definition of critical void ratio of sand during shearing (Misra, 2020) 39

Figure 2.22 Undrained behaviour of loose soil in stress path diagram (Been and Jefferies, 2004) 40

Figure 2.23 Typical results of sand at different void ratio on undrained shear test (Yang *et al.,* 2015) 41

Figure 2.24 Particle structure of silty sand in loose state b) Volumetric contraction after application of stress (Bayat and Bayat, 2013 after Lade and Yamamuro, 1997) 42

Figure 2.25 CSL of several clean sand (re-draw from Jefferies and Been, 2006) 43

Figure 2.26 CSL of sand with different percentage of fines content (Phan *et al*., 2016) 44

Figure 2.27 Geological map of Peninsular Malaysia (DMGM, 2019) 47

Figure 2.28 Major earthquake events due to Sumateran subduction zone (USGS, 2019) 48

Figure 2.29 Tectonic plate around Malaysia (Hall *et al*., 2008) 49

Figure 2.30 Geological map of Sabah, Malaysia (DMGM, 2019) 50

Figure 2.31 Water turned to dark-coloured after Ranau earthquake in 2015 (Tongkul, 2015) 50

Figure 2.32 PGA map of Peninsular Malaysia for 500 years return period (Adnan *et al.,* 2005) 51

Figure 2.33 Seismic hazard map for return period of 500 years (Marto *et al*., 2007) 52

Figure 2.34 PGA map using different seismic sources (Manafizad *et al.,* 2016) 52

Figure 2.35 PGA map of Peninsular of Malaysia for 475 return period (Shoushtari *et al.,* 2018) 53

Figure 3.1	Research Framework	60
Figure 3.2	Sample of research materials to reconstitute sand matrix soils	61
Figure 3.3	Flow for classification test	64
Figure 3.4	Illustration and picture of sieve test on sand samples	66
Figure 3.5	JEOL (JSM-6380LA) series of Scanning Electron Microscope	69
Figure 3.6	Cooling Tech USB Digital Microscope built with 2.0 Megapixel Camera	70
Figure 3.7	Test arrangement	70
Figure 3.8	GDS ELDYN main component	73
Figure 3.9	GDS ELDYN machine at UTM Skudai, Malaysia	75
Figure 3.10	Process for preparation of cylindrical reconstituted sample on triaxial pedestal	77
Figure 3.11	Completed samples on triaxial pedestal	78
Figure 3.12	Schematic picture for sample setup in triaxial test	79
Figure 3.13	Typical results on saturation stage (Rees, 2013)	80
Figure 3.14	Typical results on B-check stage (Rees, 2013)	81
Figure 3.15	Typical results on consolidation stages (Rees, 2013)	82
Figure 3.16	Schematic illustration on Vylastic sleeve position	83
Figure 3.17	Mohr circles plot (Tan, 2015)	85
Figure 3.18	Geotechnical Centrifuge Center building at DPRI, Kyoto University, Japan	87
Figure 3.19	Centrifuge facility at DPRI, Kyoto University, Japan	87
Figure 3.20	Prototype foundation of sand matrix soil layer at 1g of earth gravity	89
Figure 3.21	Model box in centrifuge test	90
Figure 3.22	Instrumentation layout in centrifuge tests	92
Figure 3.23	Procedure in the preparation of the viscous fluid	93
Figure 3.25	Saturating the sample in model box before centrifuge test	94
Figure 3.24	Schematic diagram of saturation system	94
Figure 4.1	Particle size distribution curves for coarse sand matrix soils	98
Figure 4.2	Particle size distribution curves for medium sand matrix soils	99

Figure 4.3 Particle size distribution curves for fine sand matrix soils 99

Figure 4.4 Particle size distribution curve of original sand with the D_{10}, D_{30}, D_{50} and D_{60} 100

Figure 4.5 Graph of coefficient of uniformity against percentage of fines content of different sizes of sand matrix soils 101

Figure 4.6 Graph of coefficient of curvature against percentage of fines content of different sizes of sand matrix soils 102

Figure 4.7 Graph of D_{10} against percentage of fines in sand matrix soils 104

Figure 4.8 Graph of D_{30} against percentage of fines in sand matrix soils 105

Figure 4.9 Graph of D_{50} against percentage of fines in sand matrix soils 105

Figure 4.10 Graph of D_{60} against percentage of fines in sand matrix soils 106

Figure 4.11 Maximum void ratio-fines content relationship of sand matrix soils 107

Figure 4.12 Minimum void ratio-fine content relationship of sand matrix soils 108

Figure 4.13 Particle density against fines content of sand matrix soils 110

Figure 4.14 XRD pattern for sand 113

Figure 4.15 XRD pattern for kaolin (Tan, 2015) 114

Figure 4.16 SEM image for coarse sand 115

Figure 4.17 SEM image for medium sand 115

Figure 4.18 SEM image for fine sand 116

Figure 4.19 Microscopic view of coarse sand matrix soils 117

Figure 4.20 Microscopic view of medium sand matrix soils 118

Figure 4.21 Microscopic view of fine sand matrix soils 119

Figure 4.22 Particle shape determination of coarse sand 121

Figure 4.23 Particle shape determination of medium sand 122

Figure 4.24 Particle shape determination of fine sand 123

Figure 4.25 A typical stress-strain relationship obtained from monotonic triaxial tests for sand 127

Figure 4.26 Excess pore water pressure development of sand from monotonic triaxial test 128

Figure 4.27 Typical test results on stress-strain graph 129

Figure 4.28 Graph of maximum deviator stress against fines content at 50 kPa of effective consolidation stress 131

Figure 4.29 Graph of maximum deviator stress against fines content at 100 kPa of effective consolidation stress 131

Figure 4.30 Graph of maximum deviator stress against fines content at 200 kPa of effective consolidation stress 132

Figure 4.31 Graph of peak deviator stress against coefficient of uniformity of sand matrix soils 133

Figure 4.32 Graph of peak deviator stress against coefficient of curvature of sand matrix soils 134

Figure 4.33 Graph of peak deviator stress against mean diameter of sand matrix soils 135

Figure 4.34 Graph of peak deviator stress against effective diameter of sand matrix soils 136

Figure 4.35 Mohr-coulomb failure envelope of sand samples 141

Figure 4.36 Graph of effective cohesion, c' against fines content, FC of sand matrix soils 143

Figure 4.37 Graph of effective friction angle, ϕ' versus fines content, FC of sand matrix soils 143

Figure 4.38 Critical state line of S70K30-C samples in stress space 145

Figure 4.39 Critical state line of coarse sand matrix soils in compression stress space 148

Figure 4.40 Critical state line of medium sand matrix soils in compression stress space 149

Figure 4.41 Critical state line of fine sand matrix soils in compression stress space 149

Figure 4.42 Critical state line of coarse sand matrix soils in υ – ln p' plot 150

Figure 4.43 Critical state line of medium sand matrix soils in υ – ln p' plot 150

Figure 4.44 Critical state line of fine sand matrix soils in υ – ln p' plot 151

Figure 4.45 Critical state line without fine content (100% sand) in υ – ln p' plot at compression space 153

Figure 4.46 Critical state line for 10% fine content of sand matrix soils in υ – ln p' plot at compression space 154

Figure 4.47 Critical state line for 20% fine content of sand matrix soils in υ – ln p' plot at compression space 154

Figure 4.48 Critical state line for 30% fine content of sand matrix soils in υ – ln p' plot at compression space 155

Figure 4.49 Critical state line for 40% fine content of sand matrix soils in υ – ln p' plot at compression space 155

Figure 4.50 Critical state line without fine content (100% sand) in q – p' plot at stress space 156

Figure 4.51 Critical state line for 10% fine content of sand matrix soils in q – p' plot at stress space 156

Figure 4.52 Critical state line for 20% fine content of sand matrix soils in q – p' plot at stress space 157

Figure 4.53 Critical state line for 30% fine content of sand matrix soils in q – p' plot at stress space 157

Figure 4.54 Critical state line for 40% fine content of sand matrix soils in q – p' plot at stress space 158

Figure 4.55 Effect of coefficient of uniformity on critical state parameters of sand matrix soils 159

Figure 4.56 Effect of coefficient of curvature on critical state parameters of sand matrix soils 161

Figure 4.57 Effect of mean diameter, D_{50} on critical state parameters of sand matrix soils 162

Figure 5.1 Plot of deviator stress against number of cycles for sample S90K10-C at 0.1 cyclic stress ratio 167

Figure 5.2 Plot of excess pore water pressure against number of cycles for sample S90K10-C at 0.1 cyclic stress ratio 167

Figure 5.3 Plot of strain against number of cycles for sample S90K10-C at 0.1 cyclic stress ratio 168

Figure 5.4 Effective stress path in stress space (q – p' plot) for sample S90K10-C at 0.1 cyclic stress ratio 169

Figure 5.5 Number of cycles for initiation of liquefaction of sand matrix soils 170

Figure 5.6 Effect of sand particle size on the number of cycles at the initiation of liquefaction, at various fine contents and cyclic stress ratio 174

Figure 5.7 Effect of coefficient of uniformity on the number of cycles at the initiation of liquefaction, at various fine contents and cyclic stress ratio 177

Figure 5.8 Effect of coefficient of curvature on the number of cycles at the initiation of liquefaction, at various fine contents and cyclic stress ratio 179

Figure 5.9 Measured acceleration at the bottom of the container, AC0 181

Figure 5.10 Ground response acceleration at 3 m and 5 m depths for loose coarse sand matrix soils with 10% fines content (S90K10-C) 181

Figure 5.11 Ground response acceleration at 3 m and 5 m depths for loose medium sand matrix soils with 10% fines content (S90K10-M) 182

Figure 5.12 Ground response acceleration at 3 m and 5 m depths for loose fine sand matrix soils with 10% fines content (S90K10-F) 183

Figure 5.13 Behaviour of excess pore water pressure in sand matrix soils at 3 m and 5 m depths in centrifuge tests 185

Figure 5.14 Excess pore water pressure response in 30 s at 3 m depth for sand matrix soils at different sand particle sizes 186

Figure 5.15 Excess pore water pressure response in 30 s at 5 m depth for sand matrix soils at different sand particle sizes 187

LIST OF ABBREVIATIONS

AASTHO	-	American Association of State Highway and Transportation Officials
ASTM	-	American Society of Testing and Materials
BS	-	British Standard
BSCS	-	British Soil Classification System
CD	-	Consolidated Drained
CE	-	Extremely high plasticity clay
CRR	-	Cyclic Resistance Ratio
CSR	-	Cyclic Stress Ratio
CSL	-	Critical State Line
CSSM	-	Critical State Soil Mechanics
CU	-	Consolidated Undrained
DIA	-	Dynamic Image Analysis
ESP	-	Effective Stress Path
ELDCS	-	Enterprise Level Dynamic Control System
EPWP	-	Excess Pore Water Pressure
ELDYN	-	Enterprise Level Dynamic Triaxial System
EC	-	Eurocode
FC	-	Fines Content
GDS	-	Geotechnical Digital System
GPS	-	Global Positioning System
JGS	-	Japanese Geotechnical Society
LL	-	Liquid Limit
MS	-	Malaysia Standards
MV	-	Very high plasticity silt
MOSTI	-	Ministry of Science, Technology and Innovation
MMD	-	Malaysia Meteorological Department
NCEER	-	National Centre for Earthquake Engineering Research
PGA	-	Peak Ground Acceleration
PSD	-	Particle Size Distribution

PTL	-	Phase Transformation Line
PWP	-	Pore Water Pressure
RSN	-	Rancangan Struktur Negeri
SEM	-	Scanning Electron Microscopic
SM	-	Silty sand
SP	-	Poorly graded sand
SP-SM	-	Poorly graded sand with silt
SPT	-	Standard Penetration Test
SPT-N	-	Standard Penetration Resistance
SSL	-	Steady State Line
SRT-DEM	-	Shuttle Radar Topography Mission – Digital Elevation Mapping
USCS	-	Unified Soil Classification System
USB	-	Universal Serial Bus
USGS	-	United State Geological Survey
UU	-	Unconsolidated Undrained
XRD	-	X-ray Diffractometry

LIST OF SYMBOLS

A	-	Activity
a_{max}	-	Peak ground acceleration
B	-	Pore pressure coefficient
c’	-	Effective cohesion
C_C	-	Coefficient of curvature
CO_2	-	Carbon dioxide
C_U	-	Coefficient of uniformity
D_{10}	-	Effective size
D_{30}	-	Diameter corresponding to 30 % finer
D_{50}	-	Mean grain size
D_{60}	-	Diameter corresponding to 60 % finer
e	-	Global void ratio
e_c	-	Critical void ratio
e_{max}	-	Maximum void ratio
e_{min}	-	Minimum void ratio
e_s	-	Intergranular void ratio
$e_{skeleton}$	-	Sand skeleton void ratio
f	-	Frequency
f_{th}	-	Threshold fines content
g	-	Acceleration of gravity
I_D	-	Density index
I_P	-	Plasticity index
M	-	Critical stress ratio in stress space
M_w	-	Moment Magnitude
N	-	Standard penetration resistance
$(N_1)_{60}$	-	Corrected N by an energy ratio of 60 % hammer efficiency
N_c	-	Number of cycles
p’	-	Mean normal effective stress
q	-	Deviator stress
q_{max}	-	Peak deviator stress

R	-	Coefficient of correlation
R^2	-	Coefficient of determination
u	-	Pore water pressure
w	-	Moisture content
Γ	-	Intercept of the CSL with υ axis in compression space
Δu	-	Excess pore water pressure
ε_a	-	Axial strain
ε_{DA}	-	Double amplitude shear strain
λ	-	Compression index in compression space
ρ_{15}	-	Density at 15 %
ρ_{50}	-	Density at 50 %
P_{max}	-	Maximum density
P_{min}	-	Minimum density
ρ_s	-	Particle density
σ	-	Total stress
σ'_{3C}	-	Effective consolidation pressure
σ'	-	Effective stress
σ'_1	-	Major principal stress
σ'_3	-	Minor principal stress
τ	-	Shear stress
τ_{cyc}	-	Cyclic shear stress amplitude
υ	-	Specific volume
ϕ'	-	Effective internal friction angle
ϕ'	-	Effective frictional angle
ϕ'_{cs}	-	Critical frictional angle
ψ	-	State parameter

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
Appendix A	Calibration Certificates	211
Appendix B	Monotonic Triaxial Test Data	215
Appendix C	Effective Stress Failure Envelope of Sand Matrix Soils	217
Appendix D	Critical State Parameter in q - p’ Stress Space	219

CHAPTER 1

INTRODUCTION

1.1 Background

Niigata Earthquake occurred in 1964 in Japan raised the awareness on how the liquefaction incident from earthquake event damaged the city of Niigata. However, past history shows that the liquefaction of soils also occurred without impact from earthquake event as reported by Jefferies and Been (2006) at Fort Peck Dam, Missouri River, USA in 1938 and Nerlerk at Canadian Beaufort Sea in 1983. As a result, many engineering professionals across the globe have undertaken an intensive study regarding the incidents. Numerous empirical demonstrations have been performed to comprehend and expose the processes of soil liquefaction and the variables that led to the circumstance. Soil liquefaction is a subsequent consequence of a seismic quake; it occurs when saturated granular soils compress, raising pore water pressures and lowering the effective stress during seismic quakes, resulting in a degradation of unconfined compressive strength (Dowrick, 2009). Due to the earth's incapacity to sustain structural integrity, liquefied soil with a lack of shear strength could potentially cause enormous damage. The Niigata earthquake on 16 June 1964 is a real-life incidence of catastrophic destruction induced by liquefaction, since it resulted in damage to bearing capacity, structural residences, and pavement surfacing aggregates (Day, 2012). The 11 March 2011 Tohoku Earthquake (Mw 9.0) in Japan's Tokyo Bay region is among the major latest liquefaction-related disasters (Sana & Nath, 2016; Bhattacharya *et al.,* 2011).

Dowrick (2009) stated that Barazangi and Dorman (1969) had produced a global seismic activity map, as shown in Figure 1.1. Malaysia is usually situated beyond the Ring of Fire, a zone of regular earthquakes and volcanic activity. Malaysia is located closed to the three major active plate boundaries; Eurasian plate, Indian-Australian plate and Philippine Sea-Pacific plate. According to the seismic hazard map of Malaysia produced by Marto *et al*. (2007), it can be said that the probability of earthquake occurs in Malaysia is low, however the impact of seismic from earthquake events is not negligible. On the other hand, the United States Geological Survey (USGS) published an updated map in 2019 that depicts the area of seismic events and volcanic activity, as shown in Figure 1.2. As a result of this statistic, the notion that Malaysia is earthquake-proof no longer holds true, as Malaysia, particularly the East Malaysian zone and the southern portion of West Malaysia, are located inside the Ring of Fire.

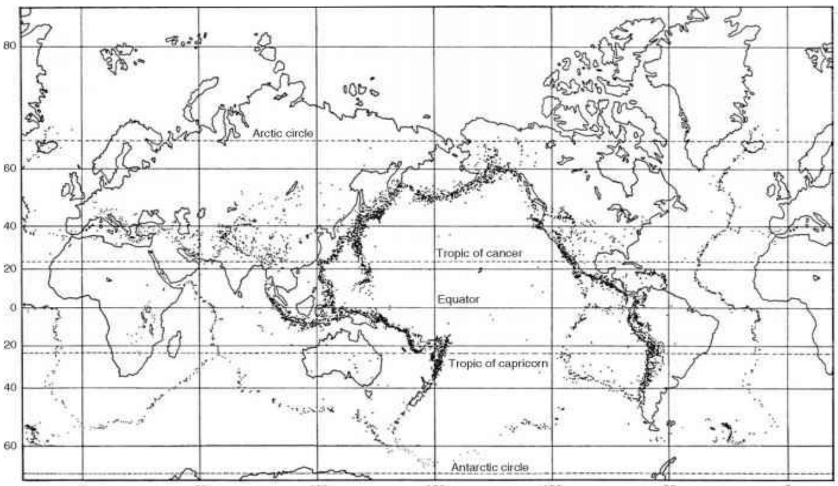

Figure 1.1 Seismic activities map of the world (Dowrick, 2009 after Barazangi and Dorman, 1969)

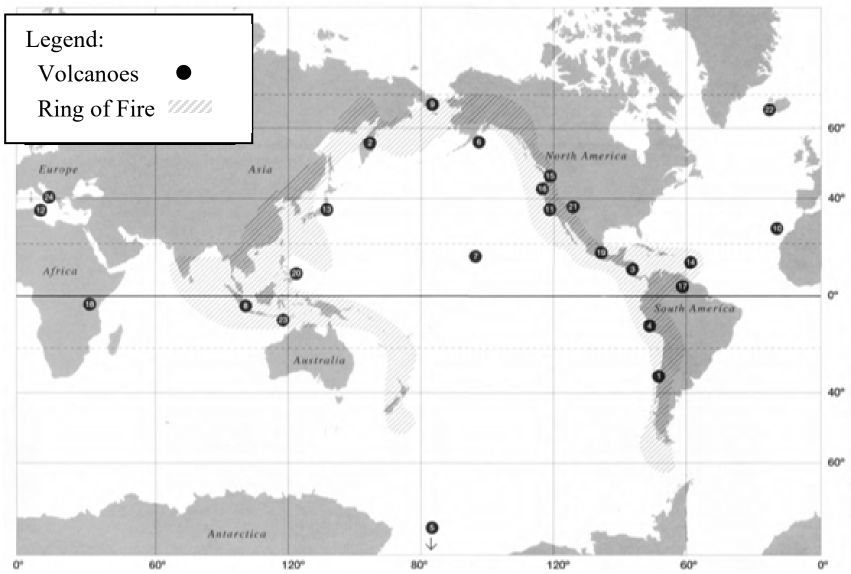

Figure 1.2 Ring of Fire (U.S. Geological Survey, 2019)

In June 2015, an earthquake of 5.9 in Magnitude (Mw) had occurred in Sabah, East Malaysia. This incident caused 18 deaths and damages to a lot of properties. Some seismic incidences have surfaced in West Malaysia since 2007, even though earthquake had never been reported in the region. For example, minor earthquakes Magnitude (Mw) less than 4.9 had occurred in Janda Baik, Bentong, Pahang in November 2007; in Jerantut, Pahang in March 2009; subsequently in Manjung, Perak on 29 April 2009; and finally in the southern areas such as in Kuala Pilah, Negeri Sembilan on 30 November 2009. As mentioned by Malaysian Meteorological Department (MMD), all the resulting vibrations were less than 4.9 in Magnitude (Mw) were categorized as weak, and did not cause any noticeable damages to the buildings or houses in the area.

Some of the proposed projects lie on the earthquake hazard zones produced by the Ministry of Science, Technology and Innovation (MOSTI) (2009) especially at Bukit Tinggi and Bentong district. It shows that, the seismic risk consideration needs to be enhanced in earthquake hazard zones to any development project to provide a safer place for population and economic growths. This challenge is affecting local construction trends and is threatening the ability to construct quality and sustainable structures. As a way forward, the Ministry of Works, Malaysia through speech by the Minister of Works during the Seminar on Geotechnical Earthquake Engineering (2016) urged that all of us must be concerned and vigilant about the risks and consequences of the natural disasters (earthquake, landslide and liquefaction, among others under stresses of seismic waves) and to take serious action to protect lives and our well-being. The detailed study on the earthquakes must be conducted to produce appropriate adjustments to current practice and policies.

The domination of sand in soil with presence of limited percentage of fine particles is known as sand matrix soils (Tan, 2015; Marto *et al.,* 2016). Historical evidence on liquefaction phenomena shows that sand matrix soils also liquefy as reported by Holzer *et al.* (2010), Orense *et al.* (2012) and Batilas *et al*. (2013). This type of soils is found in abundance in Malaysia. Laboratory test conducted by Tan (2015) on the effects of fines content by up to 40% on liquefaction resistance of sand matrix soils have shown that the liquefaction resistance increases with increases of plasticity of soils. They found that the threshold fines content, f_{th} for sand-kaolin mixtures was 25% which liquefaction occurred. Similar findings were reported by Perlea *et al.* (2000), however the percentage of fines content occurred at different value was 15-20%. Other factors such as types of fines content, void ratios, relative densities, particle shape and sizes, particle size distribution and cyclic strength is believed to cause the liquefaction occurred at different percentage of fines content. The effects of fines content have been well-studied to-date, however other factors which contribute to increase or decrease in liquefaction resistance need to be investigated such as particle size and grading characteristics of sand. Sieve analysis used to determine the particle size distribution of soil samples. From this analysis, the percentages of sizes of particles can be obtained. The results from particle size distribution were used to calculate the grading parameters of soils (Coefficients of Uniformity and Curvature). Holtz and Kovacs (1981) stated that soils gradation is an indicator of other engineering properties such as compressibility, shear strength, and hydraulic conductivity.

In general, the undrained shear strength of soil is influenced by its particle size and morphological characteristics (Ghadr and Assadi-Langroudi, 2019). Igwe *et al.* (2004) stated that the study on influence of particle size distribution on liquefaction needs to be carried out in order to obtain enough information for conclusions to be drawn. Literature search conducted in the research showed that a certain number of studies have been carried out focusing on the effects of particle size and grading characteristics of sand matrix soils, but it was also revealed that there are still not enough data and information for a global agreement. Recent research works on particle size and grading characteristics by Choobbasti *et al.* (2014), Hakam *et al*. (2016), Zhou *et al.* (2017), Peacock (1971), Aydan *et al.* (2008), and Wei *et al.* (2020) have reported contradictory or inconsistent findings. For example, Peacock (1971) reported that the mean grain size, D_{50} of 0.08 mm is most susceptible to liquefaction, whereas Aydan *et al.* showed that approximately 80% of liquefied soils have D_{50} between 0.113 mm and 0.338 mm. Further investigation, clarification and validation are needed.

Kokusho (2012) and Kuerbis *et al*. (1988) stated that the coefficient of uniformity (C_U) is an important factor in controlling the liquefaction resistance of sands. However, this factor is considered to be not applicable to sand matrix soils condition as shown by Yilmaz *et al.* (2008) and Choobbasti *et al.* (2014), who reported that there is no correlation between C_U and coefficient of curvature, C_C, in cyclic resistance as the liquefaction indicator.

As mentioned above, there are not enough conclusive findings on the relationship between C_U and the liquefaction resistance of soils. As sand in natural consist of different percentage of fines and particle size, a study on the effects of particle size and grading characteristics of sand on liquefaction resistance of sand matrix soil need to be carried out. Because any soil naturally has a different size distribution and a varying fraction of fines content, a good conclusion cannot be expected unless these factors are taken into account. There is not enough evidence at this point to obtain a global agreement in describing how the particle size and grading characteristics of sand particles influence on the soil liquefaction resistance under dynamic loading. Most of the research conducted on compositional characteristics of soils without considering the effects of particle size and grading characteristics of sand in sand matrix soils. It also shows that the study using tropical sand and silt or clay on liquefaction resistance are still limited. Generally, soil liquefaction occurred in undrained condition. As mentioned by Das (2013), it difficult to model the soil behaviour for undrained and over-consolidated soils if the volume change of soils ignored. For this reason, the critical state soil mechanics (CSSM) framework is expected to provide a better interpretation of results than the Mohr-Coulomb failure theory (Tan, 2015). Although no volume change allowed under undrained condition, any volume change was automatically observed and saved into files through data acquisition unit provided using recent triaxial machine. At the end of monotonic test, the samples were tested for moisture content to be back-calculated on the specific volume at particular mean normal effective stress.

Tongkul (2015) shows some form of liquefaction occurred at Poring Hot Spring, Ranau, Sabah after magnitude 6.0 earthquake in 2015. The mud and water were ejected from underground and flow out due to the shaking and as a result turned the water to black. The mud and water move up because of liquefaction, which gathers at the interface between the clay layer and sand layer (Shao et. al, 2020). The characteristics of potentially liquefiable soil are found in many areas along the shoreline of Malaysia (Hashim *et al.,* 2017). Therefore, it is necessary to accumulate and analyse basic scientific data, elucidate the information, and establish more general and integrated understandings of liquefaction based on the obtained knowledge. The is the overall aim of this research. As a result, it is also expected that the outcome of this research makes contributions to the establishment of national-level disaster mitigation measures in Malaysia.

1.2 Problem Statement

Liquefaction resistance of sand matrix soils or sand fine mixtures has been extensively studied by the previous researchers since 1964 as a result of dramatic damages by earthquakes due to the seismic liquefaction phenomena in Niigata, Japan and Alaska, USA. To date, the factors affecting on the liquefaction resistance, such as sample preparation techniques, relative densities, aging and cementation methods, soil types, effective confining pressures, cyclic loading, and frequencies are well investigated and understood. However, until the end of the last decade, not much work had been conducted on the effects of particle shapes and sizes, grading characteristics, particle arrangements, and fines contents. The effects of fines contents on liquefaction susceptibility of sand matrix soils are in general agreement among the previous studies, but it is not conclusive enough to be applicable to all the types of sand with different physical characteristics. Although sand is the dominant material in sand matrix soils, there is still not enough effort in considering the effect of particle size and grading characteristics of sand as the main factor in altering liquefaction resistance. Hence results are still vague and contradictory.

Typical practices are biased to use the original sand to investigate the liquefaction resistance without considering the effect of particle size and the types of fines content whether it contain silts or clay. This may lead the misleading on the results on liquefaction resistance of soils samples. Previous studies reported that the presence of fines in sand could either increases or decreases the liquefaction resistance of sand matrix soils. Due to that reason, most of the researchers focusing on the role of fines in liquefaction resistance of sand matrix soils. The effect of fines content on liquefaction susceptibility of sand matrix soils is generally in great agreement but it is not conclusive enough to be applicable on all types of sand with different physical characteristics. Although the sand is the dominant material in sand matrix soils, not much efforts was given on the characterization of the roles of sand as the main factor in altering liquefaction resistance. Besides that, the research findings on the effect of particle size and grading characteristics of sand on liquefaction resistance of sand matrix soils is contradictory. Therefore, there is a need to investigate the effect of particle size and grading characteristics of sand on liquefaction resistance of sand matrix soils. In fact, there are not many studies yet done on the liquefaction susceptibility of soils in Malaysia due to an earthquake, particularly on sand matrix soils. Therefore, it becomes essential to develop fundamental understanding on liquefaction resistance of sand matrix soils of different particle sizes and grading curves, which could contribute towards disaster preparedness and prevention in the future, particularly in Malaysia.

1.3 Research Objectives

The research is aimed to investigate the effects of particle size and grading characteristics of sand on liquefaction resistance of sand matrix soils. In order to achieve the research aim, three (3) objectives have been identified and set as follows.

1) To evaluate the particle size, the grading characteristics, and the physical properties of sand matrix soils at various compositions of sand and fines.

2) To establish the critical state line as the failure envelope of sand matrix soils from the results of monotonic undrained triaxial tests.

3) To characterize the liquefaction susceptibility of sand matrix soils from the cyclic triaxial tests and validate through the centrifuge tests.

1.4 Scope and Limitation

In order to answer the problem statement that has been identified, laboratory tests had been carried out in accordance to respective British Standard (BS1377-2:1990 Classification Test (British Standards Institution, 2010a) and BS1377-8:1990 Effective Shear Strength Tests (British Standards Institution, 2010c)), American Society for Testing and Materials (ASTM D5311-M13 Standard Test Method for Load Controlled Cyclic Triaxial Strength of Soil (American Society for Testing and Materials, 2013)), (ASTM D3999 Standard Test Methods for the Determination of the Modulus and Damping Properties of Soils Using the Cyclic Triaxial Apparatus) and some cited journal publication including the test procedure introduced by Yamamuro and Lade (1997) on maximum density and minimum density of sand matrix soils. Portable microscope named as Cooling Tech USB Digital Microscope has a capability to view the particle size up to 500 times using built-in camera of 2.0 Megapixel. The used of this microscope shows a reliable result as reported by Alvin John (2014) for soils at different relative density. The research has been conducted under the scopes and limits as follows.

1) Sand and Kaolin were obtained from river mining sites (largely used for construction) at Johor and Kaolin (M) Sdn. Bhd, Selangor, respectively. The selection of kaolin is because it is more stable and less problematic compared to bentonite. Since it contains low plasticity fines, as a result kaolin shows less swelling and shrinking compared to bentonite.

2) Maximum void ratio represents the loosest state of samples while minimum void ratio shows the densest state of samples. All samples of sand matrix soils were prepared with targeted relative density of 15% for loose condition. Void ratio of each sand matrix samples at 15% relative density was back calculated as references.

3) Sand matrix soils were artificially prepared as follows: Clean sands were separated into three grain size ranges; coarse sands (2.0 mm to 0.6 mm); medium sands (0.6 mm to 0.2 mm); and fine sands (0.2 mm to 0.06 mm). These

three grain sizes of sand were mixed with low plasticity fines (kaolin) at different percentages (0% to 40%) by weight to prepare sample specimens.

4) GDS Automated Enterprise Level Dynamic Triaxial System (ELDYN) was used to carry out the monotonic and cyclic triaxial tests for all reconstituted sand matrix soils samples.

5) Wet tamping method with 5% moisture content was used to prepare the 50 mm x 100 mm sample for triaxial tests. No curing period was applied.

6) All samples were prepared to a target relative density for loose state soil. Three different effective consolidation pressures of 50, 100 and 200 kPa were applied in monotonic triaxial tests. As the most susceptible liquefy soils (loose state) found less than 15m depth, the effective consolidation pressure 50kPa, 100kPa and 200kPa was chosen to replicate the soil at different depth. The volume changes before shearing were automatically observed and saved into files through data acquisition unit (ELDCS) provided using ELDYN machine. At the end of monotonic test, the samples were tested for moisture content to be backed calculated on the specific volume at particular mean normal effective stress.

7) All samples were tested under isotropically consolidated undrained condition. The constant strain rate was fixed at 0.1 mm/min until the sample reached the maximum of 25% axial strain. Monotonic triaxial test was terminated when the maximum axial strain reached 25% (Head and Epps, 2011) (Tan, 2015). However, the failure criteria for reached critical state when the soil was sheared to 20% of strain or when the u become constant.

8) Two-way undrained cyclic triaxial tests were conducted on reconstituted loose sand matrix soil samples with cyclic frequency of 1 Hz at 100 kPa effective confining pressure. At 15% relative density, loose sand matrix soils were reconstituted by moist tamping method and void ratio at 15% were carefully kept as initial condition. Similar method was applied at monotonic test. Termination process during cyclic triaxial test was capped at maximum 10% of axial strain or 100 cycles, whoever encounter first. However, double amplitude axial strains of 5% was used for initiation of liquefaction or when

pore water pressure equal to consolidation pressure. The samples then were collected and tested for moisture and void ratio results.

1.5 Significance of the Research

The findings and knowledge of the research make substantial contributions to enhance the fundamental theory and to provide engineering practice of soil liquefaction evaluation for construction industry. This study provides better understanding on the role of sand in liquefaction resistance of sand matrix soil. By incorporating the theoretical framework of critical state soil mechanics, the fundamental understanding on how the particle size and grading characteristics influence the liquefaction resistance of sand matrix soils will be improved.

1.6 Thesis Outline

This thesis consists of six chapters as follows,

1) Chapter 1 describes the background of study which is associated with the liquefaction resistance and the rationale of this study. To achieve the aim of this study, problem statement, objectives and scope are presented followed by significance of this study.

2) Chapter 2 presents the literature review which starts from the introduction and description of liquefaction. Factors affecting the liquefaction resistance of soils from past research was reviewed. This chapter also reported and discussed the relationship between critical state parameter on liquefaction resistance. A short introduction on the findings replicating a model to represent the actual condition of soil is presented through a centrifuge sub-topic. The important of this study for Malaysia condition is presented through a seismic hazard research in Malaysia.

3) Chapter 3 explains how the research had been conducted to achieve the aims of this research. This chapter include testing program, laboratory test and small-scale test using centrifuge facilities provided by Kyoto University, Japan. Details on the experimental setup, testing and data collection are discussed in this chapter.

4) Chapter 4 discusses the results on the characteristics of sand matrix soils particularly on the aspect of index properties and strength properties of sand matrix soils at different percentage of fines content. This chapter focused on the shear strength of the sand matrix soil using two different criteria; Mohr-Coulomb failure criteria and the critical state failure criteria. Relationship between the critical state parameters and the particle size as well as the grading characteristics are discussed.

5) Chapter 5 presents and discusses the results from cyclic triaxial tests and centrifuge tests. The relationship between particle size and grading characteristics of sand matrix soil are evaluated and their effects to liquefaction resistance are discussed thoroughly.

6) Chapter 6 presents the conclusions and recommendation for future research.

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LIST OF PUBLICATIONS

Indexed Journal

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