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CHAPTER C1
INTRODUCTION

C1.3 SEISMIC DESIGN CRITERIA

The objective of this standard is to provide design criteria, which when properly implemented in design and construction, produce seismically robust structures, systems, and components (SSCs). Seismically robust structures, systems, and components safeguard against the accidental release of nuclear material to the workers, the public, and the environment. The criteria focus on cast-in-place reinforced concrete and structural steel systems. The construction details required for these structural systems, according to referenced materials standards such as ACI 349 (ACI 2013b) and AISC N690 (AISC 2018), should ensure seismic ruggedness with a high degree of reliability. This design standard should be read in conjunction with ASCE 1 (ASCE 1982), ASCE 4 (ASCE 2016b), and other codes and standards referenced herein.

Requirements for structural systems with a demonstrated poor seismic performance record, such as unreinforced masonry or precast concrete using conventional gravity connections, have been purposely omitted from this standard and should not be used in the primary seismic load path.

The criteria presented in this standard do not discourage the use of any structural system with reliable seismic performance. Guidance is provided (in Section 1.5 and in the commentary) to develop criteria for seismically rugged structural systems not discussed herein that ensure the same degree of safety as those structural systems explicitly addressed.

This standard prescribes design criteria that are graded according to tolerable risk. Those SSCs whose failure results in more serious undesirable consequences to the facility workers, the public, or the environment are designed for more stringent criteria, as measured by seismic design category (SDC) and limit state (LS), as defined in ANS 2.26 (ANS 2017) and as described in this commentary. Four of the five SDCs identified in ANS 2.26 are considered in this standard: SDC 2, SDC 3, SDC 4, and SDC 5, as listed in Table 1-1. All four of the limit states identified in ANS 2.26 are considered in this standard, LS A, LS B, LS C, and LS D, as listed in Table 1-2.

The seismic performance of an individual SSC is defined by two measures that together form a seismic design basis (SDB): a qualitative description of the acceptable level of damage, and a quantitative annual frequency that damage will exceed the acceptable level.

The qualitative description of acceptable damage is referred to as an LS. The four LSs are reproduced from ANS 2.26 in Table 1-2 and range from A (significant damage) to D (negligible damage). Design loads in Chapters 5 and 8 and deformation limits in Chapter 5 are used to limit SSC damage to the degree associated with the assigned LS. Components, equipment, and distribution systems assigned lower tolerable damage are designed for higher seismic loads. Structural systems with lower tolerable damage should satisfy more stringent (smaller) criteria for drift ratios (Table 5-2) and plastic hinge rotations (Table 5-3) than those assigned higher tolerable damage.

For each SSC, the maximum annual frequency of seismic damage exceeding the limit state is the target performance goal (P_F). Table 1-1 presents performance goals for SDC 2 (4×10^{-4}) through SDC 5 (1×10^{-5}). Design basis earthquake (DBE) shaking is defined for each SDC. Chapter 2 presents criteria to define DBE shaking. The frequency of exceeding an LS is a function of fragility, seismic hazard, and the rate of change of the hazard. Limit state exceedance frequency is calculated by integrating a fragility curve over the derivative of a seismic hazard curve, where the two curves share the same abscissa (e.g., spectral acceleration at 5 Hz). Rigorous modern probabilistic seismic hazard results, including the maps prepared by the US Geological Survey (USGS), indicate that the rate of change of ground motion intensity versus exceedance frequency is not constant throughout the United States. As a consequence, design to a prescribed ground motion hazard would result in varying LS exceedance probabilities at different locations for SSCs with an identical fragility. Figure C1-1 plots the 2014 USGS 5 Hz spectral acceleration versus the annual frequency of exceedance for sites with a near-surface shear wave velocity of 760 m/s (2,490 ft/s). The curves have been normalized at 2% probability of exceedance in 50 years. Figure C1-1 shows that the slope of the hazard curve, and therefore the frequency of exceedance of an LS, varies across the country. For instance, in coastal California (e.g., at SLAC National Accelerator Laboratory in Menlo Park), the ratio of the spectral acceleration associated with a 10-fold increase in hazard ranges from about 1.5 to 3.5, whereas in the Central and Eastern United States (e.g., Oak Ridge, Tennessee) those ratios range from 2.5 to 5.

Seismic performance can be improved by decreasing the level of allowable damage (LS), by decreasing the annual frequency of exceeding that damage (P_F), or by some combination of the two. For instance, a structure to be designed to have an annual probability of 4×10^{-5} (SDC 4) of suffering damage that exceeds limited permanent distortion (LS C) would be assigned SDB 4C. The expected performance could be improved by changing the LS to D (the structure remains essentially elastic) or by changing the exceedance probability to 1×10^{-5} (SDC 5). In this standard, the most stringent seismic requirements are associated with SDB-5D, and the least stringent are associated with SDB-2A.

The performance goals of Table 1-1 represent the annual frequency of unacceptable performance (as defined by its LS) for each safety-related SSC. As such, these SSC-specific performance goals cannot be compared with performance goals (e.g., collapse prevention or life safety) for commercial (nonnuclear) buildings. Importantly, the performance goal of 4×10^{-4} for an

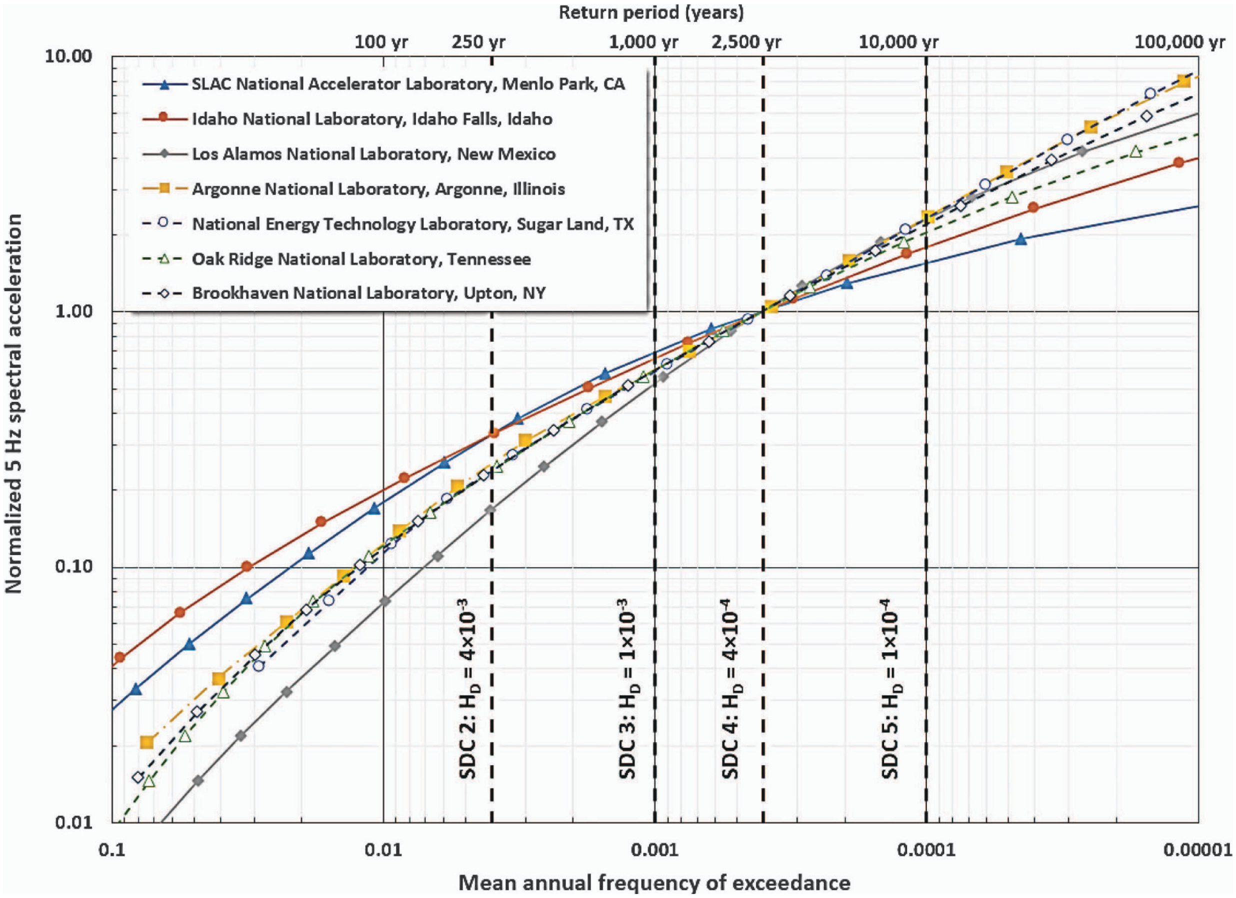

Figure C1-1. Normalized 5 Hz spectral acceleration at selected US DOE sites.

SDC 2 SSC in this standard cannot be compared to the building-level collapse prevention goal of ASCE 7.

Chapter 2 of this standard provides a method to define DBE response spectra. Load effects on SSCs are calculated by analysis of a building model according to ASCE 4 for the seismic demands of Chapter 2, as modified by inelastic energy absorption factors, according to Chapters 5 and 8. Detailing according to the requirements of the referenced materials standards, as modified by Chapter 6, should enable an SSC to achieve its seismic design basis.

C1.4 INTEGRATION OF OTHER CODES AND STANDARDS WITH ASCE 43

Specific ANS standards that address seismic design of SSCs in nuclear safety-related facilities are the following:

- ANSI/ANS 2.26-R2017 (ANS 2017), *Categorization of Nuclear Facility Structures, Systems, and Components for Seismic Design* provides guidelines and criteria for selecting SDCs and limit states, which are inputs to this standard. ANSI/ANS 2.26 identifies five SDCs (SDC 1 to SDC 5) based on the importance of the consequences of failure and defines four limit states (A to D) based on damage and ability to perform safety function(s). ANSI/ANS 2.26 uses a graded approach to ensure that the level of conservatism and rigor in design is appropriate for facility characteristics, such as hazards to workers, the public, and the environment. The combination of SDC and limit state defines the seismic design basis (SDB) for each SSC. Thus, an SSC with SDB-3C would use criteria for SDC 3 and Limit State C. A total of 20 SDBs are defined in ANS 2.26 that can match seismic design criteria to SSC safety function and importance, implementing a graded approach.

  The seismic design criteria and methods specified in this standard (ASCE 43), however, are intended to achieve the same performance goals given in ANS 2.26-R2017 for SDC 3 through SDC 5. Both ANS 2.26 and the previous version of this standard defer seismic design of SDC 1 and SDC 2 SSCs to the International Building Code, which in turn points to ASCE 7 (ASCE 2016a). This standard now includes design provisions for SDC 2 SSCs using a newly introduced performance goal and the associated seismic design criteria. This standard (ASCE 43) does not discuss or provide seismic design criteria for SDC 1 SSCs.
- ANSI/ANS 2.27-R2016 (ANS 2016a), *Criteria for Investigations of Nuclear Facility Sites for Seismic Hazard Assessments* provides requirements and recommended practices for conducting site-specific investigations and acquiring data sets needed to characterize seismic sources for probabilistic seismic hazard analysis. The data sets provide information for site response and soil–structure interaction analyses needed for design of nuclear facilities. It requires site investigations "in sufficient scope and detail necessary to support the evaluations required by ANSI/ANS-2.29 and ASCE 43-05 and to support the objectives of ANSI/ANS-2.26." Accordingly, it provides guidance for selecting different levels of site investigation based on the highest SDC of SSCs at the site and using a graded approach.

- ANSI/ANS 2.29-R2016, *Probabilistic Seismic Hazard Analysis* (ANS 2016b) establishes requirements for performing these calculations. Like ANSI/ANS 2.27, it requires the use of a graded approach and provides guidance for the selection of a degree of complexity for the hazard analysis. Additional requirements and guidance have been provided in this standard (ASCE 43) for performing site-specific probabilistic seismic hazard analysis, site response analysis, and for establishing uniform hazard response spectra (UHRS).

Standards used in the seismic design of nuclear safety-related structures include the following:

- ASCE 1, *Guidelines for Design and Analysis of Nuclear Safety-Related Earth Structures* (ASCE 1982) provides criteria and guidelines to be used in construction of earth structures forming part of the ultimate heat sink or acting to protect nuclear power plant sites from flood, storm surge, or other types of natural or artificial external load phenomena.
- ASCE 4, *Seismic Analysis of Safety-Related Nuclear Structures* (ASCE 2016b) provides minimum requirements and acceptable methods for the seismic analysis of a nuclear facility. ASCE 4 also provides a methodology for calculating seismic response in structures and to derive input motions for use in the seismic design qualification of electrical and mechanical systems and components located in or supported by buildings or other civil structures.
- ASCE 7, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures* (ASCE 2016a) provides minimum design load requirements and procedures to determine the effects of loads for the design of buildings and other civil structures, as well as mechanical and electrical distribution systems and components.

Other codes and standards used in the seismic design of nuclear safety-related structures include the following:

- ACI 349, *Code Requirements for Nuclear Safety-Related Concrete Structures and Commentary* (ACI 2013b) addresses the design and construction of concrete structures that form part of a nuclear safety-related facility. These facilities include concrete structures inside and outside a nuclear reactor containment system, but not concrete reactor vessels or their concrete containment structures (which are defined in a Joint ACI-ASME Committee 359 Code, ACI 2015). ACI 349 is based on ACI 318 (ACI 2014) except that (a) it includes loads and load combinations applicable to nuclear structures, and (b) some of the prescriptive details of ACI 318 for special systems are relaxed in recognition of the smaller nonlinear demands placed on nuclear structures.
- ASME, *Boiler and Pressure Vessel Code*, Section III, "Rules for Construction of Nuclear Facility Components" (ASME 2019a).
- ANSI/AISC N690 2018, *Specification for Safety-Related Steel Structures in Nuclear Facilities* (AISC 2018) applies to the construction of safety-related nuclear steel structures. This specification includes design loads, load combinations, and requirements for treatment of impact and impulse loads; it is otherwise compatible with ANSI/AISC 360 2016, *Specification for Structural Steel Buildings* (AISC 2016c). Only those sections that differ from the ANSI/AISC 360 specification provisions are included in the N690 specification.

Codes and standards used in the design and seismic qualification of mechanical and electrical equipment and distribution systems and components are identified in Chapter 8 of this standard and its associated commentary.

C1.5 ALTERNATIVE METHODS TO MEET THE INTENT OF THIS STANDARD

The DBE ground motion is defined in Equation (2-1) in terms of a design response spectrum (DRS). Structures whose elements are designed for DRS demands using design capacities derived in accordance with referenced materials standards, as modified in this standard, are expected to achieve the target performance goal listed in Table 1-1. The DRS is formulated to achieve both of the following:

1. Less than about a 1% probability of unacceptable performance for the DBE ground motion, and
2. Less than about a 10% probability of unacceptable performance for a ground motion equal to 150% of the DBE ground motion.

Alternative methods that achieve the target performance goal are acceptable.

Seismic fragility functions (i.e., conditional probabilities of unacceptable performance versus seismic demand) are typically assumed to be lognormally distributed so that they can be fully described by two terms: a median and an estimate of the composite variability, β [Equation (C1-11)], a logarithmic standard deviation. The median in this case is a seismic margin factor, $F_{PF=50\%}$, where F_{PF} is the ratio of the acceleration corresponding to a conditional failure probability PF to the DBE acceleration. Satisfying the two target levels of conservatism defined here results in the following seismic margin factors $F_{1\%}$, $F_{5\%}$, $F_{10\%}$, and $F_{50\%}$, corresponding to a 1%, 5%, 10%, and 50% conditional probability of unacceptable performance (i.e., failure), respectively:

β	$F_{1\%}$	$F_{5\%}$	$F_{10\%}$	$F_{50\%}$
0.30	1.10	1.35	1.50	2.20
0.40	1.00	1.31	1.52	2.54
0.50	1.00	1.41	1.69	3.20
0.60	1.00	1.50	1.87	4.04

For a logarithmic standard deviation less than 0.39, the second conditional failure probability controls. For β greater than 0.39, the first goal controls. By satisfying both goals, the following margins are achieved:

$$F_{1\%} \geq 1.0$$
$$F_{5\%} \geq 1.3$$
$$F_{10\%} \geq 1.5$$
$$F_{50\%} \geq 2.2$$

Factors of Safety Achieved by Seismic Acceptance Criteria

Introduction. In this standard, component design strengths are assumed, namely, component nominal strengths according to ACI and AISC multiplied by action-specific strength reduction factors (ϕ), and strength according to ASME Service Level D. Seismic demand is calculated according to ASCE 4, using the seismic hazard of Chapter 2 of this standard. Limit state–

dependent inelastic energy absorption factors can be implemented according to Chapters 5 and 8 to reduce seismic demands for actions associated with ductile response.

Estimation of Median Conservatism Introduced by Standard Seismic Acceptance Criteria. The median seismic capacity, $C_{50\%}$, can be estimated from

$$C_{50\%} = \frac{S_{50\%}}{D_{50\%}} F_{\mu 50\%} \text{DBE} \qquad \text{(C1-1)}$$

where

$S_{50\%}$ = Median estimate of the component's seismic strength,
$D_{50\%}$ = Seismic demand for DBE input, and
$F_{\mu 50\%}$ = Inelastic energy absorption factor.

The standard seismic capacity, C_{STD}, is given by

$$C_{\text{STD}} = \frac{S_{\text{STD}}}{D_{\text{STD}}} F_{\mu\text{STD}} \text{ DBE} \qquad \text{(C1-2)}$$

where

S_{STD} = Deterministic strength,
D_{STD} = Demand, and
$F_{\mu\text{STD}}$ = Nonlinear factors,

as defined in accordance with this standard. Defining R_S, R_D, and R_N as the median conservatism ratios associated with this standard,

$$S_{50\%} = R_S S_{\text{STD}}$$
$$D_{50\%} = D_{\text{STD}}/R_D$$
$$F_{\mu 50\%} = R_N F_{\mu\text{STD}} \qquad \text{(C1-3)}$$

and

$$C_{50\%} = R_C C_{\text{STD}} \qquad \text{(C1-4)}$$

$$R_C = R_S R_D R_N \qquad \text{(C1-5)}$$

where R_C is the overall median conservatism ratio associated with the acceptance criteria of this standard. The values of R_S, R_D, and R_N are estimated in the following three subsections.

Median Strength Conservatism Ratio. Based on a review of median capacities from past seismic probabilistic risk assessment studies with respect to US code-specified ultimate strengths for a number of failure modes, code *design* strengths have at least a 98% probability of exceedance for ductile failure modes if conservatisms for material strengths, empirical equations, and strain-rate effects are considered. For low-ductility failure modes such as out-of-plane shear in concrete walls and slabs, an additional 1.33 factor is applied to the 98th percentile capacity. This factor accounts for the additional margin provided by standards for the design strength of low-ductility failure modes. Accordingly,

$$\text{(Ductile)} \qquad R_S = e^{2.054\beta_S} \qquad \text{(C1-6)}$$

$$\text{(Low ductility)} \qquad R_S = 1.33e^{2.054\beta_S}$$

where β_S is the *strength* logarithmic standard deviation, typically in the range of 0.2 to 0.4, and 2.054 is the standard normal variate for a 2% nonexceedance probability (NEP).

Median Demand Conservatism Ratio. The goal of ASCE 4 is to calculate seismic demands with an 80% probability of nonexceedance conditioned on a design response spectrum. Analysis of multiple soil columns and enveloping the resultant spectra according to Chapter 5 of ASCE 4 is assumed to achieve the 80th percentile. The median demand ratio, R_D, can therefore be estimated as

$$R_D = e^{0.842\beta_D} \qquad \text{(C1-7)}$$

where β_D is the *seismic demand* logarithmic standard deviation for a specified seismic input, typically between 0.2 and 0.4 and 0.842 is the standard normal variate for a 20% NEP.

Median Nonlinear Conservatism Ratio. In this standard, the nonlinear factor is aimed at the 5% NEP level. For ductile failure modes such as flexure, the median nonlinear factor ratio, R_N, is

$$\text{(Ductile)} \qquad R_N = e^{1.645\beta_N} \qquad \text{(C1-8)}$$

where β_N is the logarithmic standard deviation for the *nonlinear* factor, typically between 0.2 and 0.4, and 1.645 is the standard normal variate for a 5% NEP.

For low-ductility (brittle) failure modes, no credit is taken for a nonlinear factor, namely,

$$\text{(Low ductility)} \qquad R_N = 1.0 \qquad \text{(C1-9)}$$

Capacity Conservatism. Combining Equations (C1-5) through (C1-8), the median capacity ratio, R_C, is

$$\text{(Ductile failures)} \qquad R_C = e^{2.054\beta_S + 0.842\beta_D + 1.645\beta_N} \qquad \text{(C1-10)}$$

$$\text{(Low ductility)} \qquad R_C = 1.33e^{2.054\beta_S + 0.842\beta_D}$$

and

$$C_{1\%} = R_C C_{\text{STD}} e^{-2.326\beta} \qquad \text{(C1-11)}$$

where β is a composite variability given by

$$\beta = [\beta_S^2 + \beta_D^2 + \beta_N^2]^{1/2} \qquad \text{(C1-12)}$$

The resulting nominal factor of safety, $F_{N1\%}$, against a 1% conditional probability of failure is

$$F_{N1\%} = \frac{C_{1\%}}{C_{\text{STD}}} = R_C e^{-2.326\beta} \qquad \text{(C1-13)}$$

and the nominal factor of safety, $F_{N10\%}$, against a 10% conditional probability of failure is

$$F_{N10\%} = \frac{C_{10\%}}{C_{\text{STD}}} = R_C e^{-1.282\beta} \qquad \text{(C1-14)}$$

Table C1-1 presents $F_{N1\%}$ for typical values of β_S, β_D, and β_N. Over this range of values,

$$F_{N1\%} \approx 1.0 \qquad \text{(C1-15)}$$

Table C1-1. Nominal Factor of Safety, $F_{N1\%}$.

Strength Variability (β_S)	Demand Variability (β_D)	Low-Ductility Failure Modes	Ductile Failure Modes $\beta_N = 0.2$	Ductile Failure Modes $\beta_N = 0.4$
0.2	0.2	1.23	1.11	1.10
	0.3	1.12	1.03	1.07
	0.4	1.00	0.94	1.01
0.3	0.2	1.26	1.17	1.21
	0.3	1.18	1.11	1.19
	0.4	1.08	1.03	1.13
0.4	0.2	1.27	1.20	1.29
	0.3	1.22	1.16	1.27
	0.4	1.14	1.10	1.23

with $F_{N1\%}$ ranging between 0.94 and 1.29, with a median value of 1.14. Table C1-2 presents $F_{N10\%}$ for typical values of β_S, β_D, and β_N. Similarly,

$$F_{N10\%} > 1.5 \tag{C1-16}$$

Accordingly, both performance statements 1 and 2 given in Section C1.5 are met.

Table C1-2. Nominal Factor of Safety, $F_{N10\%}$.

Strength Variability (β_S)	Demand Variability (β_D)	Low-Ductility Failure Modes	Ductile Failure Modes $\beta_N = 0.2$	Ductile Failure Modes $\beta_N = 0.4$
0.2	0.2	1.66	1.59	1.84
	0.3	1.63	1.59	1.88
	0.4	1.57	1.57	1.89
0.3	0.2	1.80	1.80	2.12
	0.3	1.82	1.82	2.18
	0.4	1.81	1.81	2.20
0.4	0.2	2.00	2.00	2.41
	0.3	2.04	2.04	2.49
	0.4	2.05	2.05	2.53