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Seismic Analysis of Safety-Related Nuclear Structures

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**Seismic Analysis of
Safety-Related Nuclear
Structures**



PUBLISHED BY THE AMERICAN SOCIETY OF CIVIL ENGINEERS

Library of Congress Cataloging-in-Publication Data

Names: American Society of Civil Engineers.

Title: Seismic analysis of safety-related nuclear structures / American Society of Civil Engineers.

Description: Reston, Virginia : American Society of Civil Engineers, 2017. | "ASCE standard ASCE/SEI 4-16." | Includes bibliographical references and index.

Identifiers: LCCN 2016045567 (print) | LCCN 2016056049 (ebook) | ISBN 9780784413937 (pbk. : alk. paper) | ISBN 9780784479988 (PDF)

Subjects: LCSH: Nuclear facilities--Evaluation--Standards--United States. | Earthquake resistant design--Standards--United States. | Nuclear facilities--Earthquake effects.

Classification: LCC TK9152.163 .A47 2017 (print) | LCC TK9152.163 (ebook) | DDC 621.48/35--dc23

LC record available at <https://lccn.loc.gov/2016045567>

Published by American Society of Civil Engineers

1801 Alexander Bell Drive

Reston, Virginia, 20191-4382

www.asce.org/bookstore | ascelibrary.org

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Errata: Errata, if any, can be found at <https://doi.org/10.1061/9780784413937>.

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ISBN 978-0-7844-1393-7 (print)

ISBN 978-0-7844-7998-8 (PDF)

Manufactured in the United States of America.

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DEDICATION



John D. Stevenson, Ph.D., P.E.
May 23, 1933–October 30, 2014

ASCE 4-16 is dedicated to Dr. John D. Stevenson: a leader in the nuclear energy industry for more than four decades, with seminal contributions in civil, structural, and mechanical engineering.

John Stevenson graduated with a bachelor of science degree from the United States Military Institute (VMI) in 1954. After two years of service in the U.S. Army Corps of Engineers and six years of service on the faculty of VMI, he completed a master of science degree at Case Institute of Technology in 1962. Two years of research on nuclear weapons effects at the IIT Research Institute in Chicago followed, after which he began doctoral studies at Case Western University. He completed his Ph.D. at Case Western in 1968.

Between 1968 and 1981, John held senior positions with Westinghouse Electric Company, Case Western Reserve University, McKee and Company, and Woodward Clyde Consultants. In 1981, he founded Stevenson and Associates, a consulting engineering firm, which grew rapidly and had offices in Cleveland, Ohio; Boston, Massachusetts; Pilsen, Czech Republic; St. Petersburg, Russia; and Bucharest, Romania. He also served as a consulting engineer to the U.S. Nuclear Regulatory Commission, the Defense Nuclear Facility Safety Board, and the International Atomic Energy Agency.

John received many awards over his career, including the American Society of Civil Engineers (ASCE) Moseiff Award in 1971, the Civil Engineer of the Year in 1991 given by the Cleveland Section of the ASCE, the ASCE Stephen Bechtel Award in 1995, and the American Society of Mechanical Engineers (ASME) Bernard Langer Award in 1997.

A hallmark of John's career in the nuclear industry, which spanned more than 40 years, is his many important contributions to codes and standards for safety-related nuclear structures published by the American Concrete Institute, American Institute of Steel Construction, American Nuclear Society, American Society of Civil Engineers, and American Society of Mechanical Engineers: a broad spectrum of important contributions that collectively are likely unmatched in the nuclear industry in the United States.

John was an active member of the ASCE Committee on Dynamic Analysis of Nuclear Structures. He brought much to the committee, including a deep understanding of mechanical components and systems and ASME codes and standards. Frequently, he was the lone advocate for mechanical engineering systems in a roomful of civil and structural engineers. His efforts to extend ASCE Standards 4 and 43 to address mechanical components and systems greatly expanded the utility of these standards, which will be forever appreciated.

Through this dedication, the members of the ASCE 4 task committee acknowledge John's seminal contributions to the seismic engineering of safety-related nuclear structures. His absence from committee deliberations and vigorous discussions is, and will be, sadly missed.

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PREFACE

Nuclear facilities process, store, or handle radioactive materials in a form and quantity that pose a potential nuclear hazard to workers, the public, or the environment. Owing to the risk associated with such hazards, these facilities must comply with stringent government regulations. Ensuring that these facilities have a lower probability of unacceptable seismic performance than conventional facilities is also important.

This standard intends to provide criteria for seismic analysis such that the responses computed in accordance with this standard will have a small likelihood of being exceeded.

Four steps in the design and construction process lead to reliable 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, and
4. Construction.

This standard provides requirements for performing Step 2. This standard may be used for analysis of either new or existing facilities.

This standard was developed with the intent that it would be used with ASCE/SEI 43, *Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities* (2005). When used with ASCE/SEI 43, this standard will produce a design that is associated with a target annual performance goal as described in ASCE/SEI 43.

Techniques other than those specified in this standard, including experience gained from past earthquakes, special analyses, and testing may also be used to determine the seismic response of structures, systems, or components (SSCs). However, such alternative methodologies shall be properly substantiated and shall conform to the intent of this standard.

This edition of the standard is an extensive update of ASCE 4-98. It incorporates recent developments in analysis procedures and the corresponding data reported in the literature. To aid the reader, the following briefly summarizes the revisions to the chapters and organization of this standard.

Chapter 1 defines the purpose and scope of the standard, use of this standard with other standards, and mandatory quality requirements.

Chapter 2 on seismic input has been rewritten and expanded to emphasize performance-based design motions in keeping with the guidance in ASCE/SEI 43 and using methodology from NUREG/CR-6728 (2001). It also includes a new section on probabilistic site response analysis.

Chapter 3 on modeling of structures is a new chapter that updates material from Section 3.1 of ASCE 4-98.

Chapter 4 on analysis of structures is a new chapter that covers the material that appears mostly in Section 3.2 of ASCE 4-98. Section 4.6 includes material on the multistep analysis of structures that appeared previously in Section 3.1.1.2 of ASCE 4-98. Chapter 4 also includes new material on nonlinear analysis of structures using the static method, the response-history method, and an approximate response-spectrum method.

Chapter 5 on soil-structure interaction modeling and analysis is a significant expansion and enhancement of the material in Section 3.3 of ASCE 4-98. Chapter 5 includes new material on

developing performance-based seismic input motions for use in soil-structure interaction analyses that reflects the corresponding updates to Chapter 2. It also includes a new section on probabilistic soil-structure interaction analysis.

Chapter 6 is a new chapter devoted to input for subsystem analysis that updates and expands upon the material in Section 3.4 of ASCE 4-98. It includes new sections on probabilistic analysis of subsystems and a new section on the effect of wave incoherence on in-structure response spectra.

Chapters 7 through 12 are also new chapters dealing with special structures that require special treatment for seismic analysis owing to their unique or complex nature. Of the six new chapters, four are expanded versions of the provisions included in ASCE 4-98. The remaining two are new additions to the standard: distribution systems (Chapter 10) and sliding and uplift analysis of unanchored components (Chapter 11).

Chapter 7 includes detailed requirements for seismic analyses of buried piping and conduits. Both simplified and advanced analyses methods are addressed.

Chapter 8 addresses analyses of the parts of nuclear facilities that are below grade. These structures range from earth-retaining walls to walls of facilities that resist the seismic loads generated during a seismic event.

Chapter 9 updates the analyses methods for aboveground liquid storage tanks. These tanks may be constructed of steel or reinforced concrete, with or without a steel liner.

Chapter 10 discusses the analytical methods that are commonly used for seismic analysis of mechanical and electrical distribution systems. The components in this category include piping, conduits, ductwork, raceway systems, and supports for these components.

Chapter 11 considers analysis of unanchored components at nuclear facilities. This chapter provides simplified approaches that can be used in determining the seismic response of such components.

Chapter 12 contains special requirements for seismically isolated structures and components. It is greatly expanded from the brief version included in ASCE 4-98.

Appendix A is an update of evaluations beyond design basis in ASCE 4-98 and focuses on assessment of seismic vulnerabilities at nuclear facilities. It addresses identification of seismic vulnerabilities, quantification of risk or margin for new facilities, and evaluation of facilities for seismic events beyond the design basis.

Appendix B is a new addition to the standard and provides guidance for performing nonlinear three-dimensional time-domain soil-structure interaction analysis.

Attachments to Chapters 1, 10, and 11; commentaries to all chapters; and appendixes A and B are nonmandatory.

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ACKNOWLEDGMENTS

The American Society of Civil Engineers (ASCE) acknowledges the work of the Seismic Analysis of Safety-Related Nuclear Structures Standards and the Task Committee on Dynamic Analysis of Nuclear Structures, both under the auspices of the Codes and Standards Activities Division of the Structural Engineering Institute. We are greatly indebted to Bechtel National, Inc., for voluntarily contributing to the preparation of this manuscript.

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In Memoriam: Dan Nuta

The Task Committee acknowledges the important contributions of Dan Nuta, an active committee member who brought reason to the standard. He was an acting structural engineer at the Indian Point Nuclear Generating Station and was responsible for implementation or review of many projects that used this standard. His good humor, his candor, and his contributions to the working group will be sorely missed.

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ABBREVIATIONS AND NOTATION

Abbreviations and Acronyms

ABS	absolute sum	NRC	Nuclear Regulatory Commission
ACI	American Concrete Institute	NSSS	nuclear steam supply system
AISC	American Institute of Steel Construction	PBSRS	performance-based surface response spectra
ANS	American Nuclear Society	PE	potential energy
ARS	acceleration response spectrum	PGA	peak ground acceleration
ASCE/SEI	American Society of Civil Engineers / Structural Engineering Institute	PGD	peak ground displacement
ASME	American Society of Mechanical Engineers	PGV	peak ground velocity
ASTM	American Society of Testing and Materials	POD	proper orthogonal decomposition
BDBE	beyond design basis earthquake	PRA	probabilistic risk assessment
BE	best estimate	PSD	power spectral density
BNL	Brookhaven National Laboratory	PSHA	probabilistic seismic hazards assessment
CDF	cumulative distribution function; core damage frequency	QA	quality assurance
CDFM	conservative deterministic failure margin	RCTS	resonant column/torsional shear
CEUS	central and eastern United States	RLE	review-level earthquake
COV	coefficient of variation	RSMAM	response spectral modal analysis method
CQC	complete quadratic combination	RVT	random vibration theory
CS	clearance to the stop	SAM	seismic anchor motion
CSDRS	certified seismic design response spectra	SCOR	soil column outcrop response
DBE	design basis earthquake	SDB	seismic design basis
D/C	demand-to-capacity ratio	SDC	seismic design category
DF	design factor	SDOF	single degree of freedom
DOE	Department of Energy	SIDRS	seismic isolation design response spectra
DRM	domain reduction method	SMA	seismic margin assessment
DRS	design response spectrum	SMACS	seismic methodology analysis chain and statistics
EPRI	Electric Power Research Institute	SPRA	seismic probabilistic risk assessment
ESAM	equivalent static analysis method	SQUG	Seismic Qualification Utilities Group
ESI	equipment-structure interaction	SRSS	square-root-of-the-sum-of-squares
FA	fragility analysis	SSC	structure, system, and component
FFT	fast Fourier transform	SSE	safe shutdown earthquake
FIRS	foundation input response spectra	SSI	soil-structure interaction
FNA	fast nonlinear analysis	SSSI	structure-soil-structure interaction
FP	friction pendulum	UB	upper bound
GMPE	ground motion prediction equation	UHRS	uniform hazard response spectrum
HCLPF	high confidence of a low probability of failure	USNRC	United States Nuclear Regulatory Commission
ISRS	in-structure response spectra	V&V	validation and verification
LB	lower bound	WUS	western United States
LCM	load coefficient method	ZPA	zero-period acceleration
LD	low damping		
LDR	low-damping rubber		
LHS	Latin hypercube simulation		
LOCA	loss-of-coolant accident		
LR	lead rubber		
LRFD	Load and Resistance Factor Design		
LVSSR	lateral-to-vertical-support-span ratio		
MCS	Monte Carlo simulation		
MDOF	multi-degree of freedom		
MSE	mechanically stabilized earth		
NEI	Nuclear Energy Institute		
NEP	nonexceedance probability		
NPP	nuclear power plant		

Notation

α	end coefficient for the hanger; instability angle (Chapter 11); dynamic amplification factor;
α_i, β_i	proportional damping coefficients for the i th part of the structure;
α, β	proportional damping coefficients;
α_h	horizontal peak ground acceleration (g);
α_e, α_κ	wave velocity coefficients;
$\alpha(\tau)$	acceleration time series;
$\alpha/2$	confidence level;
β	hysteretic damping; slope of back of wall to vertical;
β_D	seismic demand logarithmic standard deviation;
β_e	effective damping;
β_{eff}	equivalent viscous damping ratio;

β_f	logarithmic standard deviation;	Λ_i	modal mass ratio;
β_H	damping ratio during full cycles of sliding displacements; logarithmic standard deviation;	μ	coefficient of friction; ductility ratio;
β_N	logarithmic standard deviation for the nonlinear factor;	μ_d	ductility demand;
β_p	P-wave damping;	μ_e	effective coefficient of friction;
β_S	strength logarithmic standard deviation; S-wave damping;	ν	Poisson's ratio;
$\beta_x, \beta_\Psi, \beta_z$	constants that are functions of the basemat dimensional ratio, L/B ;	ν_c	Poisson's ratio of concrete;
$\Gamma_{c\alpha}$	a row of secondary system participation factors, consisting of one term for each connecting degree of freedom;	ν_s	Poisson's ratio of steel;
Γ_j	participation factor for j th mode;	ρ	mass density;
Γ_{sj}	participation factor for support s , j th mode;	ρ_{12}	correlation coefficient between any two acceleration time series;
γ	shear strain; soil unit weight; coefficient defined in Chapter 11;	σ	standard deviation;
γ_{pw}	plane wave coherency representing random horizontal spatial variation of ground motion;	σ_{ax}	axial stress;
$\gamma(\omega)$	coherency function;	σ_{axial}	maximum axial stress in tank wall;
δ	maximum uplift at opposite end of the building; angle of wall friction;	$\sigma_h, \sigma_{hoopmax}$	maximum hoop stress in tank wall;
δ_s	best-estimate sliding displacement; sliding displacement;	σ_v	effective yield stress;
Δ	hanger displacement;	σ_{ymmax}	maximum von Mises stress in tank wall;
Δf_i	total frequency variation;	σ_2^0	lateral dynamic soil pressure against the retaining structure for 1.0g horizontal earthquake acceleration;
$\Delta f_{0.8}$	total frequency range over spectral amplitudes that exceeds 80% of the peak spectral amplitude;	τ	shear stress;
Δh	longest side of an element in a finite element model;	τ_{max}	maximum shear stress in tank wall;
Δ_{max}	maximum relative joint displacement; maximum positive horizontal displacement of an isolator;	ϕ	angle of friction of soil; code-specified strength reduction factor;
Δ_{min}	minimum negative horizontal displacement of an isolator;	$\phi_{ci}, \{\phi_{ci}\}$	mode vector value from the primary system's modal displacement at the location of attachment of the secondary system;
ΔP_{AE}	dynamic soil pressure;	$\{\phi_j\}$	shape of mode j ;
$\Delta T, \Delta t$	time step;	$\{\phi_{s\alpha}\}$	α th normalized modal vector of the secondary system;
$\Delta_x^*, \Delta_y^*, \Delta_z^*$	translation components of input;	$[\phi]_i$	normalized mode-shape matrix of i th subsystem (fixed base);
ϵ_{eff}	effective shear strain;	$[\phi]$	mode-shape matrix;
ϵ_{ij}	correlation coefficient for the i th and j th modes;	Φ_{max}	upper bound for maximum curvature of the buried structure as a whole;
$(\epsilon_a)_{max}$	maximum axial strain;	Ω_o	seismic force amplification factor required to account for structural overstrength;
θ	rocking rotation angle; tangent angle for tank roof;	ω	circular frequency (rad/s);
$\theta_{max}, \theta_o, \theta_{om}$	maximum joint rotation; maximum rocking angle;	ω_e	effective circular frequency;
$\theta_x^*, \theta_y^*, \theta_z^*$	rotational components of input;	$\bar{\omega}_j$	damped circular frequency of j th mode of the system;
$\ddot{\theta}$	rotational acceleration;	ω_j	undamped circular frequency of j th mode;
λ	damping ratio for a material as a fraction of critical damping;	ω_k	circular frequency of the k th mode of the subsystem (rad/s); frequency of interest;
$\lambda, \lambda_1, \lambda_2$	damping values associated with spectral amplitudes S, S_1 , and S_2 ;	ω_{max}	highest significant circular frequency of interest;
λ_j	damping ratio for the j th mode, expressed as a fraction of critical damping;	ω_{min}	lowest significant circular frequency of interest;
λ_k	critical damping ratio of the k th mode of the subsystem;	$\omega_{s\alpha}$	circular frequency of the i th uncoupled secondary system mode (rad/s);
$[\lambda K]_i$	stiffness matrix for the i th element or subsystem in the global coordinate system, scaled by the damping ratio of the i th element as a fraction of critical damping;	ω_v	vertical liquid circular natural frequency;
$[\lambda M]_i$	mass matrix for i th element or subsystem in the global coordinate system, scaled by the damping ratio of the i th element as a fraction of critical damping;	ω_2	fundamental circular frequency of the sloshing mode;
λ_w	wavelength of the dominant seismic wave;	ξ	separation distance between locations used in coherency function (m);
		A	area under the normalized seismic soil pressure curve; amplitude of the upward wave in a soil layer;
		A_C	soil contact area;
		A_p	cross-sectional area of the pipe;
		A_g	gross area of concrete section;
		A_s	gross area of reinforcing steel;
		A_V	peak vertical acceleration;
		A_w	area of web;
		a	acceleration; dynamic amplification factor; base-to-height ratio; peak acceleration of the ground motion;

a_{\max}	maximum ground acceleration;	E_t, E_u	lower and upper bound values of modulus of elasticity of uncracked concrete;
a_1, a_2, a_3	coefficients used in coherency function;	E_x, E_y	spring stiffnesses;
B	bandwidth-to-central-frequency ratio; width of the basemat perpendicular to the direction of horizontal excitation; amplitude of the downward wave in a soil layer; width of the base in the rocking direction;	$E(t)$	cumulative energy of the acceleration time series;
B_Ψ	coefficient used in equivalent rocking damping coefficient calculation;	F	force resisted by longitudinal brace;
b	minimum horizontal distance from the edge of the body to center of gravity;	F_a	axial force in buried structure;
C	seismically induced longitudinal compressive force per unit length in the tank shell;	F_r	resultant force due to dynamic soil pressure acting on earth-retaining walls;
C_I	coefficient defined in Chapter 11;	F_H	correction for difference between the lateral inertial mass, M_L , and the vertical resisting mass, M ; horizontal directionality factor;
C_{MRI}	coefficient defined in Chapter 11;	F_{\max}, F_{\min}	horizontal forces corresponding to Δ_{\max} and Δ_{\min} for an isolator, respectively;
C_R	coefficient of restitution; coefficient defined in Chapter 11; rocking coefficient of restitution;	$F_{N1\%}$	nominal factor of safety against 1% conditional probability of failure;
C_{STD}	standard seismic capacity;	$F_{N10\%}$	nominal factor of safety against 10% conditional probability of failure;
C_v	coefficient that is a function of Poisson's ratio; coefficient of variation;	F_{RS}	resisting force to sliding;
$[C]$	damping matrix;	F_V	correction for probabilistically combined vertical ground motion; vertical directionality factor; maximum vertical response of the empty tank shell;
$[C_{FB}]_i$	fixed-base damping matrix of i th subsystem;	F_μ	inelastic force reduction factor;
$[C_H]$	effective damping force matrix due to velocity drag effects of water;	$F_{\mu STD}$	deterministic inelastic force reduction factor defined in accordance with ASCE/SEI 43-05;
$[C_H^*]$	partitioned portion of effective damping force matrix due to velocity drag effects of water;	$F_{\mu 50\%}$	median estimate of inelastic force reduction factor;
$[C]_i$	damping matrix for i th subsystem or part of structure;	$F(\omega)$	Fourier amplitude of the acceleration time series computed of the duration t_m ;
$C_{1\%}$	coefficient defined in Chapter 1;	f	friction force per unit length; fundamental frequency of fluid (Hz); ground motion frequency (Hz); longitudinal direction frequency;
$C_{10\%}$	coefficient defined in Chapter 1;	f_1	parameter defined in Chapter 11;
$C_{50\%}$	median seismic capacity;	f_c^c	specified compressive strength of concrete;
c	apparent wave velocity; distance from neutral axis to outer extreme fiber;	f_c	central frequency for the frequencies that exceed 80% of the peak amplitude;
c_s	sliding coefficient;	$f_c(\xi)$	coefficient used in coherency function;
c_t	equivalent torsional damping coefficient;	f_e	effective rocking frequency;
c_x	equivalent horizontal damping coefficient;	$(f_e)_n$	natural frequency of the n th subsystem
c_z	equivalent vertical damping coefficient;	f_{em}	lowest natural frequency at which the horizontal input spectral acceleration demand, SAH_{DEM} , is maximum;
c_Ψ	equivalent rocking damping coefficient;	f_{es}	lowest natural frequency at which the horizontal 10% damped vector spectral acceleration, SA_{VH} , equals c_s ;
D	hysteric damping ratio; tank diameter;	f_i	frequency of i th mode of system; dominant fixed-base frequency for flexible structures;
$[D]_i$	diagonal matrix with $D_{kk} = 2\lambda_k M_k^* \omega_k = 2\lambda_k \omega_k$;	f_j	structural frequency at frequency j ;
D_{BD}	90th percentile displacement for DBBE shaking at the plan center of mass of the isolated superstructure;	f_l	frequency below which all modes are periodic;
D_D	80th percentile displacement for DBE shaking at the plan center of mass of the isolated superstructure;	f_{\max}	maximum friction force per unit length between the pipe and surrounding soil;
D_{STD}	deterministic seismic demand defined in accordance with ASCE/SEI 43-05;	$f_{Nyquist}$	Nyquist frequency;
D_v	coefficient that is a function of Poisson's ratio;	f_s	frequency of secondary system; piping fundamental frequency; soil column frequency taken as $V_s/4H$;
$D_{50\%}$	seismic demand for a specified DBE input; median seismic demand;	f_r	frequency above which all modes are rigid;
d	displacement; peak displacement of the ground motion; liquid slosh height;	f_v	frequency at which the peak spectral velocity occurs;
dt	increment of the time signal;	G	shear modulus;
E	Young's modulus (modulus of elasticity);	G_c	shear modulus of reinforced concrete;
E_B	lateral beam stiffness;	G_l, G_u	lower and upper bound values of shear modulus of uncracked concrete;
E_c	modulus of elasticity of concrete;	G/G_o	ratio of reduced shear modulus to original (low strain) shear modulus;
E_{DL}	energy dissipated by viscous damping during a cycle of sliding;		
EDC	energy dissipated per cycle for an isolator;		
E_{DS}	energy dissipated during a cycle of sliding;		
E_H	elastic foundation stiffness;		
E_s	modulus of elasticity of steel;		
E_{sct}	secant modulus of elasticity;		

g	acceleration due to gravity;	k_x, c_x	equivalent horizontal spring and damping constants;
H	story height; embedment depth (height); fluid height (ft); wall height below grade;	$k_{x\psi}$	coefficient used in computation of center of resistance;
H_C	height to the center of resistance;	k_z, c_z	equivalent vertical spring and damping constants;
H_{CB}, H_{CT}	height to the bottom and top of the knuckle at the top of the tank cylinder;	k_ψ, c_ψ	equivalent rocking spring and damping constants;
H_{CE}	effective height of the intersection of the cylinder and fitted sphere;	k_1, k_2	parameters defined in Section C3.6.2;
H_F	height from the tank base to the top of the domed roof;	k^*	complex wave number;
H_L	liquid depth;	L	concentrated weight equivalent length of pipe;
H_{SC}	distance from tank base to roof for a flat-roofed tank;		distance between the braced supports; length of basemat; half wavelength; distance between flexible joints of the long linear buried structure;
h	center-of-gravity height; thickness of shell;		length of cylinder; length of raceway segment;
h_D	distance from the top of the spherical dome to its intersection with the cylinder;		horizontal distance between two adjacent walls;
h_L	height to center of gravity for the lateral inertial mass;	L_1	hanger height;
h_{sc}	freeboard (slosh height clearance);	l_c	twice the distance from the top of the fluid to the center of the sloshing fluid mass (see Fig. 3-1);
I	importance factor;		
I_o	total mass moment of inertia of structure and basemat about rocking axis at the base;	l_h	maximum span between straight spans of pipe;
I_B	mass moment of inertia of the rigid body;	l_1	twice the distance from the bottom of the basin to the center of the impulsive fluid mass (see Fig. 3-1);
I_g	gross moment of inertia;		
I_{post}	hanger bending moment of inertia;	l_v	nominal deadweight spacing length;
I_t	polar mass moment of inertia of structure and basemat;	l_1, l_2, l_3	pipe span lengths;
i	slope of ground surface behind retaining wall;	M	mass of the tray raceway supported by the hanger, or vertical resisting mass; mass of a structure or component; number of response parameters of interest; constrained modulus; vertical mass resisting rocking;
K	distributed mass of the piping system; load coefficient used in the seismic load coefficient method analysis; structural stiffness; liquid bulk modulus; active earth pressure coefficient with earthquake effect;	$[M]$	mass matrix;
K_{AE}	second-slope stiffness;	$[M_H^*]$	partitioned effective (or added) mass matrix due to effects of water ($n \times n$);
K_d	load coefficients;	$[M_H]$	effective (or added) mass matrix due to effects of water ($n \times n$);
K_{hi}, K_v	stiffness of longitudinal brace;	$[M_H^*]_{12}$	partitioned vector from the effective mass matrix that couples the submerged structure degrees of freedom with basin wall ($n \times 1$);
K_l	lateral stiffness of hanger; transverse bending stiffness of the hanger;	$[M_{H12}]$	vector for the effective mass matrix that couples the submerged structure's degrees of freedom with the basin wall ($n + 1 \times 1$);
K_t	complex stiffness used in frequency-domain analyses;		mass matrix for the i th part of the structure;
K^*	stiffness matrix;	$[M]_i$	combined overturning moment at the tank base;
$[K]$	a square matrix representing the stiff contribution of the secondary system to the stiffness matrix of the coupled primary-secondary system for the connecting degrees of freedom;	M_B	median value of the ratio of SA_{fi}/TSA_f
$[K_{cc}^s]$	stiffness matrix for the i th part of the structure;	M_f	in-plane moment;
$[K]_i$	torsional rigidity;	M_{ip}	lateral inertial mass;
K_p	elastic stiffness;	M_L	vector of missing mass quantities at each degree of freedom ($n \times 1$);
K_u	stiffnesses of i th wall or column, assuming rigid connection to floor, in x and y directions, respectively;	$\{M_m\}$	out-of-plane moment;
K_{xi}, K_{yi}	equivalent linear stiffness;	M_{op}	overturning moment;
k_e	equivalent horizontal stiffness of an isolator;	M_{OT}	mass matrix of the primary system;
k_{eff}	peak horizontal ground acceleration at the top of the wall (g);	$[M_p]$	modal mass of primary structure for mode i ;
k_h	approximate rotational stiffness;	M_{pi}	resultant overturning moment about base of retaining structure for pressure distribution;
k_R	initial stiffness;	M_r	mass of substructure or subsystem; total mass of secondary system;
k_o	secant stiffness reduction factor; secant stiffness;	M_s	basin structure mass at node i ;
k_s	unbraced hanger stiffness; equivalent torsional spring constant;	M_{s_i}	parameters defined in Section C3.6.2; overturning moments caused by impulsive and sloshing modes excluding bottom pressure effects;
k_t	peak vertical ground acceleration at the top of the wall (g);	M_1, M_2	parameters defined in Section C3.6.2;
k_v		$M_1, M_2, M_{11}, M_{12}, M_{22}$	

M_1, M_2	overturning moments caused by impulsive and sloshing modes including bottom pressure effects;	$R(t)$	combined response time history;
m	mass per unit length of the raceway system; number of modes considered; ductility factor; meter; number of logarithmically spaced frequencies; total soil mass;	$R(\omega)$	response in the frequency domain;
N	number of hangers in the segment; number of modes considered in the analysis without missing mass; number of modes considered for the analysis; number of statistical response analysis simulations; number of probability bins; number of Monte Carlo simulations; number of points required for FFT analysis; number of simulated soil profiles; number of acceleration time series;	r	reduction in rotational velocity during one cycle of response; horizontal radius of the roof;
NF	number of subsystem natural frequencies;	r_{ia}	modal mass ratio for primary system mode i and secondary system mode a ;
NS	number of substructures being assembled;	r_K	knuckle radius;
n	number of dynamic degrees of freedom or number of elements considered; number of acceleration points in a series; number of modes;	S	code-allowed normal stress;
P	axial load; mean of Gaussian distribution;	S, S_1, S_2	spectral amplitudes associated with damping values $\lambda, \lambda_1,$ and λ_2 ;
P_A	active component of the overall soil pressure during a seismic event;	S_a, SA	spectral acceleration;
P_{AE}	active soil pressure during the seismic event;	$S_a(f)$	spectral acceleration value applicable at the base of the raceway support at frequency f ;
P_{base}	pressure at the base of tank wall;	$S_a(f_s, 30\%)$	acceleration spectral value of the free-field response at the soil column frequency obtained at the depth of the bottom of the wall in terms of acceleration response spectrum at 30% damping;
P_d	dynamic pressure;	SA_{fi}/TSA_{fi}	ratio of spectral acceleration of conditioned record to the target spectral acceleration at frequency f_i ;
P_m	maximum lateral seismic soil pressure;	SAH_{CAP}	horizontal spectral acceleration capacity;
P_s	static pressure;	SAH_{DEM}	horizontal input spectral acceleration demand;
P_t	total pressure;	$SAH_{DEM,E}$	horizontal input spectral acceleration demand at the elastic frequency and elastic damping;
P_v	hydrodynamic pressure due to vertical motion;	SA, SA_H, SA_V	spectral accelerations;
P_1, P_2	hydrodynamic pressure caused by impulsive and sloshing modes; impulsive pressure and convective pressure in tank due to vertical excitation;	SA_{H_1}, SA_{H_2}	10%-damped spectral accelerations for each of the two orthogonal horizontal components;
\bar{P}	nonexceedance probability;	S_{all}	longitudinal stress in the pipe due to other than seismic inertia load;
$p(y)$	normalized soil pressure distribution;	S_{Amax}	highest spectral acceleration in the interval between the highest target frequency and the frequency at the ZPA;
Q	generalized force;	SA_{VH}	horizontal 10%-damped vector spectral acceleration;
$Q_d W$	zero-displacement intercept;	$SA_{VH,E}$	vector horizontal spectral acceleration demand at the elastic frequency;
Q_y	yield force;	S_{a_v}	vertical spectral acceleration of the tank base at the vertical liquid response mode natural frequency;
R	length from base corner to center of gravity = $[b^2 + h^2]^{1/2}$; combined response due to the three orthogonal components of earthquake motion; radius of circular basemat; tank radius; total response of parameter of interest;	S_{a1}	spectral acceleration at the fundamental impulsive mode;
R_C	overall median conservatism ratio associated with the acceptance criteria;	S_{a2}	spectral acceleration at the fundamental sloshing mode;
R_D	median conservatism ratio associated with seismic demand defined in accordance with ASCE/SEI 43-05; spherical dome segment radius;	$S_{ii}(\omega), S_{jj}(\omega)$	auto PSD functions of the motions at locations i and j ;
R_{Ii}, R_{Ij}	response for the I th component of motion; maximum probable response obtained by response-spectrum analysis of i th (j th) mode of vibration due to excitation of I th direction (= 1, 2, 3);	$S_{ij}(\omega)$	cross-PSD between the motions at locations i and j ;
R_i	contribution to the response parameter of interest caused by the i th component of seismic input;	SF_{yield}	safety factor against yield in tank wall;
R_N	median nonlinear factor ratio;	S_m	stress intensity;
R_p	response modification factor;	S_p	maximum longitudinal pressure stress;
R_S	median conservatism ratio associated with component strength defined in accordance with ASCE/SEI 43-05;	S_{peak}	peak spectral acceleration in gravity unit from the DRS or ISRS;
		S_{STD}	deterministic estimate of component strength defined in accordance with ASCE/SEI 43-05;
		S_t	code allowable stress when design basis seismic inertia stresses are included;
		S_u	specified minimum ultimate stress;
		S_v	spectral velocity;
		S_y	specified minimum yield stress;
		S_{vmax}	maximum spectral velocity;
		$S(f, \lambda)$	response spectra (function of frequency and damping);
		$S(\omega)$	one-sided PSD;

$S_{50\%}$	median estimate of component strength;	W_c	concentrated weight on pipe span;
s	second;	W_e	effective flange width;
$T(\omega)$	transfer function for the structure at circular frequency ω ;	W_p	unit weight of pipe;
$T(\omega_k)$	transfer function for the structure at circular frequency of interest ω_k ;	W_s	tank shell weight;
$[T_r]_i$	connectivity matrix between the rigid-body motions about the base coordinates and the free degrees of freedom of the subsystem;	W_T	total liquid weight;
t	time; cylindrical tank wall thickness;	W_1, W_2	effective liquid impulsive and sloshing weights;
t_m	equivalent strong motion duration;	w_c	unit weight of concrete;
$\{U_b\}$	vector indicating direction of ground acceleration with respect to global coordinates;	X, Y	two acceleration time series;
$\{U_o^*\}$	foundation input motion;	$\{X\}$	relative displacement vector;
$\{U_{sc}\}$	secondary system influence matrix consisting of one influence vector for each connecting degree of freedom, c . The influence vector for a connecting degree of freedom is the displacement vector of the secondary system when the particular degree of freedom undergoes a unit displacement;	$\{\dot{X}\}$	relative velocity vector;
u	displacement;	$\{\ddot{X}\}$	relative acceleration vector;
\ddot{u}_g	ground or base acceleration;	\bar{X}_i, \bar{Y}_i	coordinates of i th wall or column elements;
$\ddot{u}_g(\omega)$	Fourier transform of the ground acceleration time history; $\ddot{u}_g(t)$;	X_{cr}, Y_{cr}	coordinates of center of rigidity;
$\{\ddot{u}_g\}$	basin acceleration time history;	X_s	height to the centroid of the tank shell;
u_y	yield displacement for LR and FP bearings;	$\{X_o\}$,	residual rigid response;
V	wall shear; static equivalent load (force); peak ground velocity;	$\{X_o(max)\}$	
V_c	nominal concrete shear capacity; compressive wave velocity (ft/s)	X_1, X_2	height above the base of the tank to the centroid of the impulsive and sloshing weights neglecting bottom pressure effects;
V_p	compression wave velocity; coefficient of variation;	X'_1, X'_2	height above the base to the centroid of impulsive and sloshing weights including bottom pressure effects;
V_s	shear wave velocity; average shear wave velocity of the soil column over the embedment height of the wall;	x	width of the basemat in contact with the soil;
V/H	ratio of vertical to horizontal spectral response;	x_1, x_2	horizontal axis;
v	peak velocity of the ground motion;	\ddot{x}, \ddot{y}	parameters defined in Section C3.6.2;
v_{max}	maximum ground velocity;	$\{Y\}$	horizontal and vertical input accelerations;
W	actual width of flange; weight of SSC, or total hanger weight; effective seismic weight of the SSC; weight of wedge; reactive weight of the structure above the isolation surface;	Y_j	vector of normal, or generalized, coordinates ($m \times 1$);
		Y_r	generalized coordinate of the i th mode;
		y	point of application for the resultant force;
		Y	depth from top of fluid; normalized height ratio;
		z	horizontal axis;
		$z_{\alpha/2}$	distance from base of retaining structure;
			depth within a soil layer;
			number of standard deviations that corresponds to the confidence level of $\alpha/2$

DEFINITIONS

The following terms are defined for general use in this standard.

ACCELERATION TIME SERIES: A sequence of acceleration and time data pairs, typically representing the acceleration response in a single direction during an earthquake. (Informally known as a time history.)

ACCELEROGRAM: A representation (either recorded or modified recorded) of the acceleration of the ground during an earthquake. The accelerogram contains acceleration and time data pairs.

APPARENT WAVE PROPAGATION VELOCITY: The apparent propagation velocity of seismic waves through the ground relative to a fixed local coordinate system.

BASEMAT: In the context of seismically isolated structures, the basemat is a thick reinforced concrete diaphragm immediately above the isolation system.

CLEARANCE TO THE STOP: The maximum horizontal distance between the superstructure of a seismically isolated structure and the stop, which can be no less than the 90th percentile displacement for 150% DBE shaking.

COMPETENT SOIL: Any natural or improved soil that has a low-strain shear wave velocity, $V_s > 1,000$ ft/s (300 m/s).

COUPLED: A descriptive term for mathematical models of structures and components that are interconnected and, because of their coupling, influence the dynamic response of each other.

CUTOFF FREQUENCY: The highest frequency used in the dynamic analysis of the structure or the soil-structure system.

DESIGN BASIS EARTHQUAKE (DBE): The description of the ground motion, defined in terms of the DRS, to be used for design.

DESIGN (OR EVALUATION) GROUND ACCELERATION: The value of the acceleration that corresponds to acceleration at zero period in the design ground-response spectrum.

DESIGN (OR EVALUATION) RESPONSE SPECTRUM (DRS): A smooth response spectrum of the input motion at the foundation level that can be used for either design or evaluation.

DISTRIBUTION SYSTEM: A system (i.e., collection of components) whose function is to distribute material/data (fluid, signals, power). Examples are piping, cable trays, conduit, and HVAC systems.

DOMINANT FREQUENCY: The frequency associated with maximum modal mass in each direction. Frequencies having a modal mass equal to 20% or more of the total structural mass are considered dominant.

DOMINANT RESPONSE PARAMETER: The response mode of the structural component with the largest contribution to deflection. For example, shear is the dominant response parameter for a squat shear wall [aspect ratio (height/length) less than 2].

DOMINANT SEISMIC WAVE (P, S, Love, Rayleigh): The type of seismic wave that dominates the local site response. The dominant seismic wave is site dependent.

DYNAMIC LATERAL EARTH PRESSURE: Lateral soil pressure induced by dynamic movements of the soil and structure (such as earthquakes); dynamic soil pressure can be either active or passive.

EQUIVALENT HORIZONTAL STIFFNESS: The value of the lateral force in a seismic isolation system, or an element thereof, divided by the corresponding lateral displacement; also termed secant stiffness.

EQUIVALENT VISCOUS DAMPING RATIO: The value of equivalent viscous damping corresponding to energy dissipated during cyclic response of a seismic isolation system.

FINISHED GRADE: The top of the ground surface at a site after cut or fill operations have been completed.

FOUNDATION: In the context of a seismically isolated structure, a foundation is a reinforced concrete foundation, including pedestals, that supports the isolators.

FREE FIELD: As used in soil-structure interaction analysis, the free-field response (acceleration, velocity, displacement) is the site response in the absence of structure.

FREE-FIELD GROUND SURFACE: Ground surface that is sufficiently distant from the site to be essentially unaffected by the vibration of site structures.

GEOMETRIC MEAN: An averaged horizontal spectral acceleration calculated frequency by frequency as the square root of the product of the spectral accelerations along orthogonal axes.

GRADED APPROACH: A process by which the level of analysis, documentation, and actions necessary to comply with requirements are commensurate with

- The relative importance to safety, safeguards, and security and of radiological and nonradiological hazards;
- The magnitude of any hazard involved;
- The life cycle stage of a facility;
- The programmatic mission of a facility;
- The particular characteristics of a facility; and
- Any other relevant factor.

GROUND MOTION HISTORY: A set of three orthogonal acceleration time series, typically two horizontal and one vertical, that represents the acceleration response of the ground during an earthquake. A ground motion history may be defined at the surface or at depth.

HIGHEST TARGET FREQUENCY: The highest frequency in the frequency range of interest that must be adequately represented in the dynamic solution of the structure or the soil-structure system.

IN-STRUCTURE RESPONSE SPECTRA (ISRS): The response spectra generated from the dynamic response of the structure at selected locations in a structure. In-structure response spectra are used for design of systems and components supported within a structure.

ISOLATION INTERFACE: In the context of seismically isolated structures, the isolation interface is the interface between the isolated superstructure and the supporting (nonisolated) foundation.

ISOLATION SYSTEM: In the context of a seismically isolated structure, the isolation system is the collection of structural elements that includes all individual isolator units, all structural elements that transfer force between elements of the isolation system, and all connections to other structural elements. The isolation system also includes structural elements that provide restraint of the seismic-isolated structure for wind loads.

ISOLATION SYSTEM EFFECTIVE DAMPING: In the context of seismic isolation systems, the isolation system effective damping is the equivalent viscous damping based on isolator hysteretic damping and corresponds to the energy dissipated during cyclic response of the isolation system. Such isolators are modeled with a linear spring and dashpot.

ISOLATOR UNIT: In the context of seismic isolation systems, an isolator unit is a horizontally flexible and vertically stiff structural element of the isolation system that permits large lateral deformations under design seismic load. An isolator unit may be used either as part of, or in addition to, the weight-supporting system of the structure.

LATERAL ACTIVE EARTH PRESSURE: Soil pressure that may be exerted by the soil that is in extension. The limiting active soil pressure is such that the soil expands outward to the point of reaching the limiting strength (shear failure) of the soil in extension. It represents the minimum lateral soil pressure.

LATERAL AT-REST EARTH PRESSURE: Soil pressure that may be exerted in a horizontal plane by the in situ soil that is not subject to either extension or compression.

LATERAL PASSIVE EARTH PRESSURE: Lateral soil pressure that may be exerted by the soil that is externally forced into compression. The limiting passive soil pressure is such that the soil is externally forced to the limiting strength (shear failure) of the soil in compression. It represents the maximum lateral soil pressure.

LICENSED PROFESSIONAL ENGINEER: An individual who is registered or licensed to practice his/her respective engineering profession as defined by the statutory requirements of the professional registration laws of the state or other governing body having jurisdictional authority.

LIMIT STATE (LS): The limiting acceptable condition of the structure, system, or component. The limit state may be defined in terms of a maximum acceptable displacement, strain, ductility, or stress. Four limit states are defined in ASCE 43-05 for nuclear safety-related SSCs.

LOAD PATH: The path of resistance consisting of structural or nonstructural members that the imposed load will follow from the point of origin (inertial forces at location of structure mass) to the point of final resistance (e.g., supporting soil).

MEAN ANNUAL HAZARD EXCEEDANCE FREQUENCY: The expected annual probability of exceedance. This value is used to determine earthquake acceleration from seismic hazard curves.

MOAT or ISOLATION GAP: In the context of a seismically isolated structure, the moat or isolation gap is the width around the perimeter of the isolated superstructure in which the superstructure can move without restriction. The width is defined by the clearance to the hard stop.

MULTISTEP METHOD: A method of structural analysis that involves calculating intermediate results in the first step and using these results as input to subsequent steps.

NONREACTOR NUCLEAR FACILITY: Facilities that contain activities or operations that involve radioactive and/or fissionable materials in such form and quantity that a nuclear hazard potentially exists to the employees, the general public, or the environment. Included are activities or operations that

- Produce, process, or store radioactive liquid or solid waste, fissionable materials, or tritium;
- Conduct separations operations;
- Conduct irradiated materials inspection, fuel fabrication, decontamination, or recovery operations;
- Conduct fuel enrichment operations; and/or
- Perform environmental remediation or waste management activities involving radioactive materials.

Linear accelerators and targets are considered nonreactor nuclear facilities. Incidental use and generation of radioactive materials in a facility operation (e.g., check and calibration sources and use of radioactive sources in research, experimental,

and analytical laboratory activities, electron microscopes, and x-ray machines) would not ordinarily require the facility to be included in this definition.

NUCLEAR FACILITY: Includes both reactor and nonreactor facilities.

ONE-STEP METHOD: In contrast to the previously defined multistep method, the one-step method is a method of structural analysis that is a single, self-contained analytical technique.

PEAK GROUND ACCELERATION (PGA): The maximum absolute value of a component of accelerogram history.

PEAK SPECTRAL ACCELERATION: The peak acceleration in an acceleration response spectrum.

PEER REVIEW: A formal review process in which an external party reviews the methodology, results, and process by which a design is developed or an evaluation is carried out. The external party shall be independent of project schedule and budget constraints.

PERFORMANCE-BASED DESIGN MOTIONS: Seismic motions (e.g., response spectra, ground motion histories, etc.) developed through probabilistic methods with the intent of providing a level of seismic input consistent with a performance goal.

RIGID: A descriptive term for structures or components whose fundamental frequency is equal to or greater than the rigid (ZPA) frequency.

RIGID FREQUENCY: The lowest frequency at which the spectral acceleration becomes practically independent of frequency and damping (and is approximately equal to the ZPA).

SEISMIC DEMAND: The demand imposed on the structure, system, or component being evaluated at the earthquake level under consideration. The seismic demand may be expressed in terms of force, moment, stress, displacement, rotation, or strain.

SEISMIC DESIGN BASIS (SDB): The combination of seismic design category (1, 2, 3, 4, or 5) and limit state (A, B, C, or D) that determines the design basis earthquake and acceptance criteria for designing SSCs. For example, Seismic Design Basis 3C would use criteria given in this standard for Seismic Design Category 3 and Limit State C.

SEISMIC DESIGN CATEGORY (SDC): A category assigned to an SSC that is a function of the severity of adverse radiological and toxicological effects of the hazards that may result from the seismic failure of the SSC on workers, the public, and the environment. SSCs may be assigned to seismic design categories that range from 1 to 5. For example, a conventional building whose failure may not result in any radiological or toxicological consequences is assigned to Seismic Design Category 1; a safety-related SSC in a nuclear-material-processing facility with a large inventory of radioactive material may be placed in Seismic Design Category 5. In this standard, the term *seismic design category* has a different meaning than it has in the International Building Code.

SIGNIFICANT: As used in this document, the term *significant* involves the use of engineering judgment, but a general rule is that when a quantitative response goal is met within 10%, the difference is not significant.

SPECTRA: Various definitions of spectra are used in soil-structure interaction and structural response analyses. These include

- **CERTIFIED SEISMIC DESIGN RESPONSE SPECTRA (CSDRS):** For standard nuclear power plants, CSDRS are site-independent seismic design response spectra that have been approved under Subpart B, "Standard Design Certifications," of Title 10, Part 52, "Early Site Permits: Standard Design Certifications; and Combined Licenses for

Nuclear Power Plants,” of the Code of Federal Regulations (10 CFR Part 52) as the seismic design response spectra for certified standard design nuclear power plants. CSDRS are used for design of the standard power plants for a range of soil profiles adopted for the generic design.

- **FOUNDATION INPUT RESPONSE SPECTRA (FIRS):** FIRS are the site-specific performance-based design response spectra characterized by horizontal and vertical spectra at the foundation level of the structure in the free field. For some nuclear structures, a minimum requirement for FIRS must be maintained. Development of FIRS shall be consistent with Chapters 2 and 5 of this standard, and the SSI modeling must account for the soil properties beneath and around the structures.
- **PERFORMANCE-BASED SURFACE RESPONSE SPECTRUM:** A site-specific performance-based response spectrum defined at the free surface and developed using probabilistic procedures similar to the development of FIRS.

SPECTRAL ACCELERATION (SA): The maximum acceleration response of a single-degree-of-freedom oscillator with a known frequency, f , and viscous damping, β , subjected to a prescribed forcing function or earthquake ground motion time history.

STOP: In the context of a seismically isolated structure, a stop is a structure, or series of structures, designed to prevent excessive displacement of the isolation system. A moat wall could serve as a hard stop.

STRUCTURE, SYSTEM, AND COMPONENT (SSC): A structure is an element, or a collection of elements, to provide support or enclosure, such as a building, free-standing tanks, basins, dikes, or stacks.

A system is a collection of components assembled to perform a function, such as piping, cable trays, conduits, or HVAC.

A component is an item of mechanical or electrical equipment, such as a pump, valve, or relay, or an element of a larger array, such as a length of pipe, elbow, or reducer.

SUPERSTRUCTURE: In the context of a seismically isolated structure, the superstructure is composed of all structural elements above the isolation system (e.g., slabs, beams, columns, and walls). For a conventional light-water reactor, the structural framing includes primary and secondary containment, internal structure to support the power generation and safety-related components and systems, and the basemat (or diaphragm) immediately above the isolation system.

UMBILICALS: In the context of seismically isolated structures, umbilical lines are nonstructural components and systems, mainly distribution systems, that cross the isolation interface and sustain the large isolator displacements (or deformations) associated with design basis and beyond design basis earthquake shaking. Examples of umbilical lines could include high-pressure steam lines from the power reactor to the turbines and cables located on trays or in ducts from emergency power systems located off the nuclear island to the power reactor.

UNIFORM HAZARD RESPONSE SPECTRA (UHRS): Response spectra derived so that the annual probability of exceeding the spectral quantity (acceleration, displacement, etc.) is the same for any spectral frequency.

WAVE INCOHERENCY: A term describing variation of horizontal and vertical ground motion due to differential arrival time of the seismic waves and heterogeneous nature of the medium beneath the foundation.

ZERO-PERIOD ACCELERATION (ZPA): The response-spectrum acceleration in the rigid range of the spectrum, typically at and above 33 Hz, which is equal to the maximum absolute value of the corresponding acceleration time series.

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CHAPTER 1

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. The standard provides methods for calculating seismic responses in structures and for deriving input motions for use in the seismic design and qualification of electrical and mechanical systems and components.

The purpose of the analytical methods is to provide reasonable levels of conservatism to account for uncertainties. The following areas for deterministic seismic analyses contain conservatism:

1. The spectra of acceleration histories used in analysis envelop the design response spectra, thus introducing some level of conservatism.
2. For soil-structure interaction, a minimum of three soil cases are analyzed using a range of soil properties, and the results are enveloped.
3. For in-structure response spectra, the peaks are broadened.
4. For structural damping, generally conservative values are specified.
5. The use of response-spectrum analysis and equivalent static methods generally results in conservative demand estimates.

For certain special structures covered in Chapters 7–12 of this standard, added conservative assumptions are incorporated into the analysis process to account for highly variable physical properties and analysis parameters. The goal of the added conservatism is to preclude underestimation of response that may lead to unacceptable behavior.

Given the seismic design response spectra, the goal of the standard is to develop seismic responses with 80% probability of nonexceedance. For probabilistic seismic analyses, the response with 80% probability of nonexceedance is selected.

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, vertical liquid storage tanks, distribution systems, anchored and unanchored components, 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 precludes the use of these structures and structural elements.

1.1.2.2 Foundation Material Stability. The analysis procedures provided herein assume that the foundation media adequately support the structures analyzed 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 analysis prescribed herein shall be combined with responses due to nonseismic loads.

1.1.3.2 Use of ASCE 4 with Other Codes and Standards. This standard provides criteria for determining the response of structural elements in new facilities when subjected to earthquake ground motion. The standard is to be used in conjunction with other national consensus standards for producing reliable structural, system, and component designs. ASCE/SEI 43 (ASCE 2005), “Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities,” presents design criteria for new nuclear facilities using the concept of seismic design bases (SDBs) defined by different seismic design categories (SDCs) and limit states associated with a graded approach. The SDC is used to set the design earthquake levels. The limit state is used to set the analysis methodology, design procedures, and acceptance criteria.

ANSI/ANS 2.26 (ANSI/ANS 2004; R2010), “Categorization of Nuclear Facility Structures, Systems, and Components for Seismic Design” and associated standards ANSI/ANS 2.27 (ANSI/ANS 2008b), “Site Characterization Requirements for Natural Phenomena Hazards at Nuclear Facilities Sites,” and ANSI/ANS 2.29 (ANSI/ANS 2008a), “Probabilistic Analysis of Natural Phenomena Hazards at Nuclear Facilities Sites,” provide criteria for selecting the SDC and limit state that establish the SDB for each structure, system, and component (SSC) at the facility. A numerical target performance goal is associated with each SDC. Performance goals are expressed as the mean annual probability of exceedance of the specified limit state of structures and equipment. The deformation limits associated with each limit state are prescribed in ASCE/SEI 43 (ASCE 2005).

1.1.3.3 Alternative Methodologies. Techniques other than those specified in this standard, including experience gained from earthquakes, special analyses, and testing, may be used in lieu of the requirements specified herein. These methods must be shown to provide seismic design input to the SSCs that is at the 80% nonexceedance level. Alternative methodologies shall be properly substantiated.

1.2 SEISMIC QUALITY PROVISIONS

The seismic analysis of nuclear structures covered by this standard will be performed under the purview of the U.S. Department of Energy (DOE) or the U.S. Nuclear Regulatory Commission (USNRC). The DOE and USNRC have regulatory quality assurance (QA) requirements that are applicable throughout the design activities, including seismic analysis. Verification