

**Determining Seismic Response of Mid-rise
Building Frames Considering Dynamic
Soil-Structure Interaction**

By

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CERTIFICATE OF AUTHORSHIP/ORIGINALITY

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

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Sydney, December 2012

ABSTRACT

Structures are often mounted on layers of soil unless bedrock is very close to the ground surface. Based on the fact that seismic waves pass through kilometres of bedrock and usually less than 100 meters of soil, soil layers play a significant role in assigning the characteristics of the ground surface movement. When the ground is stiff enough, the dynamic response of the structure will not be influenced significantly by the soil properties during the earthquake, and the structure can be analysed under the fixed base condition. When the structure is resting on a flexible medium, the dynamic response of the structure will be different from the fixed base condition owing to the interaction between the soil and the structure. This difference in behaviour is because of the phenomenon, commonly referred to as soil-structure interaction (SSI), which if not taken into account in analysis and design properly; the accuracy in assessing the structural safety, facing earthquakes, could not be reliable. Performance-based engineering (PBE) is a technique for seismic evaluation and design using performance level prediction for safety and risk assessment. Soil-structure interaction particularly for unbraced structures resting on relatively soft soils may significantly amplify the lateral displacements and inter-storey drifts. This amplification of lateral deformations may change the performance level of the building frames. Thus, a comprehensive dynamic analysis to evaluate the realistic performance level of a structure should consider effects of SSI in the model.

In this study, an enhanced numerical soil-structure model has been developed which treats the behaviour of soil and structure with equal rigor. Structural elements of the soil-structure model are capable of capturing both elastic and inelastic structural behaviour as well as structural geometric nonlinearity (large displacements) in dynamic analysis. Adopting direct method of analysis, the numerical model can perform fully nonlinear time history dynamic analysis to simulate realistic dynamic behaviour of soil and structure under seismic excitations accurately. Fully nonlinear method precisely follows any prescribed nonlinear constitutive relation and adopts hysteretic damping algorithm enabling strain-dependent modulus ($G/G_{max} - \gamma$) and damping functions ($\xi - \gamma$) to be incorporated directly to capture the hysteresis curves and energy-absorbing characteristics of the real soil. In order to avoid reflection of outward propagating waves back into the model, viscous boundaries comprising independent dashpots in the normal and shear directions are placed at the lateral boundaries of

the soil medium. In addition, the lateral boundaries of the main grid are coupled to the free-field grids at the sides of the model to simulate the free-field motion which would exist in the absence of the structure.

The proposed numerical soil-structure model has been verified and validated by performing experimental shaking table tests at the UTS civil laboratories. For this purpose, a prototype soil-structure system including a building frame resting on a clayey soil has been selected and scaled with geometric scaling factor of 1:30. The soil-structure physical model consists of 15 storey steel structural model, synthetic clay mixture consists of kaolinite, bentonite, class F fly ash, lime, and water, and laminar soil container, designed and constructed to realistically simulate the free field conditions in shaking table tests. A series of shaking table tests were performed on the soil-structure physical model under the influence of four scaled earthquake acceleration records and the results, in terms of maximum structural lateral and vertical displacements, were measured and compared with the numerical predictions. Comparing the predicted and observed values, it is noted that the numerical predictions and laboratory measurements are in a good agreement. Therefore, the numerical soil-structure model can replicate the behaviour of the real soil-structure system with acceptable accuracy.

In order to determine the elastic and inelastic structural response of regular mid-rise building frames under the influence of soil-structure interaction, three types of mid-rise moment resisting building frames, including 5, 10, and 15 storey buildings are selected in conjunction with three soil types with the shear wave velocities less than 600m/s, representing soil classes C_e ($V_s=600m/s$), D_e ($V_s=320m/s$), and E_e ($V_s=150m/s$) according to Australian Standards, having three bedrock depths of 10, 20, and 30 metres. The structural sections are designed after conducting nonlinear time history analysis, based on both elastic method, and inelastic procedure considering elastic-perfectly plastic behaviour of structural elements. The designed frame sections are modelled and analysed, employing Finite Difference Method adopting FLAC2D software under two different boundary conditions: (i) fixed base (no soil-structure interaction), and (ii) flexible base considering soil-structure interaction. Fully nonlinear dynamic analyses under the influence of four different earthquake records are conducted and the results in terms of lateral displacements, inter-storey drifts, and base shears for both mentioned boundary conditions are

obtained, compared, and discussed. According to the numerical and experimental investigations, conducted in this study, soil-structure interaction has significant effects on the elastic and inelastic seismic response and performance level of mid-rise moment resisting building frames resting on soil classes D_e and E_e . Thus, the conventional elastic and inelastic design procedures excluding SSI may not be adequate to guarantee the structural safety of regular mid-rise moment resisting building frames resting on soft soil deposits.

Based on the numerical results, a simplified design procedure is proposed in which inter-storey drifts under the influence of soil-structure interaction for each two adjacent stories can be determined and checked against the criterion of life safe performance level. This can be used to ensure the performance levels of the mid-rise moment resisting building frames under the influence of SSI remain in life safe level, and the seismic design is safe and reliable. Structural engineers and engineering companies could employ the proposed simplified design procedure for similar structures as a reliable and accurate method of considering SSI effects in the seismic design procedure instead of going through the whole numerical procedure which could be complicated and time consuming.

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TABLE OF CONTENTS

1. INTRODUCTION.....	1
1.1 General.....	1
1.2 Significant of Soil-Structure Interaction.....	2
1.3 Objectives and Scope of Study.....	3
1.4 Organisation of the Thesis.....	5
2. LITERATURE REVIEW ON SOIL-STRUCTURE INTERACTION.....	7
2.1 Background.....	7
2.2 Soil-Structure Interaction (SSI).....	8
2.2.1 Principles of Soil-Structure Interaction.....	9
2.3 Modelling Soil Medium for Soil-Structure Interaction Analysis.....	13
2.3.1 Winkler Model (Spring Model).....	13
2.3.2 Lumped Parameter on Elastic Half-Space.....	14
2.3.3 Numerical Methods.....	17
2.4 Effects of Soil-Structure Interaction on Seismic Behaviour of Building Frames.....	20
2.4.1 Effects of Shear Wave Velocity of Subsoil on Seismic Response.....	22
2.4.2 Effect of SSI on Seismic Response of Braced Building Frames.....	23
2.4.3 Effect of SSI on Seismic Response of Unbraced Building Frames.....	24
2.5 Building Codes Recommendations.....	27
2.6 Relationships for Considering SSI Effects in Seismic Design.....	30
2.7 Shaking Table Experimental Tests.....	32
2.8 Summary.....	37
3. NUMERICAL SIMULATION OF SOIL-STRUCTURE INTERACTION.....	40
3.1 Soil-Structure System in Direct Method.....	40
3.2 Finite Difference Software, FLAC2D.....	41
3.3 Numerical Idealisation of Soil-Structure System.....	42
3.4 Structural Elements.....	43
3.4.1 Beam Structural Elements Geometric and Mechanical Properties.....	44

3.4.2	Local Systems and Sign Conventions of Beam Structural Element	45
3.5	Soil Elements	46
3.5.1	Soil Elements Constitutive Model and Parameters	49
3.5.2	Soil Damping	49
3.5.3	Soil Shear Modulus	52
3.5.4	Backbone Curves for Cohesive Soils	54
3.5.5	Backbone Curves for Cohesionless Soils	55
3.6	Interface Elements	56
3.7	Boundary Conditions	58
3.7.1	Lateral Boundary Conditions	58
3.7.2	Bedrock Boundary Condition	61
3.7.3	Distance between Soil Boundaries	61
3.8	Dynamic Analysis of Soil-Structure Systems	62
3.8.1	Numerical Procedures for Dynamic Analysis of Soil-Structure Systems	62
3.8.2	Hysteretic Damping Formulation and Implementation	65
3.9	Summary	67
4.	EXPERIMENTAL STUDY AND VERIFICATION	69
4.1	General	69
4.2	Prototype Characteristics	70
4.3	Scaling Factors for Shaking Table Testing	70
4.3.1	Adopted Geometric Scaling Factor	73
4.4	Structural Model Design and Construction	75
4.4.1	Characteristics of Structural Model	75
4.4.2	Design of Structural Model	76
4.4.3	Construction of Structural Model	78
4.5	Soil Container Design and Construction	79
4.5.1	Characteristics of Laminar Soil Container	79
4.5.2	Design of Laminar Soil Container	80
4.5.3	Construction of Laminar Soil Container	84
4.6	Soil Mix Design	86

4.6.1	Characteristics of Soil Model.....	86
4.6.2	Development of Soil Mix.....	88
4.6.3	Properties of the Selected Soil Mix.....	94
4.7	Scaling of Adopted Earthquake Acceleration Records	95
4.8	Instrumentation and Data Acquisition System	97
4.9	Shaking Table Tests on Fixed Base Structural Model.....	99
4.9.1	Shaking Table Tests Procedure.....	100
4.9.2	Determining Structural Damping Ratio	101
4.9.3	Fixed base Model Test Results	101
4.10	Shaking Table Tests on Soil-Structure Model.....	103
4.10.1	Test Preparations and Setup	104
4.10.2	Shaking Table Tests on Flexible Base Model.....	107
4.10.3	Flexible Base Model Test Results.....	108
4.11	Verification of Numerical Models Using Shaking Table Test Results	110
4.12	Summary.....	117
5.	NUMERICAL PARAMETRIC STUDY	119
5.1	Introduction	119
5.2	Characteristics of Adopted Structure Models.....	120
5.3	Nonlinear Time-History Dynamic Analysis.....	120
5.3.1	Geometric Nonlinearity and P-Delta Effects in Time-History Analysis.....	121
5.3.2	Utilised Ground Motions in Time History Analyses	123
5.4	Geotechnical Characteristics of employed Subsoils.....	124
5.5	Utilised Soil and Interface Parameters in FLAC Soil-Structure Model	125
5.6	Structural Section Design of the Models Using SAP2000	127
5.6.1	Elastic Structural Design of the Models	128
5.6.2	Inelastic Structural Design of the Models.....	131
5.7	Determining Seismic Response of the Models Considering Dynamic Soil- Structure Interaction	134
5.8	Results and Discussions.....	135
5.8.2	Base Shear.....	154

5.8.3	Lateral Deflections and Inter-storey Drifts	154
5.9	Summary.....	157
6.	SIMPLIFIED DESIGN PROCEDURE FOR PRACTICAL APPLICATIONS	159
6.1	Introduction	159
6.2	Developing Initial Form of the Empirical Relationship	160
6.3	Proposed Simplified Design Procedure	162
6.4	Worked Example	167
6.5	Summary.....	170
7.	CONCLUSIONS AND RECOMMENDATIONS.....	171
7.1	Conclusions	171
7.2	Recommendations and Future Works.....	175
	REFERENCES.....	176
	APPENDIX A	190

LIST OF FIGURES

Figure 2.1: Coupled dynamic model of structure and soil for horizontal and rocking motions proposed by Wolf (1985)	10
Figure 2.2: Equivalent one-degree-of-freedom system presented by Wolf (1985)	11
Figure 2.3: Redundant coupled dynamic model of structure with zero rotation of mass and of soil for horizontal and rocking motions (Wolf, 1985)	12
Figure 2.4: Winkler foundation model.....	13
Figure 2.5: Soil modelling in Lumped Parameter method.....	15
Figure 2.6: Modelling soil medium using numerical methods; (a) 2D model; (b) 3D model.....	18
Figure 2.7: Flexible cylindrical soil container (Meymand, 1998)	35
Figure 2.8: Laminar soil container developed by Taylor (1997)	36
Figure 3.1: Soil-structure system in direct method	40
Figure 3.2: Soil-structure model simulated in FLAC2D.....	42
Figure 3.3: Components of the soil-structure model.....	43
Figure 3.4: Modelling structural elements using beam structural elements.....	43
Figure 3.5: General beam structural element cross-section in y-z plane (after Itasca, 2008)	44
Figure 3.6: Coordinate system of beam structural elements (after Itasca, 2008).....	45
Figure 3.7: Sign convention for forces and moments of beam elements (after Itasca, 2008)	46
Figure 3.8: Two dimensional plane-strain soil grids consisting of quadrilateral elements	47
Figure 3.9: (a) Overlaid quadrilateral elements used in soil-structure model; (b) typical triangular element with velocity vectors; (c) nodal force vector (after Malvern, 1969).47	
Figure 3.10: Wave amplitude dissipation in soil medium.....	51
Figure 3.11: Hysteretic stress-strain relationships at different strain amplitudes	52

Figure 3.12: Relations between G/G_{max} versus cyclic shear strain for cohesive soils (after Sun et al., 1998).....	54
Figure 3.13: Relations between damping versus cyclic shear strain for cohesive soils (after Sun et al., 1998).....	54
Figure 3.14: Relations between G/G_{max} and cyclic shear strain for cohesionless soils (after Seed et al., 1986)	55
Figure 3.15: Relations between damping ratio and cyclic shear strain for cohesionless soils (after Seed et al, 1986).....	56
Figure 3.16: Interface elements including normal (k_n) and shear (k_s) springs	56
Figure 3.17: Boundary conditions for soil-structure model.....	58
Figure 3.18: Preliminary lateral boundary condition for soil medium (after Chopra and Gutierrez, 1978)	58
Figure 3.19: Simulating lateral boundary conditions for soil-structure model.....	60
Figure 4.1: Dimensional characteristics of the prototype	70
Figure 4.2: Scale model of soil structure interaction problem.....	74
Figure 4.3: Structural model dimensions	75
Figure 4.4: 3D numerical model of the structural model in SAP2000.....	77
Figure 4.5: Construction detail drawings of the structural model.....	77
Figure 4.6: Cut and drilled steel plates by the UTS engineering workshop.....	78
Figure 4.7: Assembling process of the structural model.....	78
Figure 4.8: Completed structural model.....	79
Figure 4.9: Adopted laminar soil container dimensions	80
Figure 4.10: 3D numerical model of the laminar soil container in SAP2000	82
Figure 4.11: Laminar soil container general plan.....	82
Figure 4.12: Construction detail drawing of the hardwood timber base plate	83
Figure 4.13: Construction detail drawing of the aluminium base frame.....	83
Figure 4.14: Construction detail drawing of the connections	84

Figure 4.15: Cutting and drilling aluminium sections at the UTS structures laboratory ..	84
Figure 4.16: (a) Cut and drilled aluminium sections; (b) ready to use welded rectangular aluminium frames	85
Figure 4.17: (a) Construction of timber base plate at the structures laboratory; (b) drilling required holes on the timber base plate	85
Figure 4.18: (a) Bolted connection between the base plate and base frame; (b) soil container walls consisting of glued aluminium frames and rubbers	86
Figure 4.19: Laminar soil container view after completion of the walls.....	86
Figure 4.20: Different dry components of the soil mix	89
Figure 4.21: (a) Soil mix cylindrical test specimen; (b) placing the mixtures into the mould with palette knives	90
Figure 4.22: Bender element piezoelectric transducers	91
Figure 4.23: Master control box of bender element system.....	91
Figure 4.24: Soil specimen placed between bender elements.....	92
Figure 4.25: PC running bender element control software	93
Figure 4.26: Shear wave velocities versus cure age for the examined mixes	93
Figure 4.27: (a) Sealed soil Mix C cylindrical test specimen of size $D=100$ mm and $h=200$ mm; (b) failed soil specimen after performing Unconfined Compression test ...	95
Figure 4.28: Kobe earthquake (1995); (a) original record; (b) scaled record.....	96
Figure 4.29: Northridge earthquake (1994); (a) original record; (b) scaled record	96
Figure 4.30: El Centro earthquake (1940); (a) original record; (b) scaled record	97
Figure 4.31: Hachinohe earthquake (1968); (a) original record; (b) scaled record	97
Figure 4.32: Utilised measuring instruments in the shaking table tests; (a) displacement transducer; (b) accelerometer	98
Figure 4.33: Fixed base structural model secured on the UTS shaking table	99
Figure 4.34: Final arrangement of the measuring instruments	100
Figure 4.35: Recorded maximum lateral deflections of fixed base 15 storey structural model under the influence of scaled Kobe (1995) earthquake.....	102

Figure 4.36: Recorded maximum lateral deflections of fixed base 15 storey structural model under the influence of scaled Northridge (1994) earthquake.....	102
Figure 4.37: Recorded maximum lateral deflections of fixed base 15 storey structural model under the influence of scaled El Centro (1940) earthquake	103
Figure 4.38: Recorded maximum lateral deflections of fixed base 15 storey structural model under the influence of scaled Hachinohe (1968) earthquake	103
Figure 4.39: Various components of the secured laminar soil container on the shaking table	104
Figure 4.40: (a) Placing the mix components and mixer near the shaking table; (b) producing and placing the soil mix into the soil container	105
Figure 4.41: Finished surface of the level soil inside the soil container	106
Figure 4.42: (a) Placing the structural model on top of the soil mix; (b) final arrangement of the level structural model on top of the soil	106
Figure 4.43: (a) Installing the displacement transducers on the structural model; (b) vertical displacement transducer installed at the level of the base plate.....	107
Figure 4.44: Final setup of the measuring instruments of the soil-structure model	107
Figure 4.45: Recorded maximum lateral deflections of flexible base model under the influence of scaled Kobe (1995) earthquake	108
Figure 4.46: Recorded maximum lateral deflections of flexible base model under the influence of scaled Northridge (1994) earthquake	109
Figure 4.47: Recorded maximum lateral deflections of flexible base model under the influence of scaled El Centro (1940) earthquake	109
Figure 4.48: Recorded maximum lateral deflections of flexible base model under the influence of scaled Hachinohe (1968) earthquake.....	109
Figure 4.49: Experimental time-history displacement results for fixed base and flexible base models under the influence of Kobe earthquake (1995).....	110
Figure 4.50: Simulated numerical fixed base model in FLAC2D	111
Figure 4.51: Simulated numerical flexible base model in FLAC2D	111

Figure 4.52: Numerical and experimental maximum lateral displacements of fixed base and flexible base models under the influence of scaled Kobe (1995) earthquake.....	113
Figure 4.53: Numerical and experimental maximum lateral displacements of fixed base and flexible base models under the influence of scaled Northridge (1994) earthquake..	114
Figure 4.54: Numerical and experimental maximum lateral displacements of fixed base and flexible base models under the influence of scaled El Centro (1940) earthquake	114
Figure 4.55: Numerical and experimental maximum lateral displacements of fixed base and flexible base models under the influence of scaled Hachinohe (1968) earthquake ..	114
Figure 4.56: Average values of the numerical predictions and experimental values of the maximum lateral displacements of fixed base and flexible base models.....	115
Figure 4.57: Average experimental inter-storey drifts of fixed base and flexible base models	116
Figure 5.1: Configurations of the cantilever beam; (a) original configuration; (b) deformed configuration.....	122
Figure 5.2: Near field acceleration record of Kobe earthquake (1995)	123
Figure 5.3: Near field acceleration record of Northridge earthquake (1994).....	123
Figure 5.4: Far field acceleration record of El-Centro earthquake (1940).....	124
Figure 5.5: Far field acceleration record of Hachinohe earthquake (1968).....	124
Figure 5.6: Adopted fitting curves for clay in this study; (a) Relations between G/G_{max} versus shear strain; (b) Relations between material damping ratio versus shear strain...	126
Figure 5.7: Adopted fitting curves for sand in this study; (a) Relations between G/G_{max} versus cyclic shear strain; (b) Relations between material damping ratio versus cyclic shear strain.....	127
Figure 5.8: Concrete sections designed for the adopted frames based on elastic design method; (a) 5 storey model (S5); (b) 10 storey model (S10); (c) 15 storey model (S15)	131
Figure 5.9: Elastic-perfectly plastic behaviour of structural elements	132
Figure 5.10: Concrete sections designed for the adopted frames based on inelastic design method; (a) 5 storey model (S5); (b) 10 storey model (S10); (c) 15 storey model (S15)	133
Figure 5.11: Numerical Models; (a) fixed base model; (b) flexible base model.....	134

Figure 5.12: Elastic storey deflections of the adopted structural models resting on soil classes C_e , D_e , and E_e with bedrock depth of 30 metres; (a) model S5; (b) model S10; (c) model S15.....	138
Figure 5.13: Elastic storey deflections of the adopted structural models resting on soil class C_e with variable bedrock depths; (a) model S5; (b) model S10; (c) model S15.....	139
Figure 5.14: Elastic storey deflections of the adopted structural models resting on soil class D_e with variable bedrock depths; (a) model S5; (b) model S10; (c) model S15.....	140
Figure 5.15: Elastic storey deflections of the adopted structural models resting on soil class E_e with variable bedrock depths; (a) model S5; (b) model S10; (c) model S15.....	141
Figure 5.16: Elastic inter-storey drifts of the adopted structural models resting on soil class C_e , D_e , and E_e with bedrock depth of 30 metres; (a) model S5; (b) model S10; (c) model S15.....	142
Figure 5.17: Elastic inter-storey drifts of the adopted structural models resting on soil class C_e with variable bedrock depths; (a) model S5; (b) model S10; (c) model S15.....	143
Figure 5.18: Elastic inter-storey drifts of the adopted structural models resting on soil class D_e with variable bedrock depths; (a) model S5; (b) model S10; (c) model S15.....	144
Figure 5.19: Elastic inter-storey drifts of the adopted structural models resting on soil class E_e with variable bedrock depths; (a) model S5; (b) model S10; (c) model S15.....	145
Figure 5.20: Inelastic storey deflections of the adopted structural models resting on soil classes C_e , D_e , and E_e with bedrock depth of 30 metres; (a) model S5; (b) model S10; (c) model S15.....	146
Figure 5.21: Inelastic storey deflections of the adopted structural models resting on soil class C_e with variable bedrock depths; (a) model S5; (b) model S10; (c) model S15.....	147
Figure 5.22: Inelastic storey deflections of the adopted structural models resting on soil class D_e with variable bedrock depths; (a) model S5; (b) model S10; (c) model S15.....	148
Figure 5.23: Inelastic storey deflections of the adopted structural models resting on soil class E_e with variable bedrock depths; (a) model S5; (b) model S10; (c) model S15.....	149
Figure 5.24: Inelastic inter-storey drifts of the adopted structural models resting on soil classes C_e , D_e , and E_e with bedrock depth of 30 metres; (a) model S5; (b) model S10; (c) model S15.....	150

Figure 5.25: Inelastic inter-storey drifts of the adopted structural models resting on soil class C_e with variable bedrock depths; (a) model S5; (b) model S10; (c) model S15.....	151
Figure 5.26: Inelastic inter-storey drifts of the adopted structural models resting on soil class D_e with variable bedrock depths; (a) model S5; (b) model S10; (c) model S15.....	152
Figure 5.27: Inelastic inter-storey drifts of the adopted structural models resting on soil class E_e with variable bedrock depths; (a) model S5; (b) model S10; (c) model S15.....	153
Figure 6.1: Results of regression analysis to find the best fit to the numerical predictions of maximum lateral deflections for elastic analysis case.....	163
Figure 6.2: Results of regression analysis to find the best fit to the numerical predictions of maximum lateral deflections for inelastic analysis case.....	164
Figure 6.3: Results of regression analysis to find the best fit to the numerical predictions of lateral storey deflections for elastic analysis case.....	165
Figure 6.4: Results of regression analysis to find the best fit to the numerical predictions of lateral storey deflections for inelastic analysis case.....	166
Figure 6.5: Determined lateral storey deflections at each level for 15 storey building resting on soil classes C_e , D_e , and E_e	168
Figure 6.6: Determined lateral storey deflections at each level for 15 storey building resting on soil class E_e with variable bedrock depths.....	168
Figure 6.7: Inter-storey drifts for 15 storey building resting on soil classes C_e , D_e , and E_e	169
Figure 6.8: Inter-storey drifts for 15 storey building resting on soil class E_e with variable bedrock depths.....	169

LIST OF TABLES

Table 2.1: The cone model properties proposed by Wolf (1994)	16
Table 2.2: Site subsoil classifications according to IBC2009.....	23
Table 2.3: Past performed shaking table tests on soil-structure systems using various types of soil containers.....	33
Table 3.1: Numerical fitting parameters in FLAC for modulus degradation modelling	67
Table 4.1: UTS shaking table specifications.....	69
Table 4.2: Scaling relations in terms of geometric scaling factor (λ)	73
Table 4.3: Dimensional characteristics of scale model considering different scaling factors.....	74
Table 4.4: Characteristics of the structural model	76
Table 4.5: Proportion of different components for the examined mixtures.....	89
Table 4.6: Properties of the selected soil mix on the second day of cure age.....	95
Table 4.7: Maximum vertical displacements of the base plate	110
Table 4.8: Adopted parameters for numerical simulation of the structural model	111
Table 4.9: Adopted soil parameters in numerical simulation of flexible base model...	112
Table 4.10: Numerical and experimental maximum vertical displacements and rotations	116
Table 5.1: Dimensional characteristics of the studied frames.....	120
Table 5.2: Utilised Earthquake ground motions	124
Table 5.3: Geotechnical characteristics of the adopted soils in this study.....	125
Table 5.4: Utilised soil interface parameters.....	127
Table 5.5: Elastic base shear ratios of flexible base to fixed base models (\tilde{V}/V).....	136
Table 5.6: Inelastic base shear ratios of flexible base to fixed base models (\tilde{V}/V).....	137
Table 5.7: Maximum elastic lateral deflection ratios of flexible base models to fixed base models ($\tilde{\delta}/\delta$).....	137

Table 5.8: Maximum inelastic lateral deflection ratios of flexible base models to fixed base models ($\tilde{\delta}/\delta$).....	137
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LIST OF NOTATIONS

A	foundation area
B	foundation width
c	damping coefficient of the structure
C	cohesion
$[C]$	damping matrix
C_h	horizontal damping coefficient of the subsoil
C_r	rocking damping coefficient of the subsoil
E	modulus of elasticity
E_{str}	modulus of elasticity of the structural material
f	natural frequency of fixed base structure
\tilde{f}	natural frequency of soil-structure system
f'_c	specified compressive strength
f_m	natural frequency of the model
f_p	natural frequency of the prototype
F_s	total shear force
F_n	total normal force
F_x	unbalanced forces in x direction from the free-field grid
F_y	unbalanced forces in y direction from the free-field grid
$\{F_v\}$	force vector
G	shear modulus of the soil
G_{max}	largest value of the shear modulus
h	height of the structure
h_s	bedrock depth
$h\theta$	lateral displacement at the top of the structure due to rotation of the base
I_c	flexural rigidity of the building columns
I_r	moment of inertia for rocking motion
k	stiffness of the structure
k_s	shear spring stiffness
k_n	normal spring stiffness
K	bulk modulus
$[K]$	stiffness matrix
K_h	horizontal stiffness coefficient of the subsoil

K_r	rocking stiffness coefficient of the subsoil
K_{ss}	soil-structure relative rigidity
k_x	lateral stiffness of the subsoil foundation
k_θ	rocking stiffness of the subsoil foundation
L	effective contact length
m	mass of the structure
$[M]$	mass matrix
M_p	plastic moment capacity
N_s	number of stories
r	radius of the foundation base
S_p	performance factor
S_u	soil shear strength
T	natural period of fixed-base structure
\tilde{T}	natural period of soil-structure system
T_n	normal traction at the model boundaries
T_s	shear traction at the model boundaries
u	lateral displacement at the top of the structure due to structural distortion
u_n	incremental relative displacement vector in normal direction
u_s	incremental relative displacement vector in shear direction
u_0	lateral displacement at the top of structure due to translation of the base
u'_0	total displacement of the base
u^g	horizontal seismic excitation
\tilde{u}^g	effective input motion
$\{u\}$	nodal displacement
$\{\dot{u}\}$	nodal velocity
$\{\ddot{u}\}$	nodal acceleration
V	base shear of fixed base structure
\tilde{V}	base shear of the structure in soil-structure system
V_p	compression wave velocity of the soil
V_s	shear wave velocity of the soil
W_D	dissipated energy in one hysteresis loop
W_S	maximum strain energy
γ	shear strain

γ_{ref}	numerical fitting parameter
δ	maximum lateral deflection of fixed base structure
$\tilde{\delta}$	maximum lateral deflection of the structure in soil-structure system
Δt	time-step
ΔS_y	mean vertical zone size at boundary grid point
η	material viscosity
θ	foundation rotation
λ	analysis type factor
μ	structural ductility factor
ν	Poisson's ratio of the soil
v_x^m	x-velocity of the grid point in the main grid
v_y^m	y- velocity of the grid point in the main grid
v_x^{ff}	x-velocity of the grid point in the free-field grid
v_y^{ff}	y- velocity of the grid point in the free-field grid
ξ	equivalent viscous damping ratio
$\tilde{\xi}$	effective damping ratio
ξ_g	hysteretic material damping of the soil
ρ	soil density
σ_y	yield stress
σ_{xx}^{ff}	mean horizontal free-field stress at the grid point
σ_{xy}^{ff}	mean free-field shear stress at the grid point
ϕ	friction angle
$\tilde{\omega}$	effective natural frequency
ω_s	natural frequency of the fixed base structure