

Second Edition

Fundamentals of EARTHQUAKE ENGINEERING

From Source to Fragility

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WILEY

Preface

This book forms one part of a complete system for university teaching and learning the fundamentals of earthquake engineering at the graduate level. The other components are the slides sets, the solved examples, including the comprehensive project, and a free copy of the computer program Zeus-NL, which are available on the book web site. The book is cast in a framework with three key components, namely (i) earthquake causes and effects are traced from source to society, (ii) structural response under earthquake motion is characterised primarily by the varying and interrelated values of stiffness, strength and ductility and (iii) all structural response characteristics are presented on the material, section, member, sub-assembly and structural system levels. The first four chapters of the book cover an overview of earthquake causes and effects, structural response characteristics, features and representations of strong ground motion and modelling and analysis of structural systems, including design and assessment response quantities. The fifth and sixth chapters are a feature of the second edition whereby two important and advanced topics that have reached a degree of maturity are addressed. [Chapter 5](#) presents probabilistic fragility analysis required in assessing earthquake impact on populations of structures. [Chapter 6](#) deals with the important topic of soil-structure interaction which affects all measures of response analysis and vulnerability to earthquakes. The slides sets cover [Chapters 1-6](#), and follow closely the contents of the book, while being a succinct summary of the main issues addressed in the text necessary for a graduate course. The slides set are intended for use by professors in the lecture room, and should be made available to the students only at the end of

each chapter. They are designed to be also a capping revision tool for students. The solved examples are comprehensive and address all the important and intricate sub-topics treated in this book. The comprehensive project is used to provide an integration framework for the various components of the earthquake source, path, site and structural features that affect the actions and deformations required for seismic design. The three teaching and learning components of (i) the book, (ii) the slides sets and (iii) the solved examples are inseparable. Their use in unison has been tested and proven in a US top tier university teaching environment for a number of years.

Foreword

Congratulations to both authors! A new approach for instruction in Earthquake Engineering has been developed. This package provides a new and powerful technique for teaching – it incorporates a book, worked problems and comprehensive instructional slides available on the web site. It has undergone numerous prior trials at the graduate level as the text was being refined.

The book, in impeccable English, along with the virtual material, is something to behold. ‘Intense’ is my short description of this book and accompanying material, crafted for careful study by the student, so much so that the instructor is going to have to be reasonably up - to - date in the field in order to use it comfortably. The writer would have loved to have had a book like this when he was teaching Earthquake Engineering.

In this second edition, the text has six main chapters and two appendices. The six main chapters centre on (a) Earthquake Characteristics, (b) Response of Structures, (c) Earthquake Input Motion, (d) Response Evaluation, (e) Fragility Relationships for Structures and (f) Seismic Soil-Structure Interaction, with two valuable appendices dealing with Structural Configurations and Systems for Effective Earthquake Resistance, and Damage to Structures. The presentation, based on stiffness, strength and ductility concepts, comprises a new and powerful way of visualizing many aspects of the inelastic behaviour that occurs in structures subjected to earthquake excitation.

The book is written so as to be appropriate for international use and sale. The text is supplemented by numerous references, enabling the instructor to pick and choose

sections of interest, and to point thereafter to sources of additional information. It is not burdened by massive reference to current codes and standards in the world. Unlike most other texts in the field, after studying this book, the students should be in a position to enter practice and adapt their newly acquired education to the use of regional seismic codes and guidelines with ease, as well as topics not covered in codes. Equally importantly, students who study this book will understand the bases for the design provisions.

Finally, this work has application not only in instruction, but also in research. Again, the authors are to be congratulated on developing a valuable work of broad usefulness in the field of earthquake engineering.

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Acknowledgements

We have written this book whilst attending to our day jobs, and expanded this Second Edition while expanding our professional responsibilities along several axes. We have not taken a summer off, or went on sabbatical leave. It has therefore been difficult to extract ourselves from the immediate and more pressing priorities of ongoing academic and personal responsibilities. That authoring the book took four years, and revising it and adding the two chapters took over a year is somewhat frustrating. The extended period has however resulted in an improved text through the feedback of end-users, mainly graduate students of exceptional talent at the University of Illinois. With the inclusion of Professor Oh-Sung Kwon from the University of Toronto (author of [Chapter 6](#) on soil-structure interaction), we included feedback from his students concerning the same chapter. Our first thanks therefore go to our students who endured the experimental material they were subjected to and who provided absolutely essential feedback. We are also grateful to a number of world-class researchers and teachers who voluntarily reviewed the book and provided some heart-warming praise alongside some scathing criticism. These are, in alphabetical order, in memoriam of Nicholas Ambraseys, Emeritus Professor at Imperial College; Mihail Garevski, Professor and Director, Institute of Seismology and Earthquake Engineering, University of Skopje 'Kiril and Methodius'; Ahmed Ghobarah, Professor at McMaster University; William Hall, Emeritus Professor at the University of Illinois; and Sashi Kunnath, Professor at the University of California. Special thanks are due to Professor Gordon Warn, at the Civil and Environmental Engineering Department, the Pennsylvania State

University, for his meticulous revision of [Chapter 5](#) on fragility analysis. Many other colleagues have read parts of chapters and commented on various aspects of the book, the set of slides and the worked examples. Finally our thanks go to six anonymous reviewers who were contacted by Wiley Intersciences to assess the book proposal, and to all Wiley staff who have been invariably supportive and patient over the years.

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Introduction

I.1 Context, Framework and Scope

Earthquakes are one of the most devastating natural hazards that cause great loss of life and livelihood. On average, 10 000 people die each year due to earthquakes, while annual economic losses are in the billions of dollars and often constitute a large percentage of the gross national product (GNP) of the country affected.

Over the past few decades earthquake engineering has developed as a branch of engineering concerned with the estimation of earthquake consequences and the mitigation of these consequences. It has become an interdisciplinary subject involving seismologists, structural and geotechnical engineers, architects, urban planners, information technologists and social scientists. This interdisciplinary feature renders the subject both exciting and complex, requiring its practitioners to keep abreast of a wide range of rapidly evolving disciplines. In the past few years, the earthquake engineering community has been reassessing its procedures, in the wake of devastating earthquakes which caused extensive damage, loss of life and property (e.g. Northridge, California, 17 January 1994; \$30 billion and 60 dead; Hyogo-ken Nanbu, Japan, 17 January 1995; \$150 billion and 6000 dead).

The aim of this book is to serve as an introduction to and an overview of the latest structural earthquake engineering. The book deals with aspects of geology, engineering seismology and geotechnical engineering that are of service to the earthquake structural engineering educator, practitioner and researcher. It frames earthquake

structural engineering within a framework of balance between 'Demand' and 'Supply' (requirements imposed on the system versus its available capacity for action and deformation resistance).

In a system-integrated framework, referred to as 'From Source-to-Society', where 'Source' describes the focal mechanisms of earthquakes, and 'Society' describes the compendium of effects on complex societal systems, this book presents information pertinent to the evaluation of actions and deformations imposed by earthquakes on structural systems. It is therefore a 'Source-to-Structure' text. Source parameters, path and site characteristics are presented at a level of detail sufficient for the structural earthquake engineer to understand the effect of geophysical and seismological features on strong ground-motion characteristics pertinent to the evaluation of the response of structures. Structural response characteristics are reviewed and presented in a new framework of three quantities: stiffness, strength and ductility, which map onto the three most important limit states of serviceability, structural damage control and collapse prevention. This three-parameter approach also matches well with the consequential objectives of reducing downtime, controlling repair costs and protecting life. By virtue of the fact that the text places strong emphasis on the varying values of stiffness, strength and ductility as a function of the available deformation capacity, it blends seamlessly with deformation-based design concepts and multi-limit state design, recently referred to as performance-based design. The book stops where design codes start, at the stage of full and detailed evaluation of elastic and inelastic actions and deformations to which structures are likely to be subjected. Emphasis is placed on buildings and bridges, and material treatment is constrained to steel and concrete. The scope of the book is depicted in [Figure I.1](#).

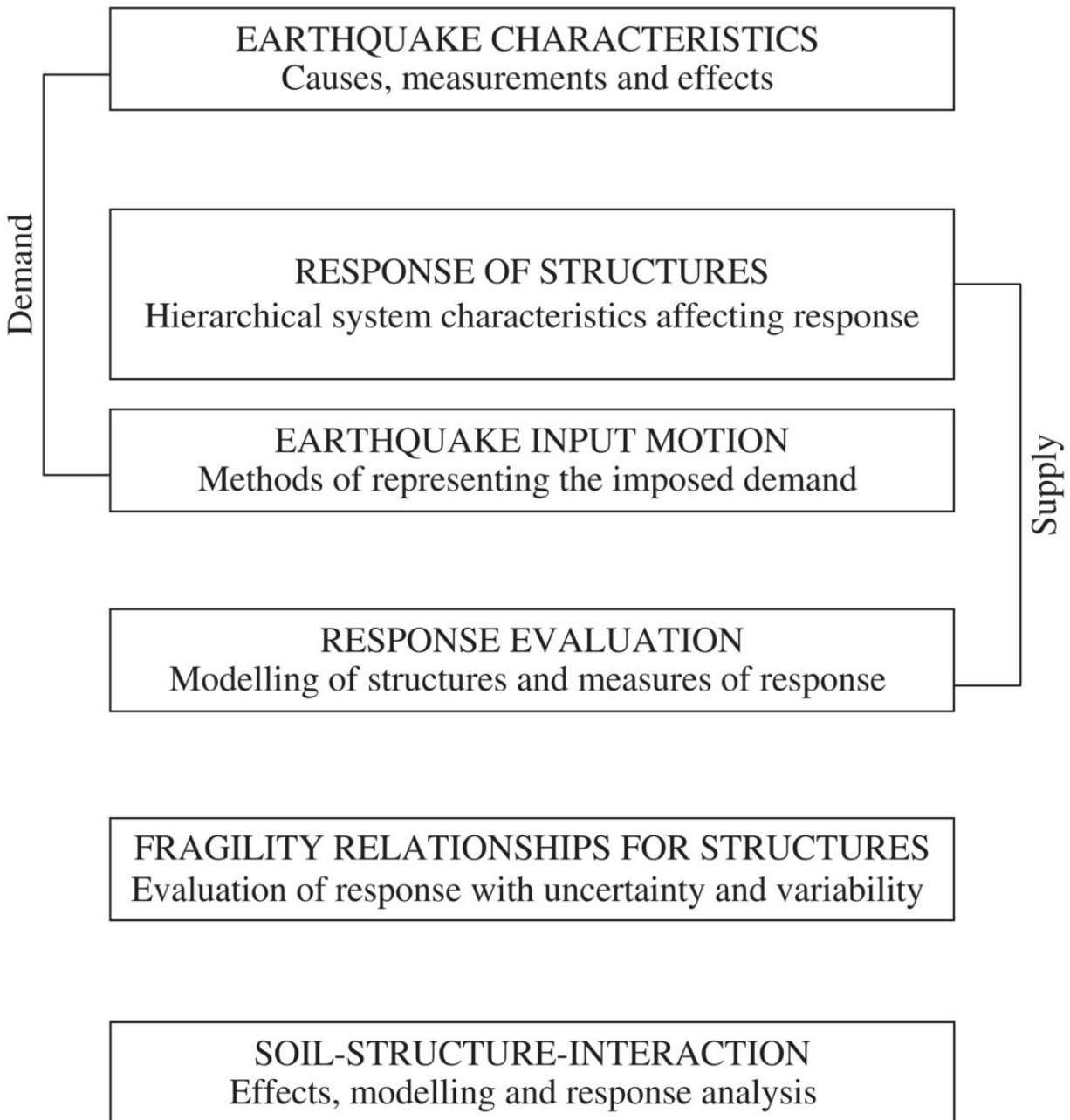


Figure I.1 Scope of the book.

Chapter 1 belongs to the Demand sub-topic and is a standard exposé of the geological, seismological and earth sciences aspects pertinent to structural earthquake engineering. It concludes with two sections; one on earthquake damage, bolstered by a detailed Appendix of pictures of damaged buildings and bridges categorised

according to the cause of failure. The last section is on earthquake losses and includes global statistics as well as description of the various aspects of impact of earthquakes on communities in a regional context.

[Chapter 2](#), which belongs to the Supply or Capacity sub-topic, establishes a new framework of understanding structural response and relating milestones of such a response to (i) probability of occurrence of earthquakes and (ii) structural and societal limit states. Viewing the response of structures in the light of three fundamental parameters, namely stiffness, strength and ductility, and their implications on system performance opens the door to a new relationship between measured quantities, limit states and consequences, as described in [Table 2.1](#). The two most important ‘implications’ of stiffness, strength and ductility are overstrength and damping. The latter two parameters have a significant effect on earthquake response and are therefore addressed in detail. All five response quantities of (i) stiffness, (ii) strength, (iii) ductility, (iv) overstrength and (v) damping are related to one another and presented in a strictly hierarchical framework of the five levels of the hierarchy, namely (i) material, (ii) section, (iii) member, (iv) connection and (v) system. Finally, principles of capacity design are demonstrated numerically and their use to improve structural response is emphasised.

[Chapter 3](#) brings the readers back to description of the Demand sub-topic and delves into a detailed description of the input motion in an ascending order of complexity. It starts with point estimates of peak ground parameters, followed by simplified, detailed and inelastic spectra. Evaluation of the required response modification factors, or the demand response modification factors, is given prominence in this chapter, to contrast the capacity response modification factors addressed in [Chapter 2](#). The

chapter concludes with selection and scaling of acceleration time histories as well as a discussion of the significance of duration on response of inelastic structures.

[Chapter 4](#) concludes the Supply sub-topic by discussing important aspects of analytically representing the structure and the significance or otherwise of some modelling details. The chapter is presented in a manner consistent with **[Chapter 2](#)** in terms of dealing with modelling of materials, sections, members, connections, sub-assemblages and systems. The final section of **[Chapter 4](#)** presents expected and important outcomes from analytical modelling for use in assessment of the adequacy of the structure under consideration as well as conventional design forces and displacements. The chapter also includes a brief review of methods of quasi-dynamic and dynamic analysis pertinent to earthquake response evaluation.

[Chapter 5](#), which is a feature of the second edition, addresses the important issue of probabilistic fragility analysis, a necessary component of regional as well as structure-specific failure probability assessment. The chapter addresses required limit states, input motion characterisation and definition of the statistical model. Applications are given to support the understanding of the concepts used in the chapter to assess the probability of reaching or exceeding limit states of performance.

[Chapter 6](#), which is also a new section of the second edition, provides an overview of the soil-structure interaction (SSI) problem and modelling methods as well as offer the perspective of a structural earthquake engineer. Due to the broad scope of the topic, this chapter does not provide a step-by-step guide on how to develop a model and run an analysis, which would require an entire book. Conversely, it includes coherent and concise descriptions of typical effects of SSI, different methods for modelling and

analysing a soil-foundation and structural system. A few representative examples of SSI analyses are introduced and the findings from each case study are summarised.

I.2 Use Scenarios

1.2.1 Postgraduate Educators and Students

As discussed in the preceding section, the book was written with the university professor in mind as one of the main users alongside students attending a graduate course. It therefore includes a large number of work assignments and additional worked examples, provided on the book web site. Most importantly, summary slides are also provided on the book web site. The slides are intended to be used in the classroom, and in final revision by students. The book and the slides have been used in teaching the postgraduate level course in earthquake engineering at the University of Illinois at Urbana-Champaign for a number of years, and are therefore successfully tested in a leading university environment. Parts of the book were also used in teaching short courses on a number of occasions in different countries. For the earthquake engineering professor, the whole book is recommended for postgraduate courses, with the exception of methods of analysis ([Section 4.7](#)) which are typically taught in structural dynamics courses that should be a prerequisite to this course. Fragility curves and soil-structure interaction (illustrated in [Chapters 5](#) and [6](#), respectively) can be conveniently taught in a specialised course for earthquake risk analysis.

1.2.2 Researchers

The book is also useful to researchers who have studied earthquake engineering in a more traditional context, where strength and direct assessment for design were

employed, as opposed to the integrated strength-deformation and capacity assessment for design approach presented in this book. Moreover structural earthquake engineering researchers will find [Chapter 3](#) of particular interest because it bridges the conventional barriers between engineering seismology and earthquake engineering and brings the concepts from the former in a palatable form to the latter. From the long experience of working with structural earthquake engineers, [Chapter 3](#) is recommended as an essential read prior to undertaking research, even for individuals who have attended traditional earthquake engineering courses. Researchers from related fields, such as geotechnical earthquake engineering or structural control, may find [Chapter 2](#) of value, since it heightens their awareness of the fundamental requirements of earthquake response of structures and the intricate relationship between stiffness, strength, ductility, overstrength and damping.

The newly added [Chapters 5](#) and [6](#) include relevant discussions that are of interest for researchers dealing with earthquake loss estimation. These chapters provide the state-of-the-art of deriving fragility relationships and illustrate the modelling and analysis procedures for accounting for the SSI phenomena.

1.2.3 Practitioners

Practising engineers with long and relatively modern experience in earthquake resistant design in high seismicity regions will find the book on the whole easy to read and rather basic. They may, however, appreciate the presentation of fundamental response parameters and may find their connection to the structural and societal limit states refreshing and insightful. They may also benefit from the modelling notes of [Chapter 4](#), since use is made of concepts of finite element representation in a specifically

earthquake engineering context. Many experienced structural earthquake engineering practitioners will find [Chapter 3](#) on input motion useful and practical. The chapter will aid them in selection of appropriate characterisation of ground shaking. The book as a whole, especially [Chapters 3](#) and [4](#) is highly recommended for practising engineers with limited or no experience in earthquake engineering. The newly added [Chapter 6](#) provides practical guidelines for the modelling and analysis procedures accounting for the SSI in the earthquake response of systems.

List of Abbreviations

AI =

Arias Intensity

AIJ =

Architectural Institute of Japan

ASCII =

American Standard Code for Information Interchange

ATC =

Applied Technology Council

BF =

Braced Frame

CBF =

Concentrically Braced Frame

CEB =

Comité Euro-international du Béton

CEUS =

Central and Eastern United States

CONV =

Convolution

COSMOS =

Consortium of Organisations for Strong-Motion
Observation Systems

COV =

Coefficient Of Variation

CP =

Collapse Prevention

CQC =

Complete Quadratic Combination

CSMIP =

California Strong-Motion Instrumentation Program

CSUN =

California State University Northridge

CTBUH =

Council on Tall Building and Urban Habitat

CUE =

Conference on Usage of Earthquakes

DC =

Damage Control

DI =

Damage Index

DL =

Dead Load

DPM =

Damage Probability Matrix

EBF =

Eccentrically Braced Frame

EERI =

Earthquake Engineering Research Institute

ELF =

Equivalent Lateral Force

EPM =

Elastic-Plastic Model

EPP =

Elastic Perfectly-Plastic

EMS =

European Modified Scale

EQ =

Earthquake

FE =

Finite Element

FF =
Fragility Function

FEMA =
Federal Emergency Management Agency

FORM =
First-Order Reliability Method

FOSM =
First-Order Second Moment

FRP =
Fibre-Reinforced Plastic

FW =
Frame-Wall structure

GM =
Ground Motion

GNP =
Gross National Product

HDS =
Hybrid Distributed Simulation

HF =
Hybrid Frame

HPGA =
Horizontal Peak Ground Acceleration

ICSMD =
Imperial College Strong-Motion Databank

ID =
Inter-storey Drift

IDA =
Incremental Dynamic Analysis

IF =
Irregular Frame

IM =
Intensity Measure

JMA =

Japanese Meteorological Agency

KBF =

Knee-Braced Frame

K-NET =

Kyoshin Net

LEM =

Linear Elastic Model

LENLH =

Linear Elastic-Plastic with Non-Linear Hardening

LEPP =

Linear Elastic-Perfectly Plastic

LESH =

Linear Elastic-Plastic with Strain Hardening

LL =

Live Load

LQ =

Love Wave

LR =

Rayleigh Wave

LRH =

Linear Response History

LS =

Limit State

MCS =

Mercalli-Cancani-Seiberg

MCSM =

Monte Carlo Simulation Method

MDOF =

Multi-Degree-Of-Freedom

MM =

Modified Mercalli

MP =
Menegotto-Pinto model

MRF =
Moment-Resisting Frame

MSK =
Medvedev-Sponheuer-Karnik

NGA =
New Generation Attenuation

NLEM =
Non-Linear Elastic Model

NRH =
Non-Linear Response History

NSP =
Non-Linear Static Pushover

OBF =
Outrigger-Braced Frame

PA =
Pushover Analysis

PDF =
Probability Density Function

PGA =
Peak Ground Acceleration

PGD =
Peak Ground Displacement

PGV =
Peak Ground Velocity

PEER =
Pacific Earthquake Engineering Research Center

PL =
Performance Level

PML =
Perfectly Matched Layer

RC =
Reinforced Concrete

RO =
Ramberg-Osgood model

RF =
Regular Frame

RSA =
Response Spectrum Analysis

RSM =
Response Surface Method

SCWB =
Strong Column-Weak Beam

SDOF =
Single-Degree-Of-Freedom

SH =
Shear Horizontal

SI =
Spectral Intensity

SL =
Serviceability Limit

SORM =
Second-Order Reliability Method

SPEAR =
Seismic Performance Assessment and Rehabilitation

SPT =
Standard Penetration Test

SRSS =
Square Root of the Sum of Squares

SSI =
Soil-Structure-Interaction

SV =
Shear Vertical

SW =

Structural Wall

TS =

Tube System

URM =

Unreinforced masonry

USA =

United States of America

USEE =

Utility Software for Earthquake Engineering

USSR =

Union of Soviet Socialist Republics

VPGA =

Vertical Peak Ground Acceleration

WCSB =

Weak Column-Strong Beam.

List of Symbols

Symbols defined in the text that are used only once, and those which are clearly defined in a relevant figure or table, are in general not listed herein.

A_v =

effective shear area

C_M =

centre of mass

C_R =

centre of rigidity

d =

distance from the earthquake source

E =

Young's modulus

E₀ =

initial Young's modulus (at the origin)

E_t =

tangent Young's modulus

f_c =

concrete compression strength

f_t =

concrete tensile strength

f_u =

steel ultimate strength

f_y =

steel yield strength

G =

shear modulus

$G_0 =$
initial shear modulus

$G_b =$
shear modulus of the bedrock

$g =$
acceleration of gravity

$H =$
total height

$H_{\text{eff}} =$
effective height

$h =$
height

$I =$
intensity
 $=$
moment of inertia

$I_i =$
Modified Mercalli intensity of the i th isoseismal

$I_{\text{JMA}} =$
intensity in the Japanese Meteorological Agency (JMA)
scale

$I_{\text{max}} =$
maximum intensity

$I_{\text{MM}} =$
intensity in the Modified Mercalli (MM) scale

$I_0 =$
epicentral intensity

$J =$
torsional moment of inertia

K =
stiffness

K_s =
secant stiffness

K_t =
tangent stiffness

K_y =
lateral stiffness

K₀ =
initial stiffness (at origin)

k_{eff} =
effective stiffness

k_f =
flexural stiffness

k_s =
shear stiffness

K_θ =
Rocking Stiffness

L_p
plastic hinge length

L_w =
wall length

M =
magnitude

=
bending moment

m_b =
body wave magnitude

M_{eff} =
effective mass

$M_L =$
local (or Richter) magnitude

$M_{JMA} =$
Japanese Meteorological Agency (JMA) magnitude

$m_r =$
rotational mass

$M_S =$
surface wave magnitude

$m_t =$
translational mass

$M_w =$
moment magnitude

$N =$
axial load

$q =$
force reduction factor

$R =$
focal distance
 $=$
force reduction factor

$r_i =$
radius of the equivalent area enclosed in the i th
isoseismal

$S_a =$
spectral acceleration

$S_d =$
spectral displacement

$SI_H =$
Housner's spectral intensity

$SI_M =$

Matsumura's spectral intensity

$S_v =$

spectral velocity

$T =$

period of vibration

$T_h =$

hardening period

$T_R =$

return period

$T_S =$

site fundamental period of vibration

$T_{S,n} =$

site period of vibration relative to the nth mode

$T_y =$

yield period

$t_r =$

reference time period

$V_{base} =$

global base shear

$V_e =$

elastic shear

$V_i =$

storey shear

$V_y =$

yield shear

$V_d =$

design base shear

$V_u =$

ultimate shear

$v_{LQ} =$
velocity of Love waves

$v_{LR} =$
velocity of Rayleigh waves

$v_P =$
velocity of P-waves

$v_S =$
velocity of S-waves

$\alpha_s =$
shear span ratio

$\beta =$
logarithmic standard deviation

$\Gamma_i =$
modal participation factor for the i th mode

$\gamma_D, \gamma_E, \gamma_L =$
load factors

$\gamma_I =$
importance factor

$\Delta =$
global lateral displacement

$\Delta_y =$
global yield lateral displacement

$\Delta_u =$
global ultimate lateral displacement

$\delta =$
lateral displacement

$\delta_i =$
storey lateral displacement

$\delta_{top} =$
top lateral displacement

$\delta_u =$
ultimate lateral displacement

$\delta_y =$
yield lateral displacement

$\varepsilon =$
strain

$\varepsilon_c =$
concrete strain

$\varepsilon_{cu} =$
concrete crushing strain

$\varepsilon_u =$
ultimate strain

$\varepsilon_y =$
yield strain

$\theta =$
rotation

$\theta_p =$
plastic rotation

$\theta_u =$
ultimate rotation

$\theta_y =$
yield rotation

$\mu =$
ductility

$\mu_a =$
available ductility

$\mu_d =$
ductility demand

$\mu_\Delta =$
global displacement ductility

$\mu_{\delta} =$
displacement ductility

$\mu_{\varepsilon} =$
material ductility

$\mu_{\theta} =$
rotation ductility

$\mu_{\chi} =$
curvature ductility

$\nu =$
Poisson's ratio

$\xi =$
damping

$\xi_{\text{eff}} =$
effective damping

$\xi_{\text{eq}} =$
equivalent damping

$\rho =$
density

$\sigma =$
normal stress

$\sigma_y =$
yielding normal stress

$\chi =$
curvature

$\chi_u =$
ultimate curvature

$\chi_y =$
yield curvature

$\Psi =$
combination coefficient