



# **BEHAVIOR OF NARROW MECHANICALLY STABILIZED EARTH WALLS UNDER EARTHQUAKE LOADING**

By

**Ahmed Saad Rabei Mahmoud**

A Thesis Submitted to the  
Faculty of Engineering at Cairo University  
In Partial Fulfillment of the  
Requirements for the Degree of  
**DOCTOR OF PHILOSOPHY**

**in**  
**CIVIL ENGINEERING - PUBLIC WORKS**

FACULTY OF ENGINEERING, CAIRO UNIVERSITY  
GIZA – EGYPT  
2018

# **BEHAVIOR OF NARROW MECHANICALLY STABILIZED EARTH WALLS UNDER EARTHQUAKE LOADING**

By

**Ahmed Saad Rabei Mahmoud**

A Thesis Submitted to the  
Faculty of Engineering at Cairo University  
In Partial Fulfillment of the  
Requirements for the Degree of  
**DOCTOR OF PHILOSOPHY**

**in**  
**CIVIL ENGINEERING - PUBLIC WORKS**

Under the Supervision of

**Prof. Dr. Mohamed Ibrahim Amer**

Professor of Geotechnical Engineering  
Faculty of Engineering  
Cairo University

**Prof. Dr. Rami Mahmoud El-Sherbiny**

Professor of Geotechnical Engineering  
Faculty of Engineering  
Cairo University

**Dr. Omar Yousef Ezzeldin**

Associate Professor of Geotechnical Engineering  
Faculty of Engineering  
Cairo University

FACULTY OF ENGINEERING, CAIRO UNIVERSITY  
GIZA – EGYPT  
2018

# **BEHAVIOR OF NARROW MECHANICALLY STABILIZED EARTH WALLS UNDER EARTHQUAKE LOADING**

By

**Ahmed Saad Rabei Mahmoud**

A Thesis Submitted to the  
Faculty of Engineering at Cairo University  
In Partial Fulfillment of the  
Requirements for the Degree of  
**DOCTOR OF PHILOSOPHY**

**in**  
**CIVIL ENGINEERING - PUBLIC WORKS**

Approved by the  
Examining Committee

**Prof. Dr. Mohamed Ibrahim Amer**

Thesis Main Advisor

**Prof. Dr. Rami Mahmoud El-Sherbiny**

Advisor

**Prof. Dr. Hussain Hamid Elmamlouk**

Internal Examiner

**Prof. Dr. Mohamed Ahmed Abd Elmtal**

External Examiner

Professor at Faculty of Engineering,  
Ain Shams University

FACULTY OF ENGINEERING, CAIRO UNIVERSITY  
GIZA – EGYPT  
2018



**Date of Birth:** 17/02/1983  
**Nationality:** Egyptian  
**E-mail:** a\_saadrabei@yahoo.com  
**Phone:** 01002324342  
**Address:** 303 Z, 1<sup>st</sup> gate, Hadayk El-Ahram, Giza, Egypt  
**Registration Date:** 01/03/2013  
**Awarding Date:** .../.../ 2018  
**Degree:** Philosophy Doctor  
**Department:** Civil Engineering - Public Works  
**Supervisors:** Prof. Dr. Mohamed Ibrahim Amer  
Prof. Dr. Rami Mahmoud El-sherbiny  
Dr. Omar Y. Ezzeldine

**Examiners:**

Prof. Dr. Mohamed Ibrahim Amer	(Thesis Main Advisor)
Prof. Dr. Rami Mahmoud El-sherbiny	(Advisor)
Prof. Dr. Hussain Hamid Elmamlouk	(Internal Examiner)
Prof. Dr. Mohamed Ahmed Abd Elmtal	(External Examiner)
(Professor at Faculty of Engineering, Ain Shams University)	

**Title of Thesis:**

BEHAVIOR OF NARROW MECHANICALLY STABILIZED EARTH WALLS UNDER EARTHQUAKE LOADING

**Key Words:**

Narrow Wall, Earthquake, Shaking Table, Digital Image, Smartphone

**Summary**

The construction of Narrow Mechanically Stabilized Earth Walls (NMSE) of aspect ratio (ratio of reinforcement length,  $L$ , to wall height,  $H$ ) below 0.70 is expanded, recently, in urban areas in limited space. When NMSE walls constructed in active seismically zone, these walls are subjected to seismic ground motion. A Series of 11 shaking table tests are performed on reduced scale NMSE wall model (1/8 of the prototype model) considering the ground motion characteristics, wall aspect ratios, facing rigidity and wall configuration. The modelled walls display that NMSE walls behave as rigid body until yield occurs at input base acceleration ranging for 0.15g to 0.44g and these accelerations is the critical accelerations which corresponding to 0.5 % top wall displacement ratio. Then, excessive deformations are observed. In addition to the traditional shaking table test instrumentations, an advanced approach is adopted using computer vision to determine the wall facing displacement and acceleration amplification of NMSE wall. The aim of using computer vision is to verify its ability to capture the wall displacement and input acceleration amplification, which can be used for more complicated experiments such investigation the reinforcement strains and the strain field.

## **Disclaimer**

I hereby declare that this thesis is my original work and that no part of it has been submitted for a degree qualification at any other university or institute.

I further declare that I have appropriately acknowledged all sources used and have cited them in the references section.

Name :

Date :

Signature :

## **Acknowledgement**

I would like to thank my supervisor Dr. Mohamed I. Amer for sharing his experience and guiding me through this research program at every stage. Without his experience, encouragement and personal support this thesis would not have been possible. I am also grateful to Dr. Rami M. El-Sherbiny for his encouragement to carry out research in geotechnical earthquake engineering and for much valuable advice over the course of my career. All thanks to Dr. Omar Ezzeldine for the many valuable discussions particularly in reviewing this thesis. Special thanks to Dr. Hazem ElAnwar, structural engineering department, Cairo University. He was very useful in performing digital image analysis using smartphone for seismic analysis. The physical experimental work reported in this thesis would not have been possible without the staff technical support at soil mechanics and foundation research laboratory, Cairo University.

I would also like to acknowledge the projects funding and grant unit at Beni Suef University for their financial support. Special thanks for Prof. Dr. Mohie Elmashd, head of construction research institute at national water research center for his cooperation in the characterization of reinforcement material.

Words are not enough to thank my family for the support they have given me during this long and sometimes difficult times. My wife Marwa has kept my life in balance with her patience, encouragement and love. Without her support this thesis would not have been possible. Though they may not realize it yet, Icel and Abd Elrahman are sources of great joy that sustain me and help keep life in perspective. Finally, I would like to thank my parents for their love and support, and for instilling in me the value of learning and hard work, and providing me with the opportunities to advance my life. Special thanks go to my brother and sisters who are always in my heart and dreams.

## Table of Contents

Acknowledgement.....	i
Table of Contents.....	iii
List of Figures .....	iii
List of Tables .....	xiiiiv
Abstract .....	xv
<b>CHAPTER 1: INTRODUCTION .....</b>	<b>1</b>
1.1 GENERAL .....	1
1.2 PROBLEM DEFINITION .....	3
1.3 RESEARCH OBJECTIVES .....	4
1.4 RESEARCH METHODOLOGY .....	4
1.5 THESIS ORGANIZATION.....	5
<b>CHAPTER 2: SEISMIC PERFORMANCE OF MSE WALLS UNDER EARTHQUAKE LOADING: LITERATURE REVIEW .....</b>	<b>7</b>
<b>2.1 GENERAL .....</b>	<b>7</b>
<b>2.2 STATIC BEHAVIOR OF NMSE WALLS.....</b>	<b>8</b>
2.2.1 Janssen's Arching Theory.....	8
2.2.2 Full Scale Tests .....	8
2.2.2.1 Model Description and Applied Pressure .....	9
2.2.2.2 Test Results.....	9
2.2.3 Centrifuge Tests .....	13
2.2.3.1 Fraydman and Keissar (1987).....	13
2.2.3.2 Take and Valsangkar (2001).....	13
2.2.3.3 Woodruff (2003).....	13
2.2.3.4 Y.-B. Lee et al. (2010).....	16
2.2.4 Finite Element Analysis of Narrow Retaining Walls and Its Applications to Narrow MSE Walls .....	18
<b>2.3 SEISMIC BEHAVIOR OF MSE WALLS.....</b>	<b>19</b>
2.3.1 General .....	19
2.3.2 Field Performance of MSE Walls under Seismic Loading .....	19
2.3.3 Case Histories.....	20
2.3.3.1 Northridge (1994) Earthquake (USA) .....	20
2.3.3.2 Kobe (1995) Earthquake (Japan) .....	21
2.3.3.3 Chi-Chi (1999) Earthquake (Taiwan) .....	21
2.3.3.5 Kocaeli (1999) Earthquake (Turkey).....	22
2.3.3.6 El Salvador (2001) Earthquake (Central America).....	22
2.3.3.7 Japanese Experience-Niigataken-Chuetsu (2004) Earthquake .....	22

2.3.4 Scaling Law and Dimensional Analysis.....	24
2.3.5 Shaking Table Tests and Modeling Technique .....	26
2.3.5.1 General.....	26
2.3.5.2 Shaking Table Models on MSE Walls with Full-height Rigid Facing ....	30
2.3.5.3 Shaking Table Models on MSE Walls with segmental (modular block) facing.....	35
<b>2.4 FINITE ELEMENT AND FINITE DIFFERENCE MODELING .....</b>	<b>40</b>
<b>2.5 SUMMARY OF SEISMIC DESIGN METHODS OF MSE WALLS.....</b>	<b>44</b>
2.5.1 Pseudo-Static Design Method .....	45
2.5.1.1 Earth Pressure Calculations .....	45
2.5.1.2 Orientation of the active failure plane .....	46
2.5.1.3 Earth Pressure Distribution.....	47
2.5.1.4 Horizontal Seismic Coefficient, $K_h$ .....	50
2.5.1.5 Vertical Seismic Coefficient, $K_v$ .....	51
2.5.2 Analysis of Reinforced Soil walls using Mononobe-Okabe Approach.....	52
2.5.2.1 NCMA-Bathurst (1998) Approach .....	52
2.5.2.2 FHWA (2001) and AASHTIO (1998) Design Guidelines .....	54
2.5.3 Displacement Calculations .....	55
2.5.3.1 Empirical Approaches that use Peak Acceleration and Peak Velocity as Reference Parameters.....	57
2.5.3.2 Empirical Approaches using Maximum Acceleration and Predominant Period as Reference Parameters .....	58
<b>2.6 DIGITAL IMAGE ANALYSIS USING SMARTPHONES.....</b>	<b>61</b>
2.6.1 General .....	61
2.6.2 Yoon et al. (2016) Approach.....	62
2.6.2.1 Yoon et al. (2016) Results .....	63
<b>CHAPTER 3: PHYSICAL MODELING STUDY OF NARROW MSE WALL: 1-g SHAKING TABLE STUDY.....</b>	<b>66</b>
<b>3.1 GENERAL .....</b>	<b>66</b>
<b>3.2 CAIRO UNIVERSITY SHAKING TABLE .....</b>	<b>66</b>
3.2.1 Shaking Table Specifications .....	66
3.2.2 Data Acquisition and Software .....	68
3.2.3 Model Wall Rigid Box .....	68
<b>3.3 MODEL WALL MATERIALS .....</b>	<b>69</b>
3.3.1 Backfill Soil Properties .....	69
3.3.2 Geogrid Reinforcement.....	74
3.3.3 Facing Panels .....	77
<b>3.4 INSTRUMENTATION.....</b>	<b>79</b>



3.4.1 Facing Displacement Transducers .....	79
3.4.2 Strain Gauges .....	79
3.4.3 Accelerometers .....	80
<b>3.5 SCALING FACTOR (Iai 1989) .....</b>	<b>84</b>
<b>3.6 METHOD STATEMENT FOR CONSTRUCTION OF TYPICAL MODEL     WALL .....</b>	<b>84</b>
<b>3.7 TEST CONFIGURATIONS .....</b>	<b>85</b>
<b>3.8 INPUT MOTION CHARACTERISTICS .....</b>	<b>88</b>
3.8.1 Fundamental Frequency of NMSE Wall .....	88
3.8.2 Shaking Table Input Base Motion .....	91
<b>CHAPTER 4: SHAKING TABLE TEST RESULTS.....</b>	<b>97</b>
<b>4.1 GENERAL .....</b>	<b>97</b>
<b>4.2 DATA PROCESSING AND Filtering .....</b>	<b>97</b>
<b>4.3 WALL MODELS AND SHAKING TABLE GROUND MOTION .....</b>	<b>98</b>
<b>4.4 TEST RESULTS .....</b>	<b>103</b>
4.4.1 Model Wall Displacement.....	103
4.4.2 Model Wall Acceleration .....	121
4.4.3 Reinforcement Loads .....	135
4.4.4 Mass Movement .....	138
<b>CHAPTER 5: ANALYSIS AND DISCUSSION OF TEST RESULTS .....</b>	<b>144</b>
<b>5.1 GENERAL .....</b>	<b>144</b>
<b>5.2 SEISMIC-INDUCED WALL DEFORMATIONS.....</b>	<b>144</b>
5.2.1 Effect of Predominant Frequency .....	144
5.2.2 Effect of Wall Aspect Ratio .....	145
5.2.3 Effect of Wall Facing Rigidity .....	146
5.2.4 Effect of Wall Configuration.....	147
5.3 AMPLIFICATION FACTOR OF NMSE WALL MODELS .....	148
5.4 AVERAGE DESIGN ACCELERATION .....	152
5.5 DISPLACEMENT BASED ON YIELD ACCELEERATION.....	156
5.6 REINFORCEMENT CONNECTIONS TENSILE LOADS.....	157
5.7 SURFACE SUBSIDENCE OF MODEL WALLS .....	159
5.8 TRADITIONAL MSE WALL VERSUS NMSE WALL .....	161
5.9 EFFECT OF MAINSHOCK-AFTERSHOCK SEQUENCE.....	163
5.9.1 General .....	163
5.9.2 Wall Displacement due to Multiple Ground Motions .....	163
5.9.3 Acceleration response due to multiple ground motions .....	163

<b>CHAPTER 6: DIGITAL IMAGE ANALYSIS USING SMARTPHONE.....</b>	<b>165</b>
6.1 GENERAL AND TEST SET-UP .....	165
6.2 DIGITAL IMAGE ANALYSIS METHODOLOGY .....	166
6.3 PREDICTION OF BASE ACCELERATION .....	168
6.4 PREDICTION OF WALL DISPLACEMENT .....	170
6.5 PREDICTION OF ACCELERATION RESPONSE .....	171
6.6 EVALUATION OF DIA TECHNIQUE.....	172
<b>CHAPTER 7: DESIGN OF NMSE WALL COMPONENT .....</b>	<b>173</b>
<b>7.1 GENERAL .....</b>	<b>173</b>
<b>7.2 MORRISON ET AL. 2006 DESIGN PROCEDURE(Publication No. FHWA- CFL/TD-06-001) .....</b>	<b>173</b>
7.2.1 Potential Modes of Failure .....	173
7.2.2 Factors of Safety .....	174
7.2.3 Internal Stability Design .....	175
7.2.4 External Stability Design .....	181
7.2.5 Global Stability Design .....	181
7.2.6 Seismic Stability Design .....	181
<b>CHAPTER 8: CONCLUSIONS AND RECOMMENDATIONS.....</b>	<b>183</b>
8.1 GENERAL .....	183
8.2 SHAKING TABLE TESTS AND DIA RESULTS .....	183
8.3 RECOMMENDATIONS FOR FUTURE RESEARCH .....	184
<b>REFERENCES .....</b>	<b>185</b>

## **APPENDECIES**

Appendix (A): Acceleration-Time Histories

Appendix (B): Reinforcement Load/Strain-Time Histories

## List of Figures

Fig. 1.1: The face length construction of MSE walls constructed in Japan.....	1
Fig. 1.2: Cost comparison of conventional retaining gravity wall and different MSE walls (after Koerner et al. (1998)) .....	2
Fig. 1.3: Configuration of proposed narrow MSE wall in front of stabilized face .....	3
Fig.2.1: The field test configuration and instrumentation layout- by Morrison et al. (2006) .....	9
Fig.2.2: The reinforcement strain distribution for connected wall .....	10
Fig.2.3: The reinforcement strain distribution for unconnected wall .....	11
Fig.2.4: The reinforcement average strain versus surcharge pressure .....	12
Fig.2.5: Cumulative lateral deformation of NMSE wall face .....	12
Fig.2.6: Photographic images from centrifuge: (a) Initial condition (gravity); (b) Working Stresses (10g); (c) Before Failure (41g); (d) Failure condition (41g)- (Woodruff, 2003) .....	15
Fig.2.7: Example of compound failure at test 2b (Woodruff, 2003) .....	16
Fig.2.8: Centrifuge model after (Lee et al. 2010): a) Schematic cross-section b) Photos .....	17
Fig.2.9: Comparison of Footing settlement between Lee et al. (2010) centrifuge model and Morrison et al. (2006) field test.....	18
Fig. 2.10: Example failed segmental MSE wall after 1990 Chi-Chi earthquake (After Koseki and Hayano 2000) .....	21
Fig. 2.11: Railway embankment collapse and repair as a result of 2004 Chuetsu earthquake (after Kitamoto et al. 2006). .....	23
Fig. 2.12: Failure of highway and adjacent railway embankment resulting from 2004 Chuetsu earthquake (JSCE2006). .....	24
Fig. 2.13: Repair of railway embankment as a result of 2004 Chuetsu earthquake (after JSCE 2006) .....	24
Fig. 2.14: Constitutive behavior of scale mode proposed by stress and strain scaling factors (from Rocha 1957) .....	26
Fig. 2.15: Preparation of shaking table model (model height=0.35 m) (Lo Grasso et al. 2005) ...	29
Fig. 2.16: Shaking table Test (Lo Grasso et al. 2005) .....	29
Fig. 2.17: Wall models used to investigate the influence of wall type and soil reinforcement arrangement on simulated seismic response (Watanabe et al. 2003) .....	30
Fig. 2.18: Example of Kobe earthquake accelerogram (Watanabe et al. 2003) .....	31
Fig. 2.19: Permanent deformations at top of wall versus peak horizontal ground acceleration coefficient (Watanabe et al. 2003). .....	31
Fig. 2.20: Final wall geometry, soil deformations and internal soil failure planes (Watanabe et al. 2003).....	32
Fig.2.21: Footing load response during base shaking of gravity wall structure (Watanabe et al. 2003).....	33
Fig.2.22: Tensile reinforcement loads through the base shaking of MSE wall (Watanabe et al. 2003) .....	33
Fig. 2.23: Development of global instability mechanism during shaking of MSE model wall (Kato et al. 2002).....	34

Fig. 2.24: Sum of tensile reinforcement loads for MSE walls with a sloped foundation toe (S) and level ground (L) (Kato et al. 2002).....	34
Fig. 2.25: Reduced-scale rigid panel wall models with a hinged toe (El-Emam and Bathurst 2005) .....	36
Fig. 2.26: Shaking table test arrangement for 1-m high GRS wall models (Bathurst et al. 2002) .....	37
Fig. 2.27: Wall displacement versus peak base acceleration for model walls with different facing types (Bathurst et al. 2002).....	37
Fig. 2.28: Full-scale shaking table test of segmental (modular block) retaining wall .....	38
(Ling et al. 2005) .....	38
Fig. 2.29: Tested walls and configurations .....	39
(Guler and Selek. 2014) .....	39
Fig. 2.30: Predicted failure planes from geotextile strains compared with Rankin failure surface (Guler and Selek. 2014).....	39
Fig.2.31: Numerical modeling of centrifuge test of segmental GRS wall .....	40
(Fujii et al. 2006) .....	40
Fig. 2.32: Comparison of physical test results and computed acceleration response of centrifuge tests of segmental MSE walls (Fuji et al. 2006) .....	41
Fig. 2.33: Comparison of physical test results and computed lateral displacement response of centrifuge tests of segmental GRS walls (Fujii et al. 2006) .....	42
Fig. 2.34. Comparison of physical test results and computed horizontal earth pressure response of centrifuge tests of segmental GRS walls .....	43
(Fujii et al. 2006) .....	43
Fig. 2.35: Predicted and observed failure surfaces from hinged toe model wall (5 reinforcement layers and $L/H = 1.0$ ) at different input base acceleration amplitudes. Note: Dark shading indicates large shear strains (El-Emam et al. 2004). .....	43
Fig. 2.36: Influence of reinforcement stiffness (J) on distribution of dynamic load increment in reinforcement layers (Bathurst and Hatami 1998) .....	44
Fig.2.37: Influence of predominant frequency of base ground motion on wall displacements (Hatami and Bathurst 2000) .....	44
Fig.2.38: forces considered in the Mononobe-Okabe (M-O) analysis.....	46
(from seed and Whitman 1970) .....	46
Fig. 2.39: Influence of seismic coefficient, $K_h$ , on the orientation of internal failure plane, $\square AE$ .....	47
Fig. 2.40: Variation of the parameter $Ch$ for base sliding and overturning modes of wall deformations with magnitude of input base acceleration coefficient (from Prakash 1981). .....	48
Fig. 2.41: Earth pressure distribution for seismic loading (from Bathurst and Cai 1995).....	48
Fig. 2.42: influence of horizontal seismic coefficient, $K_h$ , wall inclination, $\square$ , wall-soil interface friction angle, $\square$ , and vertical seismic coefficient, $K_v$ , on location of normalized total arm, $Y_{total}/H$ (from Bathurst and Cai 1995).....	49
Fig. 2.43: Variation of seismic coefficient, $K_h$ , calculated using different equations with normalized horizontal acceleration amplitude.....	50

Fig. 2.44: Influence of seismic coefficients $K_h$ , $K_v$ and wall inclination, $\alpha$ , on the dynamic earth force PAE. ....	51
Fig. 2.45: Potential failure modes for reinforced soil walls with full-height rigid panel facings (from Bathurst et al. 1996) .....	53
Fig. 2.46: Geometry and forces used to calculate reinforcement loads for reinforced soil retaining walls (from NCMA-Bathurst 1997). ....	53
Fig. 2.47: Forces used to calculate reinforcement loads for reinforced soil retaining walls (from FHWA 2001, AASHTO 1998).....	54
Fig. 2.48: Illustration of Newmark's sliding block method to calculate permanent displacement of earth structures (unsymmetrical displacement). ....	56
Fig. 2.49: Summary of proposed relationships that use peak acceleration and peak velocity as reference parameters to calculate seismic-induced displacement .....	59
(from Cai and Bathurst 1996). ....	59
Fig. 2.50: Rigid block in sloping surface analogy and different pulses used in displacement calculation (from Sarma 1979). ....	59
Fig. 2.51: Summary of proposed relationships that use maximum acceleration and predominant period as reference parameters to calculate seismic-induced displacement (from Cai and Bathurst 1996) .....	61
Fig. 2.52. The computer vision based displacement measurement procedure;.....	63
Fig. 2.53: Comparison between the transfer functions using different measuring instruments (Figure best seen in color). ....	65
Fig. 3.1: MTS platform, servo-hydraulic actuator and remote station control system .....	67
Fig. 3.2: A schematic configuration for the platform and servo-hydraulic actuator dimensions...67	
Fig. 3.3: The rigid (container) box assembled into Cairo University shaking table .....	69
Fig. 3.4: Particle size distribution for backfill sand .....	71
Fig. 3.5: Modified Proctor test results for backfill sand .....	71
Fig. 3.6: Shear Stress and volumetric deformation versus horizontal displacement for backfill sand from direct shear test .....	72
Fig. 3.7: Direct shear test results expressed as peak secant and secant residual shear strength ....	72
Fig. 3.8: Direct shear box test results expressed as peak secant friction angle, secant residual friction angle, and dilation angle versus normal stress.....	73
Fig. 3.9: Stress ratio and axial strain for backfill sand from Triaxial test.....	73
Fig. 3.10: P-q diagram .....	74
Fig. 3.11: Wide-width strip tensile testing (ASTM 4595-86) of Hate ® 23.142 GR reinforcement (performed in NWRC).....	75
Fig. 3.12: Wide-width tensile test results for reinforcement specimens tested in machine direction at different strain rates .....	76
Fig. 3.13: Global versus local axial strain performance geogrid specimens tested in machine direction at different strain rates.....	77
Fig.3.14a: Rigid facing system used in this investigation .....	78
Fig.3.14b: Half gabion facing system used in this investigation .....	78
Fig.3.14c: Wraparound facing system used in this investigation .....	78

Fig.3.15: LVDTs Types used to measure the reduced-scale model lateral displacement.....	81
Fig.3.16: Strain gauges attached to the reinforcement layers (plan).....	82
Fig.3.17: instrumentations layout plan .....	82
Fig.3.18: Accelerometers types used to measure the modeled wall acceleration response .....	83
Fig.3.19: Example for model bracing system used for model construction .....	85
Fig.3.20: Rigid configuration used for reduced scale NMSE walls no. 1, 2, 3, 4, 5, 6, 10 and 11	86
Fig.3.21: Half gabion configuration used for reduced scale NMSE wall no.7 .....	87
Fig.3.22: Facing systems used in this investigation for reduced scale NMSE wall no. 8 .....	87
Fig.3.23: Configuration of model wall no. 9 .....	88
Fig.3.24: Back-bone curve for the sand backfill used in this investigation .....	90
Fig.3.25: Variation of two dimensional fundamental frequencies with the shear modulus values	90
Fig.3.26: Displacement, velocity, and input base acceleration versus time for Walls 1 and 4 to 9 .....	92
Fig.3.27: Displacement, velocity, and input base acceleration versus time for Walls 2.....	93
Fig.3.28: Displacement, velocity, and input base acceleration versus time for Walls 3.....	94
Fig.3.29: Input base acceleration frequency content .....	95
Fig.3.30: Measured input base acceleration versus time for Walls 10 when applying-(San-Fernando 1971) earthquake .....	96
Fig.3.31: Measured input base acceleration versus time for Walls 11 when applying-(Kobe 1995) earthquake .....	96
Fig. 4.1: NMSE Wall models Configurations.....	99
Fig. 4.2: Measured input base acceleration characteristics of predominant frequency 2.5 Hz (Walls 1, 4, 5, 6, 7, 8, 9).....	100
Fig. 4.3: Measured input base acceleration characteristics of predominant frequency 5 Hz-(Wall 2) .....	100
Fig. 4.4: Measured input base acceleration characteristics of predominant frequency 1 Hz-(Wall 3) .....	100
Fig.4.5: Measured input base acceleration versus time for Walls 10 .....	101
Fig.4.6: Measured input base acceleration versus time for Walls 11 (Kobe(1995) earthquake) .	101
Fig. 4.7: Peak base accelerations of shaking table for the tested model walls.....	101
Fig. 4.8: Shaking table acceleration response in frequency domain for different model walls ...	102
Fig. 4.9: NMSE Model wall facing lateral deformation and input base acceleration-time histories for model wall (Wall 1) .....	104
Fig. 4.10: NMSE Model wall facing lateral deformation and input base acceleration-time histories for model wall (Wall 2) .....	105
Fig. 4.11: NMSE Model wall lateral deformation and input base acceleration-time histories for model wall (Wall 3).....	106
Fig. 4.12: NMSE Model wall lateral deformation and input base acceleration-time histories for model wall (Wall 4).....	107
Fig. 4.13: NMSE Model wall facing lateral deformation and input base acceleration-time histories for model wall (Wall 5) .....	108

Fig. 4.14: NMSE Model wall facing lateral deformation and input base acceleration-time histories for model wall (Wall 6) .....	109
Fig. 4.15: NMSE Model wall facing lateral deformation and input base acceleration-time histories for model wall (Wall 7) .....	110
Fig. 4.16: NMSE Model wall facing lateral deformation and input base acceleration-time histories for model wall (Wall 8) .....	111
Fig. 4.17: NMSE Model wall facing lateral deformation and input base acceleration-time histories for model wall (Wall 9) .....	112
Fig. 4.18: NMSE Model wall facing lateral deformation and input base acceleration-time histories for model wall (Wall 10) .....	113
Fig. 4.19: NMSE Model wall facing lateral deformation and input base acceleration-time histories for model wall (Wall 11) .....	114
Fig. 4.20: Illustration of outward horizontal deformations and rotation of the facing at different input base acceleration amplitudes (walls from 1 to 5). .....	117
Fig. 4.21: Illustration of outward horizontal deformations and rotation of the facing at different input base acceleration amplitudes (walls from 6 to 9). .....	118
Fig. 4.22: Illustration of outward horizontal deformations and rotation of the facing for walls 10 and 11. ....	119
Fig. 4.23: Lateral displacements measured of the facing panel and response accelerations at different for one second window (Wall2). ....	120
Fig. 4.24: Schematic diagram for accelerometers positions within the backfill for walls no. (1 to 9).....	121
Fig. 4.25: Schematic diagram for accelerometers positions for walls no. (9&10). ....	121
Fig. 4.26: Input base acceleration and reinforced backfill response acceleration-time histories for Walls (1 and 4) Note: for wall 1, the shaking was stopped at time $t = 35$ S.....	123
Fig. 4.27: Input base acceleration and reinforced backfill response acceleration-time histories for Wall no. 10 .....	124
Fig. 4.28: Input base acceleration and reinforced backfill response acceleration-time histories for Wall no. 11 .....	125
Fig. 4.29: Fast Fourier Transformations (FFTs) for the input base and response accelerations for wall model (Wall2).....	127
Fig. 4.30: Fast Fourier Transformations (FFTs) for the input base and response accelerations for wall model (Wall 3).....	128
Fig. 4.31: Fast Fourier Transformations (FFTs) for the input base and response accelerations for wall model (Wall 4).....	129
Fig. 4.32: Amplification factor profile-wall 1, 4 ( $L/H = 0.4$ , $f = 2.5$ Hz).....	130
Fig. 4.33: Amplification factor profile-wall 2 ( $L/H = 0.4$ , $f = 5.0$ Hz).....	130
Fig. 4.34: Amplification factor profile-wall 3 ( $L/H = 0.4$ , $f = 1.0$ Hz).....	130
Fig. 4.35: Amplification factor profile-wall 5 ( $L/H = 0.3$ , $f = 2.5$ Hz).....	130
Fig. 4.36: Amplification factor profile-wall 1, 6 ( $L/H = 0.2$ , $f = 2.5$ Hz).....	131
Fig. 4.37: Amplification factor profile-wall 7-half gabion face ( $L/H = 0.3$ , $f = 5.0$ Hz).....	131
Fig. 4.38: Amplification factor profile-wall 8-wraparound face ( $L/H = 0.3$ , $f = 2.5$ Hz).....	131