ASCE 4-98

ASCE
STANDARD

American Society of Civil Engineers

Seismic Analysis of Safety-Related Nuclear Structures and Commentary

This document uses both Système International (SI) units and customary units.

ASCE

ASCE 4-98

American Society of Civil Engineers

Seismic Analysis of Safety-Related Nuclear Structures and Commentary

This document uses both Système International (SI) units and customary units.

Published by the American Society of Civil Engineers
1801 Alexander Bell Drive
Reston, Virginia 20191-4400

ABSTRACT

This standard provides requirements for performing analyses for the purpose of new structure design or existing structure evaluation that will lead to the reliability of structures under earthquake motions. The goal of this standard is to provide rules and analysis parameters that are expected to produce seismic responses that have about the same probability of non-exceedance as the input. Specifications of input motions are provided. Analysis standards are given for modeling of structures, analysis of structures, soil-structure interaction modeling and analysis, input for subsystem seismic analysis, and special structures such as buried pipes and conduits, earth-retaining walls, above-ground vertical tanks, raceways, and seismic-isolated structures. Non-mandatory Appendix A provides a discussion on Seismic Probabilistic Risk Assessments and Seismic Margin Assessments.

Library of Congress Cataloging-in-Publication Data

American Society of Civil Engineers.
Seismic analysis of safety-related nuclear structures and commentary / American Society of Civil Engineers.
p. cm.
Includes bibliographical references and index.
ISBN 0-7844-0433-X
1. Nuclear facilities—Evaluation—Standards—United States. 2. Earthquake resistant design—Standards—United States. 3. Buildings—Earthquake effects.
I. Title.
TK9152.163 .A47 1999
621.48'35—dc21 99-051970

Photocopies. Authorization to photocopy material for internal or personal use under circumstances not falling within the fair use provisions of the Copyright Act is granted by ASCE to libraries and other users registered with the Copyright Clearance Center (CCC) Transactional Reporting Service, provided that the base fee of $8.00 per article plus $.50 per page is paid directly to CCC, 222 Rosewood Drive, Danvers, MA 01923. The identification for ASCE Books is 0-7844-0433-X/00/$8.00 + $.50 per page. Requests for special permission or bulk copying should be addressed to Permissions & Copyright Dept., ASCE.

Copyright © 2000 by the American Society of Civil Engineers, All Rights Reserved.
Library of Congress Catalog Card No: 99-051970
ISBN 0-7844-0433-X
Manufactured in the United States of America.

STANDARDS

In April 1980, the Board of Direction approved ASCE Rules for Standards Committees to govern the writing and maintenance of standards developed by the Society. All such standards are developed by a consensus standards process managed by the Management Group F (MGF), Codes and Standards. The consensus process includes balloting by the balanced standards committee made up of Society members and nonmembers, balloting by the membership of ASCE as a whole, and balloting by the public. All standards are updated or reaffirmed by the same process at intervals not exceeding 5 years.

The following Standards have been issued.

ANSI/ASCE 1-82 N-725 Guideline for Design and Analysis of Nuclear Safety Related Earth Structures

ANSI/ASCE 2-91 Measurement of Oxygen Transfer in Clean Water

ANSI/ASCE 3-91 Standard for the Structural Design of Composite Slabs and ANSI/ASCE 9-91 Standard Practice for the Construction and Inspection of Composite Slabs

ASCE 4-98 Seismic Analysis of Safety-Related Nuclear Structures

Building Code Requirements for Masonry Structures (ACI 530-99/ASCE 5-99/TMS 402-99) and Specifications for Masonry Structures (ACI 530.1-99/ASCE 6-99/TMS 602-99)

ASCE 7-98 Minimum Design Loads for Buildings and Other Structures

ANSI/ASCE 8-90 Standard Specification for the Design of Cold-Formed Stainless Steel Structural Members

ANSI/ASCE 9-91 listed with ASCE 3-91

ASCE 10-97 Design of Latticed Steel Transmission Structures

SEI/ASCE 11-99 Guideline for Structural Condition Assessment of Existing Buildings

ANSI/ASCE 12-91 Guideline for the Design of Urban Subsurface Drainage

ASCE 13-93 Standard Guidelines for Installation of Urban Subsurface Drainage

ASCE 14-93 Standard Guidelines for Operation and Maintenance of Urban Subsurface Drainage

ASCE 15-98 Standard Practice for Direct Design of Buried Precast Concrete Pipe Using Standard Installations (SIDD)

ASCE 16-95 Standard for Load and Resistance Factor Design (LRFD) of Engineered Wood Construction

ASCE 17-96 Air-Supported Structures

ASCE 18-96 Standard Guidelines for In-Process Oxygen Transfer Testing

ASCE 19-96 Structural Applications of Steel Cables for Buildings

ASCE 20-96 Standard Guidelines for the Design and Installation of Pile Foundations

ASCE 21-96 Automated People Mover Standards—Part 1

ASCE 21-98 Automated People Mover Standards—Part 2

SEI/ASCE 23-97 Specification for Structural Steel Beams with Web Openings

ASCE 24-98 Flood Resistant Design and Construction

ASCE 25-97 Earthquake-Actuated Automatic Gas Shut-Off Devices

FOREWORD

The material presented in this publication has been prepared in accordance with recognized engineering principles. This Standard and Commentary should not be used without first securing competent advice with respect to their suitability for any given application. The publication of the material contained herein is not intended as a representation or warranty on the part of the American Society of Civil Engineers, or of any other person named herein, that this information is suitable for any general or particular use or promises freedom from infringement of any patent or patents. Anyone making use of this information assumes all liability from such use.

PREFACE

There are four steps in the design and construction process that lead to the reliability of nuclear safety-related structures under earthquake motions:

1. Definition of the seismic environment;
2. Analysis to obtain response information;
3. Design or evaluation of the various structural elements;
4. Construction.

In the practice of structural engineering design and construction, sufficient conservatism is intentionally added in order to achieve the desired performance. The purpose of this standard is to provide requirements for performing Step 2 for design of new facilities. This standard may also be used for evaluation of existing facilities. The intent of the analysis methodology is that the output parameters maintain about the same probability of non-exceedance as the input. This is accomplished by specifying methods for analysis with essentially no conservative bias except for small levels of conservatism added only to account for modeling uncertainties such as selection of material properties, mass, geometry, and damping. For example, use of this standard will produce seismic responses that have about a 90% chance of not being exceeded for an input response spectrum specified at the 84th percentile non-exceedance level. No attempt has been made to compensate for excess conservatism or lack of conservatism in the other steps.

In response to changing perceptions of seismic hazard for operating facilities or for quantification of risk or margin for new facilities, evaluation of facilities for seismic events beyond the design basis may be performed. This is discussed in Appendix A, which is nonmandatory.

Techniques other than those specified in this standard, including experience gained from past earthquakes, special analyses, and testing may also be used. However, such alternative methodologies shall be properly substantiated and shall conform to the intent of this standard.

ACKNOWLEDGMENTS

The American Society of Civil Engineers (ASCE) acknowledges the work of the Nuclear Standards Consensus Committee and the Working Group on Revision of ASCE Standard 4.

Nuclear Standards Consensus Committee

J. D. Stevenson, Chairman

J. Antebi
D. L. Becker
J. G. Bennett
J. F. Costello
F. Feng
J. P. Gnaedinger
A. K. Gupta
R. P. Kassawara
R. P. Kennedy
W. S. LaPay
T. R. Satyan-Sharma
P. J. Wang

Working Group on Revision of ASCE Standard 4
Seismic Analysis of Safety Related Nuclear Structures

R. C. Murray, Chairman
T. A. Nelson, Vice-Chairman

J. G. Bennett
T. M. Cheng
C. J. Costantino (Section 2 Lead)
H. J. Dahlke
J. M. Eidinger
C. R. Farrar
R. P. Gallagher
L. D. Gerdes
R. C. Guenzler
A. K. Gupta
A. H. Hadjian
Q. A. Hossain
J. J. Johnson
A. F. Kabir
N. C. Karanjia
R. P. Kassawara
R. M. Kenneally
C. A. Kircher
D. P. Moore (Appendix A Lead)
T. A. Nelson (Section 3.1 & 3.2 Lead)
D. A. Nuta (Section 3.3 Lead)
E. Odar
M. S. Power
N. Prasad (Section 3.5 Lead)
J. W. Reed
S. A. Short
A. K. Singh
K. M. Vashi (Section 3.4 Lead)

Original Working Group on ASCE 4-86
Seismic Analysis of Safety-Related Nuclear Structures

R. P. Kennedy, Chairman
R. P. Gallagher, Vice-Chairman

O. B. Abhat
R. S. Alexandru
L. D. Gerdes
A. Ghose
R. C. Guenzler
A. K. Gupta
A. H. Hadjian
Q. A. Hossain
J. J. Johnson
A. F. Kabir
N. C. Karanjia
C. W. Lin
D. P. Moore
D. A. Nuta
M. S. Power
J. W. Reed
A. K. Singh
R. J. Stuart
C. V. Subramanian
Y. K. Tang
G. R. Thiers
K. M. Vashi

CONTENTS

PREFACE v
ACKNOWLEDGMENTS vi

Standard

1.0 GENERAL 1
1.1 INTRODUCTION 1
1.1.1 Purpose 1
1.1.2 Scope 1
1.1.2.1 Types of Structures Covered by This Standard 1
1.1.2.2 Foundation Material Stability 1
1.1.3 General Requirements 1
1.1.3.1 Use of Analysis Results 1
1.1.3.2 Alternative Methodologies 1
1.2 DEFINITIONS 1
1.3 NOTATION 2

2.0 SEISMIC INPUT 4
2.1 SEISMIC GROUND MOTIONS 4
2.1.1 General Requirements 4
2.2 RESPONSE SPECTRA 5
2.2.1 General Requirements 5
2.2.2 Site-Specific Horizontal Response Spectra 5
2.2.3 Site-Independent Horizontal Response Spectra 5
2.2.4 Vertical Response Spectra 6
2.3 TIME HISTORIES 6
2.4 POWER SPECTRAL DENSITY FUNCTIONS 8
2.4.1 PSD Computed from Time Histories 8
2.5 ADDITIONAL REQUIREMENTS FOR STRUCTURES SENSITIVE TO LONG PERIOD MOTIONS 8
2.5.1 Spectral Shape 9
2.5.2 Time Histories 9

3.0 ANALYSIS 9
3.1 MODELING OF STRUCTURES 9
3.1.1 General Requirements 9
3.1.1.1 Models for Horizontal and Vertical Motions 9
3.1.1.2 Multistep and One-Step Methods of Seismic Response Analysis 9
3.1.1.2.1 Models for multistep analysis 10
3.1.1.2.2 Models for one-step analysis 10
3.1.1.3 Discretization Considerations 10
3.1.1.3.1 Selection of finite element type 10
3.1.1.3.2 Selection of mesh size 10
3.1.1.3.3 Reduction of dynamic degrees of freedom 10
3.1.2 Structural Material Properties 10
3.1.2.1 Modulus of Elasticity and Poisson's Ratio 10
3.1.2.1.1 Concrete 10
3.1.2.1.2 Steel 10
3.1.2.1.3 Aluminum 10
3.1.2.2 Damping 10

3.1.3 Modeling of Stiffness 11
3.1.3.1 Stiffness of Reinforced Concrete Elements 11
3.1.4 Modeling of Mass 11
3.1.4.1 Discretization of Mass 11
3.1.4.2 Determination of Modal Mass 11
3.1.5 Modeling of Damping 12
3.1.5.1 Damping Properties of Structures 12
3.1.5.1.1 Proportional damping (Rayleigh damping) 12
3.1.5.2 Composite Damping 12
3.1.5.2.1 Substructures with Known Damping Ratios 13
3.1.5.2.2 Substructures with Proportional Damping 13
3.1.5.3 Composite Modal Damping 13
3.1.5.4 Alternate Composite Modal Damping 13
3.1.6 Modeling of Hydrodynamic Effects 13
3.1.6.1 General Requirements 13
3.1.6.2 Dynamic Analysis Formulation for Submerged Structures 13
3.1.6.3 Building Model Hydrodynamic Mass Effects 14
3.1.7 Dynamic Coupling Criteria 15
3.1.7.1 General Requirements 15
3.1.7.2 Single-Point Attachment 15
3.1.7.3 Multipoint Attachment and Static Constraint 15
3.1.8 Requirements for Modeling Specific Structures 15
3.1.8.1 General Requirements 15
3.1.8.1.1 Structures with rigid floors 15
3.1.8.1.2 Structures with flexible floors 16
3.1.8.1.3 Requirements for lumped-mass stick models 16
3.1.8.2 Requirements for Frame Structures 17
3.1.8.3 Requirements for Shear-Wall Structures 17
3.1.8.4 Requirements for Plate and Shell Structures 17
3.1.8.5 Requirements for Adjacent Structures 18
3.2 ANALYSIS OF STRUCTURES 18
3.2.1 General Requirements 18
3.2.2 Time History Method 18
3.2.2.1 General Requirements 18
3.2.2.2 Linear Methods 18
3.2.2.2.1 Modal superposition 19
3.2.2.2.2 Direct integration 19
3.2.2.3 Nonlinear Methods 19
3.2.3 Response Spectrum Method 20
3.2.3.1 Linear Methods 20
3.2.3.2 Nonlinear Methods 20
3.2.4 Complex Frequency Response Method 20
3.2.4.1 General Requirements 20
3.2.4.2 Response Time History 20
3.2.4.3 Methods to Compute Transfer Functions 21
3.2.5 Equivalent-Static Method 21
3.2.5.1 General Requirements 21
3.2.5.2 Cantilever Models with Uniform Mass Distribution 21
3.2.5.3 Other Simple Structures 21
3.2.6 Multiply-Supported Systems 22
3.2.6.1 General Requirements 22
3.2.6.2 Time History Method 22

3.2.6.3 Response Spectrum Method 22
3.2.7 Combination of Modal and Component Responses 22
3.2.7.1 Response Spectrum Analysis 22
3.2.7.1.1 General modal combination rule 22
3.2.7.1.2 Combination of spatial components 23
3.2.7.1.3 Multiple response parameters 23
3.2.7.2 Combination of Spatial Components for Time History Analysis 24
3.3 SOIL-STRUCTURE INTERACTION MODELING AND ANALYSIS 24
3.3.1 General Requirements 24
3.3.1.1 Fixed-Base Analysis 24
3.3.1.2 Spatial Variations of Free-Field Motion 25
3.3.1.3 Three-Dimensional Effects 25
3.3.1.4 Nonlinear Behavior of Soil 25
3.3.1.5 Structure-to-Structure Interaction 25
3.3.1.6 Effect of Mat and Lateral Wall Flexibility 25
3.3.1.7 Uncertainties in SSI Analysis 25
3.3.1.8 Model of Structure 26
3.3.1.9 Embedment Effects 26
3.3.1.10 Wave Incoherence 26
3.3.2 Subsurface Material Properties 26
3.3.2.1 General Requirements 26
3.3.2.2 Shear Modulus 26
3.3.2.3 Material (Hysteretic) Damping Ratio 26
3.3.2.4 Poisson's Ratio 26
3.3.3 Direct Method 26
3.3.3.1 Seismic Input for Model Boundaries 27
3.3.3.2 Lower Boundary 27
3.3.3.3 Selection of Lateral Boundaries 27
3.3.3.4 Soil Element Size 28
3.3.3.5 Time Step and Frequency Increment 28
3.3.4 Impedance Method 28
3.3.4.1 Determination of Input Motion 28
3.3.4.2 Determination of Foundation Impedance Functions 29
3.3.4.2.1 Equivalent foundation dimensions 29
3.3.4.2.2 Uniform soil sites 29
3.3.4.2.3 Layered soil sites 29
3.3.4.2.4 Embedded foundations 29
3.3.4.3 Analysis of Coupled Soil-Structural System 30
3.4 INPUT FOR SUBSYSTEM SEISMIC ANALYSIS 30
3.4.1 General Requirements 30
3.4.1.1 Types of Seismic Input for Subsystem Analysis 30
3.4.1.2 Direction and Locations for In-Structure Response Spectra or Time Histories 31
3.4.1.3 Subsystem Input Away from Reference Location 31
3.4.1.4 In-Structure Displacements and Rotations 31
3.4.2 In-Structure Response Spectra 31
3.4.2.1 Methods for Generation of In-Structure Response Spectra 31
3.4.2.1.1 Time history method 31
3.4.2.1.2 Direct spectra-to-spectra methods 32
3.4.2.2 Frequency Interval for Generation of In-Structure Response Spectra 32
3.4.2.3 Treatment of Uncertainties in Generating In-Structure Response Spectra 32

3.4.2.4 Interpolation of In-Structure Response Spectra for Intermediate Damping 32
3.4.3 In-Structure Time History Motions 33
3.4.3.1 Methods for Generation of In-Structure Time History Motions 33
3.4.3.2 Equivalent Broadening and Lowering of In-Structure Time History Motions 33
3.4.3.3 Time Interval and Data Precision Requirements for In-Structure Time History Motions 33
3.4.4 Structural Model or Characteristics for Coupled Subsystem Analysis 33
3.4.4.1 Supporting Soil-Structure Model 33
3.4.4.2 Base Excitation 33
3.5 SPECIAL STRUCTURES 33
3.5.1 General Requirements 33
3.5.2 Buried Pipes and Conduits 34
3.5.2.1 Straight Sections Remote from Anchor Points, Sharp Bends, or Intersections 34
3.5.2.1.1 Maximum axial strain ignoring friction 34
3.5.2.1.2 Maximum axial strain considering friction 34
3.5.2.1.3 Maximum curvature 34
3.5.2.1.4 Maximum joint displacement and rotation in segmented structures 35
3.5.2.2 Forces on Bends, Intersections, and Anchor Points 35
3.5.2.3 Anchor Point Movement 35
3.5.3 Earth-Retaining Walls 35
3.5.3.1 General Requirements 35
3.5.3.2 Elastic Solution 35
3.5.3.3 Active Solution 35
3.5.4 Above-Ground Vertical Tanks 35
3.5.4.1 General Requirements 35
3.5.4.2 Horizontal Impulsive Mode 36
3.5.4.2.1 Effective weight of fluid—Impulsive mode 36
3.5.4.2.2 Spectral acceleration—Impulsive mode 36
3.5.4.2.3 Overturning moment at base of tank—Impulsive mode 37
3.5.4.2.4 Hydrodynamic pressure on tank shell—Impulsive mode 37
3.5.4.3 Horizontal Sloshing (Convective Mode) 37
3.5.4.3.1 Effective weight of fluid—Sloshing mode 37
3.5.4.3.2 Spectral acceleration—Sloshing mode 37
3.5.4.3.3 Overturning moment at base of tank—Sloshing mode 37
3.5.4.3.4 Hydrodynamic pressure on tank shell—Sloshing mode 37
3.5.4.3.5 Fluid slosh height—Fundamental sloshing mode 37
3.5.4.4 Vertical Fluid Response Mode 38
3.5.4.4.1 Hydrodynamic pressure on tank shell—Vertical mode 38
3.5.4.5 Other Considerations 38
3.5.4.5.1 Overturning moment and longitudinal compressive force 38
3.5.4.5.2 Hoop tension in tank shell 38
3.5.4.5.3 Freeboard requirements 38
3.5.4.5.4 Special provision for full tanks 38
3.5.4.5.5 Attached piping 38
3.5.4.5.6 Tank foundation 38
3.5.5 Raceways 38
3.5.5.1 General Requirements 38
3.5.5.2 Damping 38

3.5.6 Seismic-Isolated Structures 39
3.5.6.1 General Requirements 39
3.5.6.2 Specification of Seismic Input Motion 39
3.5.6.3 Modeling of Structures 39
3.5.6.4 Response Spectrum Analysis 40
3.5.6.5 Time History Analysis 40

Nonmandatory Appendix

A1.0 NONMANDATORY APPENDIX A: EVALUATIONS BEYOND THE DESIGN BASIS 41
A1.1 INTRODUCTION 41
A2.1 HISTORY OF SPRA AND SMA 41
A3.1 PURPOSE AND OVERVIEW OF SEISMIC PROBABILISTIC RISK ASSESSMENT 42
A4.1 PURPOSE AND OVERVIEW OF SEISMIC MARGIN ASSESSMENT METHODOLOGY 44
A5.1 COMPARISON OF SEISMIC EVALUATION METHODOLOGIES 47
A6.1 COMPARISON OF SPRA TO STANDARD 47
A7.1 COMPARISON OF SMA TO STANDARD 51
A8.1 REFERENCES 53

Commentary

C2.0 SEISMIC INPUT 55
C2.1 SEISMIC GROUND MOTIONS 55
C2.1.1 General Requirements 55
C2.2 RESPONSE SPECTRA 55
C2.2.1 General Requirements 55
C2.2.2 Site-Specific Horizontal Response Spectra 56
C2.2.3 Site-Independent Horizontal Response Spectra 56
C2.2.4 Vertical Response Spectra 56
C2.3 TIME HISTORIES 57
C2.3.1 General Requirements 57
C2.4 POWER SPECTRAL DENSITY FUNCTIONS 59
C2.5 ADDITIONAL REQUIREMENTS FOR STRUCTURES SENSITIVE TO LONG-PERIOD MOTIONS 59
C2.5.1 Spectral Shape 59
C2.5.2 Time Histories 60

C3.0 ANALYSIS 61
C3.1 MODELING OF STRUCTURES 61
C3.1.1 General Requirements 61
C3.1.1.1 Models for Horizontal and Vertical Motions 61
C3.1.1.2 Multistep and One-Step Methods of Seismic Response Analysis 61
C3.1.1.3 Discretization Considerations 62
C3.1.1.3.2 Selection of mesh size 62
C3.1.1.3.3 Reduction of dynamic degrees of freedom 62
C3.1.2 Structural Material Properties 62
C3.1.2.1 Concrete 62
C3.1.2.2 Damping 62
C3.1.3 Modeling of Stiffness 62
C3.1.3.1 Stiffness of Reinforced Concrete Elements 62
C3.1.4 Modeling of Mass 63
C3.1.4.1 Discretization of Mass 63
C3.1.4.2 Determination of Nodal Mass 64

C3.1.5 Modeling of Damping 64
C3.1.5.1 Damping Properties of Structures 64
C3.1.5.1.1 Proportional damping (Rayleigh damping) 64
C3.1.5.2 Composite Damping 64
C3.1.5.2.1 Substructures with known damping ratios 64
C3.1.5.2.2 Substructures with proportional damping 64
C3.1.5.3 Composite Modal Damping 64
C3.1.5.4 Alternate Composite Modal Damping 64
C3.1.6 Modeling of Hydrodynamic Effects 64
C3.1.6.1 General Requirements 64
C3.1.6.2 Dynamic Analysis Formulation for Submerged Structures 64
C3.1.6.3 Building Model Hydrodynamic Mass Effects 66
C3.1.7 Dynamic Coupling Criteria 67
C3.1.7.2 Single Point Attachment 67
C3.1.7.3 Multipoint Attachment and Static Constraint 67
C3.1.8 Requirements for Modeling Specific Structures 67
C3.1.8.1.3 Requirements for lumped-mass stick models 67
C3.1.8.3 Requirements for Shear-Wall Structures 68
C3.1.8.4 Requirements for Plate and Shell Structures 68
C3.2 ANALYSIS OF STRUCTURES 70
C3.2.2 Time History Method 70
C3.2.2.1 General Requirements 70
C3.2.2.2.1 Modal superposition method 70
C3.2.2.2.2 Direct integration 71
C3.2.2.3 Nonlinear Methods 71
C3.2.3 Response Spectrum Method 72
C3.2.3.1 Linear Methods 72
C3.2.3.2 Nonlinear Methods 73
C3.2.4 Complex Frequency Response Meethod 73
C3.2.4.1 General Requirements 73
C3.2.4.2 Response Time History 74
C3.2.4.3 Methods to Compute Transfer Functions 74
C3.2.5 Equivalent-Static Method 74
C3.2.5.1 General Requirements 74
C3.2.5.3 Other Simple Structures 75
C3.2.6 Multiply-Supported Systems 75
C3.2.6.1 General Requirements 75
C3.2.6.2 Time History Method 75
C3.2.6.3 Response Spectrum Methods 75
C3.2.6.3.1 Envelope spectrum method 75
C3.2.6.3.2 Multiple-spectrum method 76
C3.2.6.3.3 Combination of inertial and seismic anchor displacement effects 76
C3.2.7 Combination of Modal and Component Responses 76
C3.2.7.1 Response Spectrum Analysis 76
C3.2.7.1.1 General modal combination rule 76
C3.2.7.1.2 Combination of components 77
C3.2.7.1.3 Multiple response parameters 77
C3.3 SOIL-STRUCTURE INTERACTION MODELING AND ANALYSIS 83
C3.3.1 General Requirements 83
C3.3.1.1 Fixed-Base Analysis 84
C3.3.1.2 Spatial Variations of Free-Field Motion 84

C3.3.1.3 Three-Dimensional Effects 85
C3.3.1.4 Nonlinear Behavior of Soil 85
C3.3.1.5 Structure-to-Structure Interaction 85
C3.3.1.6 Effect of Mat and Lateral Wall Flexibility 86
C3.3.1.7 Uncertainties in SSI Analysis 86
C3.3.1.8 Model of Structure 86
C3.3.1.9 Embedment Effects 87
C3.3.1.10 Wave Incoherence 87
C3.3.2 Subsurface Material Properties 87
C3.3.2.1 General Requirements 87
C3.3.2.2 Shear Modulus 88
C3.3.2.3 Damping Ratio 88
C3.3.2.4 Poisson's Ratio 88
C3.3.3 Direct Method 89
C3.3.3.1 Seismic Input for Model Boundaries 89
C3.3.3.3 Selection of Lateral Boundaries 90
C3.3.3.4 Soil Element Size 90
C3.3.3.5 Time Step and Frequency Increment 91
C3.3.4 Impedance Method 91
C3.3.4.1 Determination of Input Motion 91
C3.3.4.2 Determination of Foundation Impedance Functions 92
C3.3.4.2.1 Equivalent foundation dimensions 92
C3.3.4.2.2 Uniform soil sites 92
C3.3.4.2.3 Layered soil sites 92
C3.3.4.2.4 Embedded foundations 92
C3.4 INPUT FOR SUBSYSTEM SEISMIC ANALYSIS 95
C3.4.1 General Requirements 95
C3.4.1.1 Types of Seismic Input to Subsystem Analysis 95
C3.4.1.2 Direction and Locations for In-Structure Response Spectra or Time Histories 95
C3.4.1.3 Subsystem Input Away from Reference Location 95
C3.4.2 In-Structure Response Spectra 96
C3.4.2.1.2 Direct spectra-to-spectra methods 96
C3.4.2.2 Frequency Interval for Generation of In-Structure Response Spectra 96
C3.4.2.3 Broadening and Lowering of Raw In-Structure Response Spectra 97
C3.4.2.4 Interpolation of In-Structure Response Spectra for Intermediate Damping 98
C3.4.3 In-Structure Time History Motions 98
C3.4.3.1 Methods for Generation of In-Structure Time History Motions 98
C3.4.3.2 Equivalent Broadening and Lowering of In-Structure Time History Motions 100
C3.4.3.3 Time Interval and Data Precision Requirements for In-Structure Time History Motions 101
C3.4.4 Structural Model or Characteristics for Coupled Subsystem Analysis 101
C3.4.4.1 Supporting Structure Model 101
C3.5 SPECIAL STRUCTURES 103
C3.5.2 Buried Pipes and Conduits 103
C3.5.2.1 Straight Sections Remote from Anchor Points, Sharp Bends, or Intersections 103
C3.5.3 Earth-Retaining Structures 104
C3.5.3.1 General Requirements 104
C3.5.3.2 Elastic Solution 104

C3.5.3.3 Active Solution 105
C3.5.4 Above-Ground Vertical Tanks 105
C3.5.4.2 Horizontal Impulsive Mode 105
C3.5.4.2.1 Effective weight of fluid—Impulsive mode 105
C3.5.4.2.2 Spectral acceleration—Impulsive mode 106
C3.5.4.2.3 Overturning moment at base of tank—Impulsive mode 107
C3.5.4.2.4 Hydrodynamic pressure on tank shell—Impulsive mode 107
C3.5.4.3 Horizontal Sloshing (Conective) Mode 107
C3.5.4.3.1 Effective weight of fluid—Sloshing mode 107
C3.5.4.3.2 Spectral acceleration—Sloshing mode 107
C3.5.4.3.3 Overturning moment at base of tank—Sloshing mode 107
C3.5.4.3.4 Hydrodynamic pressure on tank shell—Sloshing mode 107
C3.5.4.3.5 Fluid slosh height—Fundamental sloshing mode 108
C3.5.4.4 Vertical Fluid Response Mode 108
C3.5.4.4.1 Hydrodynamic pressure on tank shell—Vertical mode 108
C3.5.4.5 Other Considerations 108
C3.5.4.5.1 Overturning moment and longitudinal compressive force 108
C3.5.5 Raceways 108
C3.5.5.1 General Requirements 108
C3.5.5.2 Damping 109
C3.5.6 Seismic Isolated Structures 110
C3.5.6.1 General Requirements 110
C3.5.6.3 Modeling of Structures 111
C3.5.6.4 Response Spectrum Analysis 111
C3.5.6.5 Time History Analysis 111

Index 115

Seismic Analysis of Safety-Related Nuclear Structures

1.0 GENERAL

1.1 INTRODUCTION

1.1.1 Purpose

This standard provides minimum requirements and acceptable methods for the seismic analyses of safety-related structures of a nuclear facility. This standard provides a methodology for calculating seismic responses in structures and to derive input motions for use in the seismic qualification of electrical and mechanical systems and components.

The purpose of the analytical methods is to provide only small levels of conservatism to account for uncertainties. The intentional conservatism is contained in the following three areas:

1. For soil-structure interaction, three cases are analyzed using different soil modulus values and the results use the envelope of the three cases.
2. For in-structure response spectra, the peaks are broadened.
3. For structural damping, conservative values are specified.

As a result, the output from the analyses using these methods will be at a slightly greater probability of non-exceedance than that of the input. For example, the seismic responses will have about a 90% chance of not being exceeded for an input response spectrum specified at the 84th percentile non-exceedance level.

1.1.2 Scope

1.1.2.1 Types of Structures Covered by This Standard

This standard is intended for use in the seismic analysis of all safety-related structures of nuclear facilities including, but not limited to, above and below ground structures, buried piping, above ground vertical tanks and structures with seismic isolation systems. Analysis of caisson and pile-supported foundations, unlined tunnels, and floating structures are not covered by this standard. However, nothing in this standard should be considered to preclude the use of these structures and structural elements.

1.1.2.2 Foundation Material Stability

The analysis procedures provided herein assume that the structures analyzed are adequately supported by their foundation materials and that no soil or rock failure occurs that would modify or void the seismic analysis.

1.1.3 General Requirements

1.1.3.1 Use of Analysis Results

The seismic responses determined from the analyses prescribed herein are to be combined with responses due to dead load and other prescribed loads.

1.1.3.2 Alternative Methodologies

Techniques other than those specified in this standard, including experience gained from past earthquakes, special analyses, and testing, may be used in lieu of the requirements specified herein. However, such alternative methodologies shall be properly substantiated and shall conform to the intent of this standard as expressed in the preface.

1.2 DEFINITIONS

The following terms are defined for general use in this standard. Specialized definitions also appear in some individual sections.

Apparent wave propagation velocity: The apparent propagation velocity of seismic waves through the ground relative to a fixed local coordinate system on the object analyzed.

Competent soil: Any natural or improved soil that has a shear wave velocity, $V_s \geq$ 1,000 fps (300 m/s).

Coupled: A descriptive term for mathematical models of structures and components that are interconnected and which influence the dynamic response of each other.

"Cut-off" frequency: The highest frequency which is adequately represented in the model for the soil structure interaction analysis procedure. It may be taken as twice the highest dominant frequency of the coupled soil-structure system for the direction under consideration, but not less than 10 Hz.

Design (or evaluation) ground acceleration: The value of the acceleration which corresponds to acceleration at zero period in the design ground-response spectrum.

Design (or evaluation) response spectrum: A smooth response spectrum of the free-field input mo-