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American National Standard Criteria for Investigations of Nuclear Facility Sites for Seismic Hazard Assessments

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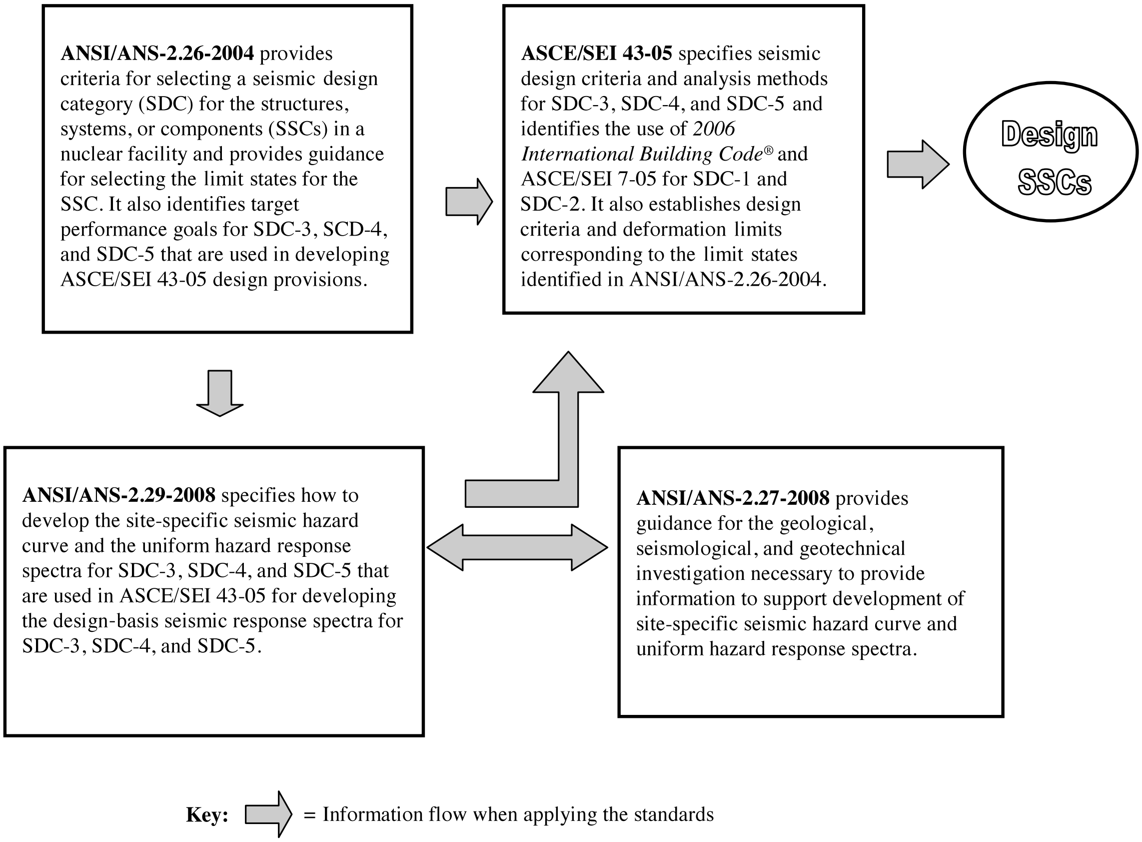
Foreword

(This Foreword is not part of American National Standard “Criteria for Investigations of Nuclear Facility Sites for Seismic Hazard Assessments,” ANSI/ANS-2.27-2008.)

This standard provides requirements and recommended practices for conducting investigations and acquiring data sets needed to characterize seismic sources for probabilistic seismic hazard analysis (PSHA). The data sets provide information for site response and soil-structure interaction analyses needed for design of those facilities. They also are used to evaluate fault rupture and associated secondary deformation and other seismically induced ground failure hazards (e.g., liquefaction, ground settlement, slope failure).

This standard is one of a group of four standards that establish requirements for the seismic design of nuclear facilities. The overall objective of these standards is to achieve a risk-informed design that protects the public, the environment, and workers from potential consequences of earthquakes. The other three standards are American National Standards Institute/American Nuclear Society ANSI/ANS-2.26-2004, “Categorization of Nuclear Facility Structures, Systems, and Components for Seismic Design”; ANSI/ANS-2.29-2008, “Probabilistic Seismic Hazards Analysis”; and American Society of Civil Engineers/Structural Engineering Institute ASCE/SEI 43-05, “Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities.” The procedural relationship among these four standards is shown in Fig. A.

The seismic design process for nuclear facilities is based on the consequences of seismic-initiated failure of structures, systems, and components (SSCs). The



ANSI/ANS-2.26-2004 provides criteria for selecting a seismic design category (SDC) for the structures, systems, or components (SSCs) in a nuclear facility and provides guidance for selecting the limit states for the SSC. It also identifies target performance goals for SDC-3, SCD-4, and SDC-5 that are used in developing ASCE/SEI 43-05 design provisions.

ASCE/SEI 43-05 specifies seismic design criteria and analysis methods for SDC-3, SDC-4, and SDC-5 and identifies the use of *2006 International Building Code*® and ASCE/SEI 7-05 for SDC-1 and SDC-2. It also establishes design criteria and deformation limits corresponding to the limit states identified in ANSI/ANS-2.26-2004.

ANSI/ANS-2.29-2008 specifies how to develop the site-specific seismic hazard curve and the uniform hazard response spectra for SDC-3, SDC-4, and SDC-5 that are used in ASCE/SEI 43-05 for developing the design-basis seismic response spectra for SDC-3, SDC-4, and SDC-5.

ANSI/ANS-2.27-2008 provides guidance for the geological, seismological, and geotechnical investigation necessary to provide information to support development of site-specific seismic hazard curve and uniform hazard response spectra.

Figure A – Schematic showing the relationships of the seismic standards

seismic design categories identified in ANSI/ANS-2.26-2004 and the design requirements specified in ASCE/SEI 43-05 satisfy target performance goals defined in terms of the annual probability of exceeding specified SSC performance limits. Achieving a target performance goal is directly related to the probability of occurrence of a seismic load that is beyond design specifications. ANSI/ANS-2.29-2008 establishes procedures for performing a PSHA needed to support selection of the seismic loads used in ASCE/SEI 43-05. This standard provides guidance for the geological and geotechnical investigations needed to provide information to support (a) seismic source characterization input to the PSHA, (b) evaluation of surface fault rupture hazards, (c) site response analyses, and (d) seismic-induced ground failure hazards.

This standard might reference documents and other standards that have been superseded or withdrawn at the time the standard is applied. A statement has been included in the reference section that provides guidance on the use of references.

Working Group ANS-2.27 of the ANS-25 Subcommittee to the Nuclear Facilities Standards Committee (NFSC) of the American Nuclear Society (ANS) had the following membership at the time of approval of this standard:

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1 Scope

This standard provides criteria and guidelines for conducting geological, seismological, and geotechnical investigations needed to provide information to support the following:

(1) seismic source characterization input to a probabilistic seismic hazard analysis (PSHA);

(2) evaluation of surface fault rupture hazard;

(3) site response analysis;

(4) seismic-induced ground failure hazard.

These criteria are applicable for Seismic Design Category (SDC)-3, SDC-4, and SDC-5 structures, systems, or components (SSCs).

This standard does not address the use of PSHA results or the selection of design-basis events for nuclear facilities. These topics are covered in American National Standards Institute/American Nuclear Society ANSI/ANS-2.26-2004, "Categorization of Nuclear Facility Structures, Systems, and Components for Seismic Design" [1][1] and American Society of Civil Engineers/Structural Engineering Institute ASCE/SEI 43-05, "Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities" [2].

> This standard is one of a series of national standards designed to provide criteria and guidelines to promote uniform and effective assessment of seismic hazards at nuclear facilities. These hazards must be properly identified and characterized commensurate with the level of risk and design requirements associated with each nuclear facility as specified in ANSI/ANS-2.26-2004 [1] and ASCE/SEI 43-05 [2]. As defined in ANSI/ANS-2.26-2004 [1], a nuclear facility is a facility that stores, processes, tests, or fabricates radioactive materials in such form and quantity that a nuclear risk to the workers, to the off-site public, or to the environment may exist. These include, but are not limited to, nuclear fuel manufacturing facilities; nuclear material waste processing, storage, fabrication, and reprocessing facilities; uranium enrichment facilities; tritium production and handling facilities; and radioactive materials laboratories. Additional criteria may be specified by the applicable regulatory authority.
>
> This standard outlines standard criteria and procedures to collect data needed as input to probabilistic analysis of seismic hazards at nuclear facilities as specified in ANSI/ANS-2.29-2008, "Probabilistic Seismic Hazards Analysis" [3]. Appropriate approaches are outlined to ensure that the current state-of-the-art methodology is being used in the site characterization. The selection of specific techniques and level of detail required to assess seismic and seismic-induced hazards is dependent on both the nature of the nuclear facility (i.e., SDC[2] as defined by ANSI/ANS-2.26-2004 [1]) and site-specific conditions.[3]

2 Acronyms and definitions

2.1 List of acronyms

ANS: American Nuclear Society

ANSI: American National Standards Institute

ASCE/SEI: American Society of Civil Engineers/Structural Engineering Institute

ASTM: American Society for Testing and Materials

BPT: Becker penetration test

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[1] Numbers in brackets refer to corresponding numbers in Sec. 5, "References."

[2] The SDCs used in this standard are not the same as the SDCs referred to in the International Building Code (IBC).

[3] In this standard, material that is double-indented indicates a commentary.

CEUS: Central and Eastern United States

CPT: cone penetration test

EPRI: Electric Power Research Institute

GPS: global positioning system

IBC: International Building Code

LiDAR: light detection and radar

MCE: maximum considered earthquake

NEHRP: National Earthquake Hazards Reduction Program

NRC: U.S. Nuclear Regulatory Commission

PGA: peak ground acceleration

PGV: peak ground velocity

PSHA: probabilistic seismic hazard analysis

QA: quality assurance

RQD: rock quality designation

SASW: spectral analysis of surface waves

SDC: seismic design category

SPT: standard penetration test

SSC: structure, system, or component

SSHAC: Senior Seismic Hazard Analysis Committee

SSI: soil-structure interaction

UHRS: uniform hazard response spectra

2.2 Definitions

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

aleatory variability: The variability inherent in a nondeterministic (i.e., stochastic, random) phenomenon (see “variability”). Aleatory variability is accounted for by modeling the phenomenon in terms of a probability model. In principle, aleatory uncertainty cannot be reduced by the accumulation of more data or additional information, but the detailed characteristics of the probability model can be improved. Sometimes aleatory variability is called “randomness.”

area source: An area of the earth’s crust that is assumed to have relatively uniform earthquake source characteristics for use in the PSHA. (See also “volumetric source zone.”)

background source zone: A part of the earth’s crust, usually of large areal dimension, within which potentially damaging earthquakes could occur that are not associated either with known fault sources or even with the uniform pattern, rate, or style of deformation or seismicity commonly identified with volumetric seismic source zones. In PSHA calculations, earthquakes that cannot be associated with other sources default to a background source zone.

blind fault: A blind fault is a fault that does not rupture all the way up to the surface and consequently does not have a surface trace. These features are usually associated with thrust faults, which are formed by compressive stresses. Blind thrust faults do not penetrate the uppermost layers of crust, but they cause the surface layers to fold over them as they deform, forming a telltale hill at the surface that reveals their presence to observers.

Central and Eastern United States (CEUS): That portion of the United States east of the Rocky Mountains (approximately the 104th parallel).

concealed fault: A fault that once ruptured to the earth’s surface but that has subsequently been buried by deposition of material atop the surface trace during the period between surface ruptures.

coseismic: A term that relates an area or occurrence of a phenomenon to the simultaneous arrival of earthquake waves.

epistemic uncertainty: Uncertainty attributable to incomplete knowledge about a phenomenon that affects the ability to model it. Epistemic uncertainty is captured by considering a range of model parameters within a given expert interpretation or multiple expert interpretations each of which is assigned an associated weight representing statistical confidence in the alternatives. In principle, epistemic uncertainty can be reduced by the accumulation of additional information associated with the phenomenon. The uncertainty in the parameters of the probability distribution of a random phenomenon is epistemic.

fault: A fracture in the earth along which blocks of crust on either side have moved with respect to one another.

fault source: A fault or zone for which the tectonic features causing earthquakes have been identified. These are usually individual faults, but they may be zones comprising multiple faults or regions of faulting if surface evidence of these faults is lacking but the faults are suspected from seismicity patterns, tectonic interpretations of crustal stress and strain, and other evidence. Regions of blind thrust faults are a good example of the latter.

hazard curve: Curve that gives the probability of a certain ground motion parameter [usually the peak ground acceleration (PGA), peak ground velocity (PGV), or response spectral values] being exceeded. Hazard curves are generally generated for periods of exposure of one year, and they give annual probabilities of exceedance.

Holocene: The geologic epoch referring to a period of time between the present and approximately 10 000 years before present. Applied to rocks or faults, this term indicates the period of rock formation or the time of most recent fault slip.

intraplate and interplate: Intraplate pertains to processes within the earth's crustal plates, while interplate pertains to processes at the interface between the plates.

kernel density: Kernel density estimation is a nonparametric approach to defining a probability distribution. It is created by centering a kernel density function (e.g., Gaussian distribution) at each data point, then summing and renormalizing these individual density functions to create the composite density function. The smoothness of the final composite density is controlled by the size of the individual kernel densities placed at each data point. Kernel density estimation is used in a seismic hazard evaluation to smooth the mapped distribution of past earthquakes that is used as a predictor of the spatial distribution for future earthquakes.

limit state: The limiting acceptable deformation, displacement, or stress that a structure, system, or component (SSC) may experience during or following an earthquake and still perform its safety function. Four limit states are identified and used by ANSI/ANS-2.26-2004 [1] and ASCE/SEI 43-05 [2].

liquefaction: The sudden loss of shear strength and rigidity of saturated, cohesionless soils, due to steady-state groundwater flow or vibratory ground motion. The term "seismic liquefaction" is used in this standard for liquefaction phenomena associated with seismic motions.

magnitude: A number that characterizes the size of an earthquake. It is related to the energy released in the form of seismic waves. Magnitude is based on measurement of the maximum motion recorded by a seismograph. Several scales have been defined, but the most commonly used are (a) local magnitude (M_L), commonly referred to as "Richter magnitude"; (b) surface-wave magnitude (M_S); (c) body-wave magnitude (m_b); and (d) moment magnitude (M_w or $\mathbf{M}$). Scales (a), (b), and (c) have limited range and applicability and do not satisfactorily measure the size of the largest earthquakes. The moment magnitude scale, based on the concept of seismic moment, is uniformly applicable to all sizes of earthquakes but is more difficult to compute than the other types. All magnitude scales yield approximately the same value for earthquakes of about magnitude 5, but for larger events, m_b, then M_L, and finally M_S progressively diverge and increasingly underestimate the size of the earthquake compared to M_w. It is important, therefore, to specify the magnitude scale being referenced, especially for larger earthquakes.

paleoseismic: Referring to the history of seismic events that is determined by looking at the layers of rock and soil beneath the surface or landforms at the surface and how they have been shifted by earthquakes that have occurred in the past.

piezometer: A nonpumping well generally of small diameter or device (tube or pipe) for measuring the elevation of a water table.

Pleistocene: The time period between ~10 000 years before present and ~1 800 000 years before present. As a descriptive term applied to rocks or faults, it marks the period of rock formation or the time of most recent fault slip, respectively.

probabilistic seismic hazard analysis (PSHA): A procedure used to develop seismic hazard curves and uniform hazard response spectra for determining the ground motion at a site to be used for seismic design. Aleatory variability and epistemic uncertainty are captured in a PSHA. Criteria and guidance for conducting a PSHA are provided in ANSI/ANS-2.29-2008 [3].

Quaternary: The geologic period comprising the past ~1 800 000 years.

randomness: See "aleatory uncertainty."

recurrence interval: The mean time period between earthquakes of a given magnitude.

response spectrum: A curve calculated from an earthquake accelogram that gives the value of peak response in terms of acceleration, velocity, or displacement of a damped linear oscillator, with a given damping ratio, as a function of its period, or frequency of vibration.

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 SDCs that range from 1 through 5. For example, a conventional building whose failure may not result in any radiological or toxicological consequences is assigned to SDC-1; a safety-related SSC in a nuclear material processing facility with a large inventory of radioactive material may be placed in SDC-5. In this standard, the term "SDC" has a different meaning than in the *2006 International Building Code®* (2006 IBC) [4]. ANSI/ANS-2.26-2004 [1] provides guidance on the assignment of SSCs to SDCs.

seismic source: Faults or volumes within the earth where future earthquakes are expected to occur. In a PSHA, all seismic sources with a potential to contribute significantly to the hazard are considered.

seismic source characteristics: The parameters that characterize a seismic source for PSHA, including source geometry, probability of activity, maximum magnitude, and earthquake recurrence.

seismotectonic: Rock-deforming processes and resulting structures and seismicity that occur over large sections of the earth's crust and upper mantle.

seismogenic crust: The brittle portion of the earth's crust capable of generating earthquakes.

shall, should, may: The word "shall" is used to denote a requirement; the word "should" is used to designate a recommendation; and the word "may" is used to denote permission, neither a requirement nor a recommendation.

site response (amplification): The amplification (i.e., increase or decrease) of earthquake ground motion by rock and soil near the earth's surface in the vicinity of the site of interest. Topographic effects, the effect of the water table, and basin edge wave propagation effects are sometimes included under site response.

spectral analysis of surface waves (SASW): An in situ seismic method for determining shear-wave-velocity profiles. It uses the dispersive characteristics of surface waves to determine the variation of the shear wave velocity (i.e., shear modulus) of layered systems at depth.

structure, system, or 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 heating, ventilation, and air-conditioning. 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.

target performance goal: Target mean annual frequency of an SSC exceeding its specified limit state. Target performance goals of 1×10^{-4}/year, 4×10^{-5}/year, and 1×10^{-5}/year are used in ASCE/SEI 43-05 [2] for SSCs defined at SDC-3 or higher.

Tertiary: The geologic period from 1 800 000 years before present to 63 000 000 years before present.

uncertainty: See "epistemic uncertainty" and "aleatory variability."

uniform hazard response spectra (UHRS): A response spectrum derived such that the annual probability of exceeding the spectral quantity (i.e., spectra acceleration, spectral displacement, etc.) is the same for all oscillator frequencies. A UHRS is determined in accordance with ANSI/ANS-2.29-2008 [3].

variability: See "epistemic uncertainty" and "aleatory variability."

volumetric source zone: A volume of the earth's crust within which future seismicity is assumed to have distributions of source properties and locations of energy release that do not vary in time and space.

3 General requirements

The geological, seismological, hydrological, and geotechnical characteristics of a site and its environs shall be investigated in sufficient scope and detail necessary to support the evaluations required by ANSI/ANS-2.29-2008 [3] and ASCE/SEI 43-05 [2] and to support the objectives of ANSI/ANS-2.26-2004 [1].

The description of the site shall, at a minimum, include the following information:

(1) geographical coordinates of the site for which there shall be no ambiguity for estimating distances from the site to the sources of potential hazards;

(2) general location map to clearly define the boundary of the site and to show the distance from the site to natural and man-made features (e.g., rivers, lakes, oceans, volcanoes, faults, dams, levees, steep slopes) and to sources of potential seismic or seismic-induced hazards (e.g., sources of earthquakes, landslides, liquefaction-susceptible deposits);

(3) detailed mapping of topographic, hydrologic, and surface and subsurface geologic materials and features, as appropriate, for the particular site conditions, with scales and contours suitable for seismic hazard assessment.

Site characterization shall be carried out by a review of pertinent literature and field investigations and shall follow the detailed requirements given in Sec. 4. Subject matter experts with knowledge and experience for fulfilling requirements specified in ANSI/ANS-2.29-2008 [3] should define the program of investigations. Data and other information obtained from prior investigations may be used, if supplemented by additional investigations at the specific locations as necessary to meet the requirements elsewhere in this standard and in ANSI/ANS-2.29-2008 [3] and ASCE/SEI 43-05 [2].

Site characterization activities shall be performed under an appropriate quality assurance (QA) program. The QA program should be conducted within the framework of the risk-informed basis for seismic design categorization and associated target performance goals as outlined in ANSI/ANS-2.26-2004 [1] and ASCE/SEI 43-05 [2], respectively, with an increasing level of rigor employed from SDC-3, SDC-4, and SDC-5. This program shall include technical peer review by independent qualified personnel with extensive knowledge and experience in pertinent aspects of site characterization. The peer review should help establish the site characterization program at the outset, help resolve site-specific problems as they emerge, and provide guidance for compliance with applicable state and federal regulatory criteria.

Site characterization studies shall be adequate to understand and quantify epistemic uncertainty in the assessment of parameters needed as input to PSHAs.

> ANSI/ANS-2.26-2004 [1] identifies five seismic design categories, SDC-1 through SDC-5, and specifies the use of 2006 IBC/ASCE/SEI 7-05, "Minimum Design Loads for Buildings and Other Structures" [5] for design of SDC-1 and SDC-2. Therefore, for sites containing facilities with SSCs only in SDC-1 or SDC-2, a site-specific PSHA is not required. ANSI/ANS-2.26-2004 [1] specifies use of ASCE/SEI 43-05 [2] design methods for SDC-3, SDC-4, and SDC-5, and ASCE/SEI 43-05 [2] requires a PSHA prepared in accordance with ANSI/ANS-2.29-2008 [3]. For sites containing facilities with SSCs in SDC-3, SDC-4, or SDC-5, site-specific characterization criteria to support a PSHA are provided in the following sections of this standard.
>
> Results of a PSHA are sensitive to aleatory variability and epistemic uncertainty in the parameters that describe seismic sources, recurrence relationships, and ground motion attenuation relationships. An explicit treatment of this uncertainty is required for input into the probabilistic analysis. As discussed in Budnitz et al. (1997) [6] [also known as the Senior Seismic Hazard Analysis Committee (SSHAC) study], PSHA incorporates both aleatory variability and epistemic uncertainty. Aleatory variability refers to the natural randomness in a process. Randomness is a char-

acteristic of the natural physical process, and increasing the amount of data will not necessarily reduce the amount of variability but only help in characterizing it more accurately. Classification of aleatory variability and epistemic uncertainty is model dependent and somewhat arbitrary. It is a matter of convention, modeling capabilities, and mathematical assumptions and convenience. Examples of elements that are modeled as aleatory variability are variation in the peak ground motion of individual recordings about a median ground motion relationship, and the location and magnitude of the next earthquake. Epistemic uncertainty is the scientific uncertainty in the process due to limited data and knowledge. It quantifies our confidence in the characterization of inherent variability in nature. Examples of epistemic uncertainties are alternative admissible models of ground motion attenuation and uncertainty in the long-term rate of slip on a particular fault. This uncertainty is dependent on the knowledge of the physical phenomena and could be due to different admissible physical interpretations, mathematical formulations, and parameters for a given phenomenon (see ANSI/ANS-2.29-2008 [3] for a more complete discussion of uncertainty treatment in PSHA). With additional data it could be possible to reduce epistemic uncertainty. For example, where boreholes are few or nonexistent, one simple test may provide sufficient evidence to eliminate possible alternative stratigraphic models.

4 Site-specific characterization criteria

The scope and degree of detail of investigations to assess seismic and seismic-induced hazards shall be based on

(1) the SDC of the SSCs making up the facilities;

(2) the geological and seismotectonic environment of the site region;

(3) the extent of prior knowledge, investigations, and data regarding the site and site region;

(4) the complexity of the surface and subsurface conditions at the site as inferred from previous information and from preliminary site investigations.

Although more detailed investigations generally are appropriate for facilities having higher SDC levels, investigations of lesser scope and detail may be appropriate when the existing knowledge of the site and region is extensive and up-to-date. Similarly, although less detailed investigations generally are commensurate with lower SDC levels, more comprehensive investigations may be needed if a site hazard exists or if investigations to define the hazards have not previously been conducted. The detailed requirements in this section are applicable for obtaining the site information that is needed for performing a PSHA in accordance with ANSI/ANS-2.29-2008 [3] guidance. General guidance for characterizing seismic sources for reactor facilities and storage facilities for dry cask independent spent-fuel storage and monitored retrievable storage installations is provided in U.S. Nuclear Regulatory Commission (NRC) Regulatory Guide 1.165 [7], NRC Regulatory Guide 3.73 [8], and NRC Regulatory Guide 1.208 [9]. These regulatory guides provide guidance for levels of investigation for the site region (i.e., 320-km radius), site vicinity (i.e., 40-km radius), site area (i.e., 8-km radius), and site (i.e., 1-km radius). This standard uses similar terminology to describe areas of investigation.

All investigations to evaluate the geological, hydrogeological, seismological, geophysical, and geotechnical aspects of a site should begin with a review of available information for the site region and a field reconnaissance of the site area. This review and field reconnaissance provide an understanding of existing knowledge and site conditions so that an efficient and cost-effective program of investigation can be designed to address issues important to the assessment of geologic and seismic hazards at each site.

Current and historical information that should be compiled and reviewed include

(1) earthquake catalogs, with seismicity information and time histories;

(2) topographic, geological, geophysical, hydrogeological, and soil maps;

(3) aerial photographs and other remote-sensing imagery;

(4) digital elevation model (DEM) data [e.g., light detection and radar (LiDAR) data, or multibeam bathymetric data];

(5) geological, seismological, geophysical, and geotechnical reports and other related literature;

(6) well records and hydrological data;

(7) records of landslides, floods, tsunamis, ground motions, and subsidence and of other events of geological, seismological, and geotechnical significance;

(8) records of past geotechnical performance of other sites and structures in the site vicinity.

Field reconnaissance evaluations of the site area should include

(1) evaluation of geomorphic, hydrological, and surface geological features;

(2) evaluation of geology and soils, including identifying rock outcroppings, soil conditions, evidence of past landslides or soil liquefaction, faults, fracture traces, and geological contacts.

Field reconnaissance of the site vicinity should be conducted to evaluate Quaternary or possible Quaternary faults for which adequate information needed to assess the timing and size of Quaternary fault displacement is not available.

4.1 Investigations to support seismic source characterization for PSHA

Seismic sources define faults or volumes within the earth where future earthquakes are expected to occur. All seismic sources with a potential to substantially affect the design or performance of nuclear facilities at a site shall be identified and characterized as outlined in ANSI/ANS-2.29-2008 [3]. Table 1 summarizes guidance for the level of investigation regarding seismic source characterization based on the seismic environment and SDC of the facility.

> Seismic sources represent locations within the earth that can reasonably be assumed to have uniform seismic characteristics, distinct from

Table 1 – Guidance for levels of investigation to identify seismic sources in different seismic environments for seismic design category (SDC-1 through SDC-5) sites

Strength of seismic environment[1]	**Maximum considered earthquake (MCE) spectral response acceleration**[2]	**Design response spectra**[3]		
		SDC-1 and SDC-2[4]	**SDC-3 and SDC-4**[4]	**SDC-5**[4]
Low	<0.1 g	Use 2006 IBC/ASCE/SEI 7-05 [4,5]	Characterize background earthquake and sources of earthquakes that contribute ≥5% at the site.	Identify and characterize fault sources and volumetric source zones within 320 km and more distant sources of earthquakes that contribute ≥5% at the site.
Moderate	0.1 to 0.3 g	Use 2006 IBC/ASCE/SEI 7-05 [4,5]	Same as above.	
High	>0.3 g	Use 2006 IBC/ASCE/SEI 7-05 [4,5]	Same as above; also characterize in detail all Quaternary faults and volumetric source zones within 40 km.	Same as above; characterize in detail Quaternary faults within 40 km of the site.

[1] Defined in ANSI/ANS-2.29-2008 [3].

[2] Based on the seismic maps provided in 2006 IBC [4] for the MCE ground motion spectral response accelerations (for 0.2- and 1.0-second periods, 5% of critical damping) and Site Class B as defined by the National Earthquake Hazards Reduction Program (NEHRP) (2003) [12]. The larger of the two values is used to define the strength of seismic environment.

[3] Following ASCE/SEI 43-05 [2], (1) use 2006 IBC/ASCE/SEI 7-05 [4,5] for SDC-1 and SDC-2 facility sites; (2) use ANSI/ANS-2.29-2008 [3], and select UHRS at 4×10^{-4}/year (mean) and 10^{-4}/year (mean) for SDC-3/SDC-4 and SDC-5 facility sites, respectively.

[4] Defined in ANSI/ANS-2.26-2004 [1].

> those of neighboring sources. The types of sources and the means of characterizing their earthquake behavior vary with the seismotectonic environment. In much of the Western United States, individual faults can be identified and treated as distinct seismic sources. Most large earthquakes have occurred on recognized or mappable faults or in association with Quaternary folds. In the Pacific Northwest and Alaska, subduction zone sources include interface and intraslab sources, in addition to crustal sources in the overriding plate. In the Central and Eastern United States (CEUS) (i.e., east of the Rocky Mountains), the causative link between the occurrence of large earthquakes and mapped faults is less clear than in the Western United States. Despite general agreement that large earthquakes in the CEUS result from slippage along fault surfaces, a clear association of even the largest historical earthquakes (e.g., the 1886 Charleston, South Carolina, earthquake) with particular faults has been difficult to determine. Thus, in the CEUS, earthquake sources are generally defined as areas or volumetric source zones. In some cases, where there is sufficient information to suggest the localization of repeated large-magnitude events, fault sources are modeled to account for such repeating large-magnitude earthquakes.

Appropriate earth sciences data to support the identification and characterization of seismic sources shall be collected. Seismic source characterization parameters needed for input for PSHA include data for (a) three-dimensional seismic source location and geometry, (b) maximum earthquake magnitude, and (c) earthquake recurrence. The procedures and criteria for developing the appropriate earth sciences input for these parameters are discussed below. The utilization of this information and methods to quantify the uncertainty associated with the estimation of seismic source parameters in the context of a PSHA are provided in ANSI/ANS-2.29-2008 [3].

> Discussions of the methods and scientific bases for characterizing seismic sources for PSHA are provided by Reiter (1990) [10], SSHAC (1997) [6], and McGuire (2004) [11]. The scope of geological characterization studies needed to assess seismic source parameters varies depending on (a) the type of facility (i.e., SDC of SSCs), (b) the quality of available data, and (c) the sensitivity of the hazard results to the uncertainty in one or more of these parameters.

4.1.1 Seismic source location and geometry

As specified in ANSI/ANS-2.29-2008 [3], each seismic source shall be defined by its location and geometry so that the distance distribution to a site of interest can be calculated in the hazard analysis.

The area of investigation shall be defined by the radial distance from the site that is required to include all earthquake sources that might significantly contribute to earthquake ground motions within the frequency band of interest at the site (Table 1). For example, the size of the area of investigation could be different between locations in the CEUS and Western United States due to the very different crustal properties governing ground motion attenuation in each region. It will also depend on the response frequency of the SSC. A facility that contains SSCs sensitive to low-frequency excitation would require the careful consideration of distant moderate to large earthquakes that are capable of propagating significant low-frequency energy to considerable distances. The choice of an investigation area and justification of that choice shall be the responsibility of the investigator. The results of a preliminary PSHA or sensitivity analysis may be utilized to aid in determining the area of investigation.

Approaches for assessing the location and geometry of fault sources and source zones are presented below. Data commonly used to identify and characterize seismic sources are summarized in Table 2.

4.1.1.1 Fault

Any fault that, if active, would pose a hazard from either surface deformation (i.e., folding or faulting) or vibratory ground motion shall be evaluated. Faults that have slipped and geologic structures that have deformed during the Quaternary period should be considered potentially active and evaluated to assess timing of most recent movement and rate of activity.

Faults and folds of the site region should be evaluated in the context of their structural development with primary attention given to their Tertiary-Quaternary evolution and relationship to the contemporary tectonic regime.

Table 2 – General data types and their primary applications in identifying and characterizing seismic sources

	Seismic source							
	Individual faults						Area/volume sources	
Data type	**Location**	**Activity**	**Length**	**Dip**	**Depth**	**Style**	**Area**	**Depth**
Geological/remote sensing								
Detailed mapping	X	X	X	X		X		
Geomorphic data	X	X	X			X	X	
Quaternary surface rupture	X	X	X			X		
Fault trenching data	X	X		X		X		
Paleoliquefaction data	X	X					X	
Borehole data	X	X		X		X		
Aerial photography	X	X	X					
Low sun-angle photography	X	X	X					
Satellite imagery	X		X				X	
Digital elevation model (DEM)	X	X	X				X	
Regional structure	X			X		X	X	
Balanced cross section	X			X	X		X	
Geophysical/geodetic								
Regional potential field data	X		X				X	X
Local potential field data	X		X	X	X	X		
High-resolution reflection data	X	X		X		X		
Standard reflection data	X			X		X		
Deep crustal reflection data	X			X	X		X	X
Tectonic geodetic/strain data	X	X		X	X	X	X	X
Regional stress data						X	X	
Seismological								
Reflected crustal phase data								X
Preinstrumental earthquake data	X	X			X	X	X	
Teleseismic earthquake data							X	
Regional network seismicity data	X	X	X	X	X		X	X
Local network seismicity data	X	X	X	X	X			X
Focal mechanism data				X		X		

NOTE—Length includes both total fault length and information on segmentation.

Geological, seismological, and geophysical investigations to characterize fault sources shall address the uncertainty in the following factors:

(1) *Fault location*: Quaternary fault traces shall be defined, and locations shall be shown in map view with sufficient detail to determine source-to-site distance. In the case of concealed or blind faults, the location of the most shallow extent of the fault shall be indicated on the fault maps.

(2) *Fault activity*: Recency of activity shall be assessed for all potential fault sources significant to the site. Geological, seismological, geodetic, and geomorphic evidence may be used to demonstrate fault activity. However, only geological evidence should be used to demonstrate fault inactivity.

(3) *Fault dip and downdip width*: To model fault sources in three dimensions, an assessment shall be made of the dip of the fault throughout the seismogenic crust. The downdip width of a fault may be assessed indirectly based on the estimated maximum depth of the seismogenic crust and the dip of the fault source. Example approaches to evaluate the angle of dip are (a) use of geometry of foreshock/aftershock and background earthquake foci to constrain fault plane orientation; (b) seismic reflection profiles, where available; (c) balanced geologic cross sections; and (d) details of outcrop patterns along range fronts.

(4) *Fault slip rate*: In evaluating the rate of Quaternary fault slip, the following factors shall be considered: (a) historical and geological evidence regarding the Quaternary displacement history of the fault, (b) the preinstrumental and instrumental seismicity data, (c) structural relationships that may indicate kinematic linkages to a known Quaternary fault, and (d) the regional tectonic setting. For faults where there are no young deposits or a stratigraphic record that can be used to assess the timing or amount of displacement, a lower limit of detection should be assessed, and the slip rate estimate should encompass the uncertainty in the potential range of values.

(5) *Sense of slip (i.e., style of faulting)*: The horizontal and vertical components of displacement and fault dip shall be assessed to properly classify the sense of slip on a fault. For cases in which a fault has experienced slip in more than one direction during its history, the emphasis should be on assessing its sense of slip in the current tectonic regime.

(6) *Concealed and blind faults*: The location, dimensions, and rate of slip of concealed and blind faults shall be evaluated. Concealed and blind potential seismic sources can be identified and characterized by a combination of subsurface interpretations (e.g., balanced cross sections, seismic reflection data) coupled with evidence for geologically young deformation (e.g., folding of Quaternary deposits and surfaces), geodetic measurements [e.g., global positioning system (GPS) and interferometric synthetic aperture radar surveys], and seismicity studies (e.g., focal mechanism analysis).

(7) *Fault length and segmentation*: Fault zones usually consist of individual fault segments. Fault segmentation provides a means for estimating the expected length of fault ruptures. The total fault length, locations of fault segments, and the boundaries between segments shall be evaluated.

The following methods are used to identify and characterize Quaternary faults:

(1) *Review of available geological mapping*: Available geological maps that show the location of faults and identify the ages of geologic units displaced by the fault shall be compiled and reviewed. Large-scale geologic maps (e.g., 1:24 000 or larger scale) prepared within the past 30 years generally provide the most reliable information for this type of assessment. In the process of obtaining and reviewing these maps, researchers who may be actively working on the geology of the area should be contacted, as needed. Possible sources of information may include universities, consulting firms, and government agencies.

(2) *Analysis of tectonic setting*: The tectonic setting of the site region shall be evaluated. Information on site physiography, topography, and surface and subsurface geology should be presented if relevant to assessing fault location and activity. Geological data should be used as the basis for discussions of the regional and site tectonic framework including contemporary stress regime, stratigraphy, structure, seismicity, and geodesy. The

distribution of tectonic features (i.e., faults and folds) should be depicted on a geological map(s) of appropriate scale. The tectonic analysis should include a discussion of tectonic evolution of the site region, with particular emphasis on the timing of inception and nature of deformation within the contemporary tectonic setting. Measured or inferred rates of crustal stress and strain, both vertical and horizontal, should be considered. The contemporary tectonic setting of the site should be presented both in the context of the site region and the larger plate tectonic setting, with emphasis on the patterns and interrelationships of regional structure and seismicity.

(3) *Detailed geological mapping*: Detailed mapping shall be performed where adequate data are not available to accurately locate the primary and secondary traces of Quaternary faults that could pose a significant ground motion or surface-fault rupture hazard and to define fault length and segmentation. Mapping also should be considered to identify sites for more detailed geomorphic analyses and subsurface paleoseismic investigations (e.g., trenching or geophysical surveys) if such studies are required. Geological mapping should include interpretation of aerial photography and LiDAR data if available, field investigations, and aerial reconnaissance if needed to confirm or further evaluate geologic features. Stratigraphic and structural features should be depicted on a geological map and one or more cross sections of appropriate scale. Emphasis should be placed on mapping Quaternary depositional and erosional events that constrain the location, timing, and amounts of current tectonic deformation. Uncertainties in each of these parameters should be discussed.

(4) *Detailed geomorphic analyses*: In addition to being a tool to identify and map Quaternary faults, geomorphic analyses should be used to assess past earthquake behavior on a fault. Geomorphic features such as stream channels, stream terraces, alluvial fan surfaces, marine terraces, and glacial moraines, especially those for which there is some age control, are commonly used to assess fault slip rate, recency of activity, and the direction and amount of displacement during an earthquake. Field- and office-based studies should be conducted to document fault displacements and to identify locations and rates of Quaternary deformation. Attention should be given to the age of geomorphic development of the site region and the youngest period of landform rejuvenation. Fault-controlled geomorphic features shall be discussed in detail with attention given to assessing fault geometry and age of the latest fault movement.

(5) *Subsurface investigations*: Subsurface investigations often provide the most definitive information on fault location and fault behavior and shall be conducted as needed to identify and characterize faults that could pose a surface-rupture hazard or significant ground motion hazard to the site. Subsurface investigations include exploratory trenching, large- and small-diameter boreholes, and geophysical profiling. Boreholes may be drilled to define the thickness and character of surficial deposits, or the depth and type of bedrock. Site-specific geophysical profiling (e.g., seismic reflection and refraction surveys designed to image various depth intervals, ground-penetrating radar, magnetic surveys, various types of electromagnetic surveys) may be employed to identify and provide preliminary characteristics of faults, folds, or fault-related deposits in the subsurface that do not exhibit substantial ground disturbance. These profiles may provide critical data on fault location and geometry and should be used to help choose specific locations for exploratory trenching. Exploratory trenching is the most commonly used method for assessing paleoseismic fault activity and sense of displacement. Sites for trenching should be carefully chosen following preliminary geological observation and mapping. Preferable sites include those having deposition of late Quaternary deposits across the fault trace and minimal episodes of erosion. Continuous deposition is preferred to provide a complete record of fault activity.

(6) *Seismicity data*: Seismicity data for the site region shall be compiled and analyzed. The seismicity data catalog should include all historical (i.e., preinstrumental) and instrumental data. Significant historical earthquakes in the site region should be described. Earthquake focal mechanisms should be compiled from available sources to aid in the

characterization of the tectonic setting of the site region and area. Analyses of the earthquake catalog shall include (a) reducing various measures of earthquake size to a uniform magnitude measure that is consistent with the ground motion attenuation relationships selected for characterizing ground motion hazard at the site and (b) determining the time period of complete reporting for various magnitude levels contained in the catalog. Seismicity analyses should include a description of magnitude measures and intensities found in the catalog, statistical relationships and procedures used to convert the various measures of earthquake size to uniform magnitude measure, and catalog completeness by magnitude levels for different time periods. The changing accuracy of epicentral locations with regard to historical and network earthquake data and the significance and limitations regarding earthquake focal depths should be addressed.

4.1.1.2 Volumetric source zones

Literature reviews shall be conducted to evaluate the seismotectonic setting of the site region and to identify volumetric source zones that are characterized by assumed uniform patterns, rates, or styles of deformation and/or seismicity and maximum magnitudes.

> Volumetric source zones, which are commonly referred to as areal or area source zones, represent regions of distributed seismicity that are not associated with specific known faults and therefore are considered to be occurring on unidentified and/or unidentifiable faults. Earthquakes in volumetric source zones generally occur at depths of from a few kilometers to a few tens of kilometers except within subducted oceanic crust where seismogenic depths can approach hundreds of kilometers. Volumetric source zones may be used to model the occurrence of earthquakes on known faults or fault zones at great distances from a site when the details of the individual faults are not significant to the PSHA.

Volumetric source zones shall be defined by boundaries shown on maps of appropriate scale to differentiate each zone. The depth range over which each volumetric source zone is seismogenic shall be defined. Volumetric source zones range in size from concentrated zones of seismicity, to regional sources, to background sources. The boundaries of each volumetric source zone should be defined to contain regions of assumed uniform seismic potential in terms of earthquake recurrence and maximum earthquake magnitude. Uncertainty in defining volumetric source zones should be expressed by considering alternative zonations or treatment of seismicity parameters as outlined in ANSI/ANS-2.29-2008 [3] (see Sec. 5.2.2 in [3]).

The following data shall be used to identify and characterize volumetric source zones:

(1) *Geologic and tectonic data*: The distribution of tectonic features (i.e., faults and folds), geophysical anomalies, and major tectonic and physiographic boundaries used to delineate source zone boundaries shall be depicted on a map of appropriate scale. Key regional or local structural features should also be depicted on one or more cross sections of appropriate scale.

(2) *Paleoseismicity data*: Paleoliquefaction and other paleoseismological investigations including detailed mapping, geomorphic analyses, and subsurface investigation of significant seismic sources shall be reviewed and analyzed with regard to location and geometry, maximum magnitude potential, and earthquake recurrence. Geological reconnaissance should be conducted within the site vicinity to evaluate evidence for the presence or absence of paleoliquefaction if geologic conditions are favorable for the development and preservation of a record of strong ground shaking.

(3) *Seismicity data*: Seismicity data for the site region shall be compiled and analyzed (see Sec. 4.1.2.1). Variations in the spatial distribution, concentration, or density of seismicity should be used to delineate source zones. Changes in focal mechanisms, which could indicate changes in the style of faulting or stress orientation, also are significant and should be noted.

Documentation of the definition of individual source zones should include discussions of regional and site tectonic framework, including contemporary stress regime, and stratigraphic relationships that constrain the timing and spatial distribution of Tertiary and Quaternary deformation, structure, and seismicity. Discussions shall address the similarities/differences among the delineated provinces that bear on the size and frequency of future earthquakes. Uncertainties in tectonic interpretations that are used to define alternative locations and geometries of volumetric source zones shall be discussed. In addition, the expected style of faulting should be evaluated.

4.1.2 Maximum earthquake magnitude

As specified in ANSI/ANS-2.29-2008 [3], the estimated maximum earthquake magnitude that a seismic source is capable of generating in the current tectonic stress regime shall be assessed for each seismic source. The maximum earthquake magnitude defines the upper bound to the earthquake recurrence relationship. Approaches used to estimate and assess maximum earthquake magnitudes for faults and volumetric source zones are described in Secs. 4.1.2.1 and 4.1.2.2.

4.1.2.1 Maximum earthquake magnitude: Faults

Assessments of maximum magnitudes for fault sources should include constraints provided by seismicity data and constraints provided by estimates of maximum dimensions of rupture.

In most cases, the historical earthquake record for individual faults is far shorter than the recurrence intervals for the largest earthquakes, and the probability that the historical record includes the maximum event is small. However, if the historical record includes a significant earthquake that can be associated with the fault, it should be assessed as either a lower bound or a best estimate of the maximum magnitude. In cases where the historical event was associated with coseismic rupture, the extent of that rupture should be evaluated in the context of the maximum rupture dimensions of the fault.

Earthquake magnitude and rupture dimensions are correlated. It follows that if rupture dimensions associated with a maximum earthquake on a fault can be estimated, the maximum magnitude should be assessed. Commonly, a number of potential rupture dimensions can be estimated (e.g., rupture length, rupture area, displacement per event), and a magnitude should be estimated for each. Paleoseismic data regarding the number of events and rupture dimensions are usually associated with considerable uncertainty. Uncertainties in the estimates of fault rupture parameters resulting from ambiguous data, lack of deposits of suitable age to evaluate location, timing, amount, and continuity of extent of Quaternary faulting, should be documented.

> Fault rupture parameters that have been shown empirically to be correlated with earthquake magnitude include rupture length, rupture area, maximum surface displacement, and average surface displacement [13,14]. The evaluation of these parameters for an individual fault includes paleoseismic investigations of the extent and variations of slip along strike of past ruptures.

4.1.2.2 Maximum earthquake magnitude: Volumetric source zones

The assessment of maximum earthquake magnitudes for volumetric source zones is particularly difficult because the physical constraint most important to the assessment, the dimensions of fault rupture, typically is not known. As a result, the primary methods for assessing maximum earthquakes for volumetric source zones should include a consideration of the historical seismicity record, paleoseismic evidence of past earthquakes, and analogies to other sources in similar tectonic environments.

Studies of the sizes of historical earthquakes associated with the volumetric source zone of interest should be made. It is possible that after the historical record has been examined, it will be concluded that the record provides no particular constraint on the estimate of maximum earthquake for the source. Alternatively, the maximum historical earthquake for the zone may be assessed as either a lower bound or best estimate of the maximum magnitude for the source.

In cases where the largest historical earthquake is judged to not be the maximum earthquake, the use of a specified incremental unit larger than the historical earthquake should be avoided if other database alternatives exist. For example, studies of the distribution and sizes of seismic-induced features such as paleoliquefaction features can provide indications of the sizes of prehistoric earthquakes, and published information regarding such features should be used in estimating the sizes of maximum earthquakes. Field studies to evaluate the presence or absence of such features in the site vicinity or region may provide additional data to constrain the size of the maximum magnitude.

Other considerations in assessing maximum earthquakes for volumetric source zones are analogies to other sources. The source of interest may be tectonically similar to another source such that their maximum earthquakes also are considered similar.

> A project by the Electric Power Research Institute (EPRI) specifically addressed problems of estimating maximum earthquake magnitude in stable continental regions using this approach. As part of this project, Johnston et al. (1994) [15] developed worldwide databases that can be used to estimate maximum earthquake magnitude for seismic sources in the CEUS.

Considerations of possible rupture dimensions also may be used in the assessment of maximum magnitudes for volumetric source zones. For example, the lengths of zones of concentrated seismicity or the dimensions of tectonic elements within a source zone may be assessed to represent maximum rupture dimensions.

4.1.3 Earthquake recurrence

As specified in ANSI/ANS-2.29-2008 [3], earthquake recurrence relationships that quantify the frequency of different magnitude earthquakes shall be assessed for each seismic source. Different approaches commonly are used to assess earthquake recurrence for fault sources and volumetric source zones, as described in Secs. 4.1.3.1 and 4.1.3.2.

4.1.3.1 Earthquake recurrence: Faults

Most faults have not ruptured even once, let alone repeatedly, during the historical period. Therefore, estimates of earthquake recurrence should be developed from a variety of approaches. The most direct approach is to date successive faulting events through paleoseismological trenching studies and fault geomorphic investigations. These studies can provide information on the actual intervals, along with uncertainties, between earthquakes on faults that directly rupture or deform (i.e., uplift or fold in the case of blind faults) the surface. Available paleoseismological data should be used to develop a fault-specific earthquake recurrence model that includes the magnitude of the event that produced the surface faulting or deformation.

Another approach is to use a geologically determined fault slip rate and an estimate of expected average displacement per event to calculate an average recurrence interval and its variability. However, as earthquake recurrence is more widely studied on faults in a variety of tectonic settings, it is clear that there is a spectrum of recurrence behavior that ranges from quasi-uniform to highly nonuniform. Evidence for spatial or temporal clustering of earthquakes should be noted. This requires that average recurrence estimates on faults be put into a long-term and regional framework.

4.1.3.2 Earthquake recurrence: Volumetric source zones

In many regions, particularly the CEUS, it is often difficult to identify the specific locations of seismogenic faults. In these areas, fault-specific paleoseismologic investigations such as those noted in Sec. 4.1.3.1 are not appropriate, and the following types of observations and data should be considered to develop information on earthquake recurrence:

(1) *Paleoliquefaction data*: The use and evaluation of shaking-induced permanent ground deformation features (e.g., paleoliquefaction) may provide information on the recurrence of ground motions that can affect a site;

(2) *Seismicity data*: Recurrence relationships should be developed from historical and instrumental seismicity with due regard for the statistical variability in these estimates;

(3) *Geodetic data*: With the emergence of GPS networks throughout the country, information on rates of strain accumulation is becoming increasingly available. Analysis of GPS constraints on regional strain rates, particularly in combination with seismicity data, should be undertaken to develop earthquake recurrence estimates for these source types. Use of these data should address limitations in the data that stem from the length of the GPS record and stability of the network stations. These data should also be compared with long-term geologically derived slip rates and deformation rates inferred from seismicity data to ensure that the inferred rates are reasonable.

Two alternative approaches may be used to characterize the spatial distribution of future earthquakes within the regional zones. The first approach considers that there is equal likelihood of occurrence of earthquakes at all locations within the source zone. An alternative interpretation that may be applied is nonuniform spatial occurrence expressed by a nonuniform spatial density function for the volumetric source zone using the recorded seismicity kernel density. This interpretation implies that future seismicity is more likely to occur near where it has in the past. This interpretation was used to develop the national seismic hazard maps for the United States [16,17,18]. More specific guidelines for developing recurrence parameters for seismic sources are provided in ANSI/ANS-2.29-2008 [3].

4.2 Fault rupture hazard characterization

The potential for surface fault rupture and associated deformation shall be determined. This assessment shall include the evaluation of both primary faults that reach the ground surface as well as secondary ground deformation (e.g., faulting, folding, tilting, warping, etc.) related to concealed or blind faults that do not reach the ground surface.

The investigation of a site and its vicinity for surface faulting shall include the following:

(1) examination for potential Quaternary surface faults at the site or for Quaternary faults that trend toward the site;

(2) evaluation of the activity and origin of any Quaternary faults detected at the site or in the site vicinity that trend toward the site and the history of their displacement by the use of appropriate and accepted techniques and methods [19,20];

(3) evaluation of the width of the Quaternary fault zone, including areas of possible secondary ground deformation.

The types of studies and areas of investigation needed to evaluate the potential for surface rupture hazard depend on the tectonic, geological, and seismological setting of the site. The assessment of surface rupture hazard requires much of the same information described in Sec. 4.1.2.1 needed to characterize fault sources for seismic source models (i.e., timing of most recent movement and rate of activity, location, geometry, sense of displacement, recurrence or rate of deformation, and maximum size or displacement per event). The assessment should include all or parts of the following studies: (a) literature and data review; (b) aerial reconnaissance and aerial photo interpretation; (c) reconnaissance and detailed geological and geomorphic mapping; and (d) analysis of historical (preinstrumental) and instrumental seismicity, hydrological, geophysical, geological, and geodetic data.

Surface fault rupture may result from either tectonic or nontectonic phenomena. Hanson et al. (1999) [19] discuss criteria for differentiating tectonic from nontectonic faults. Nontectonic faults may have similar physical characteristics as tectonic faults, but they are very different in terms of origin and potential hazard. The identification and characterization of surface fault rupture hazards require the ability to distinguish among tectonically induced faulting, faulting induced by strong ground motions, and faulting caused by nontectonic phenomena. Tectonic faults include both structures capable of producing earthquakes and secondary structures that are produced by earthquakes but are not themselves capable of generating an earthquake. Examples of secondary tectonic faults include hanging-wall deformation above a concealed thrust fault and various types of strong ground motion phenomena (e.g., ridge-crest shattering, basin-margin fracturing, etc.). Nontectonic phenomena that can result in surface deformation at a facility site, but are not capable of producing significant earthquakes and vibratory ground motion (i.e., are nonseismogenic), include those produced by gravitational processes (e.g., landslide features, etc.), dissolution phenomena, subsidence due to extensive fluid extraction, sediment loading and dewatering (e.g., soft-sediment deformation), evaporite migration (e.g., salt dome and salt flowage structures), sediment compaction (e.g., growth faults, subsidence structures, etc.), glaciers (e.g., ice push features), and glacio-isostatic rebound (e.g., popups).

Results of site investigations shall provide documentation of the presence or absence of surface fault rupture hazards at the site. Where it is determined that surface fault rupture hazards are not present, sufficient data and discussion to clearly justify this determination shall be presented. In cases where engineered design for fault displacement or engineered stabilization measures are feasible, sufficient data regarding the mechanism, location, timing, and scale of deformation shall be provided to evaluate design options.

4.3 Geotechnical investigations

The geotechnical investigations should include, but not necessarily be limited to,

(1) defining site soil and near-surface geologic strata properties as may be required for hazard evaluations, engineering analyses, and seismic design;

(2) evaluating the effects of local soil and site geologic strata on ground motion at the ground surface;

(3) evaluating dynamic properties of the near-surface soils and geologic strata;

(4) conducting soil-structure–interaction (SSI) analyses;

(5) assessing the potential for soil failure or deformation induced by ground shaking (liquefaction, differential compaction, and landsliding).

4.3.1 Information review and site reconnaissance

Review of available information, including results of previous investigations, and site reconnaissance shall be performed to support subsurface investigations, laboratory testing, and engineering analyses described in Secs. 4.3.2.1, 4.3.2.2, and 4.4, respectively. This information is essential for understanding the general geological and geotechnical conditions of the site, so that the later phases of geotechnical investigations can be effectively and efficiently planned. This information also provides a framework in which new data can be properly evaluated and applied to the design and evaluation of the foundations and assessment of potential site geotechnical hazards.

Available information may include

(1) topographical, geological, geophysical, hydrogeological, and soil survey maps;

(2) aerial photographs and other remote-sensing imagery;

(3) geological and geotechnical reports and other related literature;

(4) well records and hydrological data;

(5) historical records and Quaternary geological evidence of landslides, floods, earthquakes, subsidence, liquefaction, and other events of geologic or geotechnical significance;

(6) past geotechnical performance of the site and other sites and structures in the site vicinity.

Site reconnaissance activities should include

(1) mapping of topographical, hydrological, and surface geological features;

(2) identifying rock outcrops, soil conditions, evidence of past landslides or soil liquefaction, faults, fracture traces, and geological contacts;

(3) detailed on-site mapping of local engineering geology and soils.

4.3.2 Site investigations

Site investigations shall be conducted as needed to characterize the geotechnical conditions at the site commensurate with the seismic design requirements of the facility (see Sec. 4.3.2.1). Geologic profile, stratification, and quantification of site soil/rock properties are needed for engineering design and evaluations of soil amplification, SSI, potential for liquefaction, differential settlement, and landslides.

An appropriate site investigation program shall be developed in consultation with a qualified geotechnical engineering representative of the project team.

Soil/rock profiles (i.e., cross sections) at the locations of the facilities shall be provided based on the results of site investigations.

> Static properties of the soils and rocks are used to help characterize the site subsurface conditions and in analyses and design of geotechnical aspects of engineered structures at the site. Index and classification properties typically include moisture content, unit weight, grain-size distribution, plasticity, specific gravity, relative density, porosity, and rock quality designation (RQD). Engineering properties typically include compressive and tensile strengths, shear strength characteristics, compressibility, overconsolidation ratio, lateral earth pressure coefficients, compaction, permeability, swelling potential, elastic constants, and creep parameters. Other properties, such as electrical resistivity and gamma logging, may be rele-

vant, as well, depending on the site, and should be considered for use in the evaluation.

Dynamic properties of the soils and rocks are used to study ground motion amplification, SSI, liquefaction potential, seismic slope stability and deformation, and foundation movements of nuclear facilities caused by seismic events. Dynamic properties typically include wave velocities (i.e., compression and shear), strain-dependent shear modulus and damping, cyclic shear resistance, and rate of loading effects on strength and modulus properties.

4.3.2.1 Subsurface exploration

Subsurface conditions shall be determined using methods appropriate for the site conditions, including borings, penetration resistance [e.g., standard penetration test (SPT), cone penetration test (CPT), and Becker penetration test (BPT)], soundings, well logs, exploratory excavations, sampling, and geophysical methods [e.g., cross-hole, downhole, spectral analysis of surface waves (SASW), and geophysical logging], that adequately characterize soil and groundwater conditions.

Appropriate investigations shall be made to determine the contribution of the subsurface soils and rocks to the loads imposed on and dynamic response of the structures subjected to seismic-induced strong ground motion.

Representative samples of soils and rocks should be obtained for classification and testing. The QA requirements shall address issues associated with retrieval, transportation, handling, and testing of soil samples. Sufficient geophysical and geotechnical data shall be obtained to allow reasonable assessments of representative soil profiles and parameters as well as their variability. The nature and extent of subsurface exploration shall be dictated by the SDC of the facilities and the desired level of confidence in the results, by the foundation requirements, and by the complexity of the anticipated subsurface conditions. The locations and spacing of borings, soundings, and exploratory excavations shall be chosen to adequately characterize subsurface conditions, including their uncertainties, and shall be located to permit the construction of geological cross sections and soil profiles needed for seismic site response studies and for design of foundations of safety-related structures and other important facilities at the site. Subsurface exploration generally employs borehole drilling and sampling and cone penetrometers. Procedures used for such exploration should comply with the applicable American Society for Testing and Materials (ASTM) standards or procedures acceptable to the regulatory agency providing oversight for the project.

A number of samples sufficient to permit laboratory determination of average properties and to indicate their variations are necessary. The appropriate number and depth of samples should be determined by the judgment of a qualified geotechnical engineer from the subsurface conditions revealed during field exploration and commensurate with the SDC classification of the facilities. The detailed scope of the program needs to be able to address all seismic issues (site response, SSI effects, foundation issues, and dynamic demands on the facilities and housed SSCs) of interest in the design.

Recommendations for site investigation for reactor facilities are presented in NRC Regulatory Guide 1.132 (2003) [21] that can be considered appropriate for facilities classified as SDC-5. NUREG/CR-5738 [22] provides additional methods for field investigations for foundations of nuclear power facilities. The number, spacing, and depth of site penetrations (borings, cone penetrometers); number and type of soil samples obtained; and associated testing program may be relaxed for evaluations of facilities of lower SDC classification. For example, for SDC-3 facilities subjected to relatively low levels of seismic demand, dynamic laboratory testing to obtain strain-dependent shear modulus and damping properties may not be necessary, and generic published relations for similar type soils may be used in their place. The depth of investigation needed for SSI evaluations, typically considered to be twice the smallest dimension of the facility, may similarly be relaxed for evaluation of SSI effects of facilities of lower seismic classification. However, information on the shallow profile (layering, shear velocity contrasts, etc.) known to be important to SSI response should be incorporated into the subsurface characterization program for all nuclear facilities of category SDC-3 and higher.

Disturbed samples are typically taken at regular intervals (e.g., 5 ft), at every change in strata, or continuously if a specific condition or hazard (e.g., liquefaction) is being assessed. They are primarily used for classification tests and must contain all of the constituents of the soil even though the soil structure is disturbed. Undisturbed samples, if deemed to be required to develop strength and stiffness properties, should be taken at specific depths or continuously depending on the design problems, testing program, and subsurface materials encountered. In obtaining disturbed and undisturbed samples, penetration resistance data should be monitored and recorded.

The material properties obtained from the soil and rock samples may not adequately represent in situ properties, due to the difficulties in duplicating the subsurface conditions in the laboratory. If the available data are not sufficient, in situ measurements and tests should be conducted to obtain the undisturbed, in situ material properties in the field. Such in situ measurements may be obtained using CPT soundings, and/or field vane, dilatometer, pressuremeter, or geophysical methodologies.

In situ measurements of wave velocities may be obtained using several methods, each of which has particular strengths depending on the site characteristics [23]. Cross-hole, downhole, and seismic cone techniques provide useful direct measurements of wave velocities in soil and rock boreholes. Because higher frequencies are used in the suspension logger (i.e., 102 kHz), some soil media require a correction to compare with results of other geophysical techniques. SASW is a useful technique for determining shear wave velocities at sites where expected subsurface conditions warrant its application. No consistently reliable technique has been developed to infer low-strain damping. Where justified, multiple methods of geophysical testing should be used to generate confidence in inferred site properties.

Groundwater conditions have significant implications for assessing seismic-induced hazards and shall be assessed at each nuclear facility site. Groundwater conditions normally are observed in borings at the time they are drilled. The groundwater level should be measured at the start of each workday for borings in progress, at the completion of drilling, and when the water levels in the borings have stabilized. It is noted that when drilling mud is used in a boring, accurate groundwater levels generally are not obtained. For these cases, or if significant seasonal fluctuation of groundwater level is anticipated, groundwater observations should be made by means of properly installed wells or piezometers that are read at regular intervals to assess the groundwater fluctuations associated with seasons and changes in surface water conditions. Piezometers can be installed to independently measure the piezometric pressures of different hydrological units, such as perched or artesian groundwater conditions. Types of piezometers and observation wells and recommended methods for their installation and maintenance are described in Dunnicliff (1988) [24] and the U.S. Army Corps of Engineers (1995) [25].

4.3.2.2 Laboratory testing

A laboratory testing program shall be carried out to identify and classify the subsurface soils and rocks and to help characterize their physical and engineering properties if such information is not available for the site. Laboratory tests for both static properties (e.g., shear strength, compressibility) and dynamic properties (e.g., shear modulus, damping, cyclic shear resistance) generally are required. Both static and dynamic tests shall be conducted in accordance with applicable ASTM standards or test procedures acceptable to the regulatory agency providing oversight to the project. The ASTM specification numbers for static and dynamic laboratory tests can be found in *Annual Book of ASTM Standards*, Volume 04.08. Sufficient laboratory test data should be obtained to allow reliable assessments of central tendency and distribution values of soil properties and their variability. Guidance for testing requirements for critical facilities is presented in NRC Regulatory Guide 1.138 [26].

Soil and rock samples for laboratory testing shall be selected after careful examination of boring records and available samples. It is important that test specimens be representative of the soil or rock unit to be tested and be accurately described to permit establishment of the stratigraphic profile. Samples should be tested as soon after reaching the laboratory as possible to minimize the effects of structural and chemical changes with time. Undisturbed tube samples of soils should be examined for evidence of disturbance. Radiographs should be used to determine the quality of soil samples, effects of sampling disturbances, and the presence of naturally occurring anomalies. Generally, tests on samples of mixed or stratified material should be avoided. It is very important to avoid or minimize disturbance of soil structure and changes of moisture during sample removal from tubes and trimming and shaping of specimens. Reconstituted or remolded samples are used when representative undisturbed samples cannot be obtained or when they are used as representative compacted fill or backfill materials. Undisturbed samples of fill should be taken for confirmatory testing during construction. Reconstituted and remolded samples should reflect the densities and moisture contents measured or anticipated under field conditions.

For coarse geological materials such as coarse gravels and sand-gravel mixtures, special testing equipment and testing facilities may be used, if deemed necessary. Larger sample size is required for laboratory tests on this type of material. It is generally difficult to obtain undisturbed samples of unconsolidated gravelly soils for laboratory tests. If it is not feasible to collect test samples and, thus, no laboratory test results are available, the dynamic properties should be estimated from the published data of similar gravelly soils and/or characterized based on in situ geophysical methods.

The dynamic sampling and testing program should be carefully planned to consider the depth range over which suitable undisturbed samples can be obtained and to characterize the material properties under the stress and strain conditions expected during the natural phenomena events. The program should evaluate the effects of the events on both static and dynamic properties. The following factors should be considered in determining the dynamic properties of soils:

(1) conditions of undisturbed test specimens, especially cohesionless materials;

(2) method of sample preparation;

(3) consolidation and saturation of specimens;

(4) wave form of cyclic loading (Note: sinusoidal loading is most frequently used);

(5) frequency of loading;

(6) duration of applied consolidation pressure.

ASTM standards give detailed procedures that are widely accepted and utilized for testing of index and engineering properties of soils and rocks. In addition, the International Society of Rock Mechanics provides commonly accepted methods for various rock property tests. Index properties tests include moisture content, unit weight, particle-size analysis, Atterberg limits, specific gravity, relative density, porosity, and RQD. Engineering properties tests include consolidation, unconfined compression, triaxial compression, direct shear, compaction, permeability, swelling potential, tensile strength, and creep tests. Field rock fracturing conditions should be considered when trying to relate field geophysical properties to laboratory data measured on small samples.

Dynamic shear modulus and damping values of soils are strain dependent. If anticipated strain levels are deemed high enough, strain dependency effects may be obtained from tests covering the range of strains to be considered in the design and evaluation. Several laboratory techniques are available to measure shear modulus and damping as functions of shear strain [23]. The measurement techniques are resonant column, cyclic triaxial, cyclic simple shear, and cyclic torsional shear. These measurements typically extend over different but overlapping strain ranges and use different excitation frequencies. The cyclic torsional shear and resonant column tests are the most widely used test methods for determining the strain-dependent shear modulus degradation and hysteretic damping of soils. Recommended test procedures for modulus and damping of soils are provided in applicable ASTM standards.

4.4 Characterization for site response analysis

As outlined in ANSI/ANS-2.29-2008 [3], the quantification of earthquake ground motions at a facility site shall include an assessment of site response effects on ground motions. The parameters for the site response analysis include descriptions of soil type, subsurface layer geometry and thickness, low strain P-wave and S-wave velocities, and density, in addition to strain-dependent dynamic shear modulus degradation and hysteretic damping ratio relations for each of the soil or soft-rock layers. Uncertainties in these material properties shall be assessed for determination of mean estimates of site response.

The characterization of subsurface layer geometry shall be sufficient to determine whether a one-dimensional (i.e., flat-layer) idealization of the site is adequate or whether two- or three-dimensional effects on site response shall be modeled. Internal friction angle, undrained shear strength, and overconsolidation ratio for clay could also be needed for nonlinear analyses.

The soil/rock column properties specified should ideally be characterized to the depth at which the subsurface materials reach the shear wave velocity of "outcrop" materials for which the attenuation relations used in development of the PSHA are directly applicable.

The available site-specific data and other pertinent data as collected from the review of available site information (e.g., seismic reflection and refraction surveys and geotechnical data) shall be used to develop a site response model. The preliminary site data may be adequate to estimate wave velocities, approximate depths of hard rock, and soil or soft-rock dynamic properties.

If upon review of available site-specific seismic, geotechnical, and geological data there is not sufficient information to develop a site response model, a supplemental geophysical and geotechnical field data acquisition program shall be developed. The program should take into account the sensitivity of the preliminary soil response analysis results to the range of possible input soil parameters. The program should focus on the most uncertain geotechnical parameters that control site response at the frequencies of most interest to facility structural and component response. Peer review should be used to establish whether a supplemental field program is needed.

If additional data on wave velocities and strain-dependent dynamic material properties are collected to obtain sufficient information to develop a site response model, those measurements shall be site specific. The field investigation plan shall be peer reviewed. Peer review should pay particular attention to the quality, reliability, and age of the available geophysical or geotechnical work conducted. Once additional data are obtained and interpreted, they shall be incorporated with the previously available site information in an updated site response model.

4.5 Site characterization for ground failure hazard

Ground failure hazard phenomena that could result in surface deformation at a facility site include liquefaction of soils, ground settlement, and slope failure. Differential ground movements potentially associated with these ground failure phenomena are a damage hazard to facilities at the site. Sufficient investigations shall be performed to assess and document the presence or absence of each of these hazards. Investigations of ground failure hazard due to surface and concealed fault rupture are specified in Sec. 4.2.

4.5.1 Liquefaction of soils

> Liquefaction is a soil behavior phenomenon in which a soil deposit situated below the groundwater table loses a substantial amount of strength due to the development of high excess pore water pressures generated and accumulated in the soil during ground shaking induced by strong earthquakes or water wave actions. Recently deposited (i.e., geologically young) and generally loose natural soils and uncompacted or poorly compacted fills are potentially susceptible to liquefaction. Loose sands and silty sands are particularly susceptible, and loose silts and gravels are susceptible as well. Dense natural soils, aged soils, and well-compacted fills generally have low susceptibility to liquefaction. General procedures for evaluating liquefaction potential, which are briefly described below, are given in NRC Regulatory Guide 1.198 (2003) [27], Youd et al. (2001) [28], and Seed et al. (2003) [29].

Investigations of potential liquefaction and related effects typically involve both geological and geotechnical engineering assessments. The following site-specific data shall be acquired and utilized with the evaluation procedures [30]:

(1) depositional and stress history and geologic age of the sediments;

(2) soil grain size distribution and density;

(3) groundwater conditions;

(4) penetration resistance of the soil (e.g., SPT, CPT, and BPT);

(5) shear wave velocity of the soil;

(6) evidence of liquefaction or nonoccurrence of liquefaction during historic seismic events.

> The most commonly utilized approach is the simplified empirical procedure that utilizes SPT blow count data. This procedure is based on the empirical correlation between cyclic stress ratio that is computed from peak ground acceleration (PGA) and SPT $(N_1)_{60}$ blow count data that differentiates the observed occurrence or nonoccurrence of liquefaction in sand deposits during earthquakes. The basic correlation was developed for magnitude 7.5 earthquakes for materials with different fines contents. The correlation may be adjusted to other magnitude events using correction factors.
>
> CPT data are also utilized with this approach by conversion to equivalent SPT blow counts, using correlations developed among cone tip resistance, friction ratio, and soil type. Direct correlations of CPT data with liquefaction potential have also been developed.

Alternative approaches, such as the evaluation of threshold strains [31] and probabilistic evaluations of site data [28], are available and may be considered to assess liquefaction potential of a site.

Liquefaction potential for a soil stratum should also be evaluated through the use of laboratory testing, by comparing the dynamic/cyclic shear resistance of the soil to the dynamic shear loading induced by the natural phenomenon hazards event. Laboratory tests for evaluating shear and other deformation behavior for soils are discussed in Sec. 4.3.2.2.

A soil behavior phenomenon similar to liquefaction is strength reduction in sensitive clays. Although this behavior phenomenon is much less common than liquefaction, it should not be overlooked as a potential cause for landsliding and lateral movements [32]. Therefore, the existence of sensitive clays at the site shall be evaluated.

4.5.2 Ground settlement

Ground settlement due to dynamic loads, change of groundwater conditions, soil expansion, soil collapse, erosion, and other causes shall be considered. Ground settlement due to ground shaking can be caused by two factors: (a) compaction of dry or partially saturated sands due to ground shaking and (b) settlement due to dissipation of dynamically induced pore water pressure in saturated sands. Differential compaction of cohesionless soils and resulting differential ground settlement could accompany liquefaction or could occur in the absence of liquefaction. The same types of geological information and soil data used in liquefaction potential assessments should be used in assessing the potential for seismic-induced ground settlement.

> Simplified procedures such as those presented by Tokimatsu and Seed (1987) [33] and Ishihara and Yoshimine (1992) [34] are available to assess potential earthquake-related settlements. Cyclic/dynamic laboratory testing with postliquefaction or postcyclic volumetric strain measurements may also be used to help assess settlement hazard.

Ground subsidence has been observed at the surface above shallow cavities formed by natural processes and by human activities including mining (particularly coal mining) and extraction of large quantities of salt, oil, gas, or groundwater [35]. Where these conditions exist near a site, consideration and investigation shall be given to the possibility that surface subsidence will occur.

4.5.3 Slope failure

Stability of natural and man-made slopes shall be evaluated when their failures could affect the safety and operation of nuclear facilities. In addition to landsliding facilitated by liquefaction-induced strength reduction (i.e., lateral spreading and/or flow sliding), instability and deformation of hillside and embankment slopes can occur due to static and dynamic forces. Previous landslides, layers or zones of weak subsurface materials, strength reduction of the materials caused by liquefaction or by wetting, hydrological conditions including pore pressure and seepage, and loading conditions imposed by other natural phenomenon events shall be considered in determining the potential for instability and deformation.

The following information, at a minimum, shall be collected for the evaluation of slope instability:

(1) slope cross sections covering areas that would be affected by slope instability;

(2) soil and rock profiles within the slope cross sections;

(3) static and dynamic soil and rock properties, including densities, strengths, and deformabilities;

(4) hydrological conditions and their variations;

(5) rock-fall events.

Various possible modes of failure shall be considered. When a slope-failure hazard exists, both static and dynamic analyses shall be performed for the stability of the slopes. Potential slope movements due to gravity or seismic inertial forces shall be evaluated using pseudostatic limit equilibrium stability analyses and deformation evaluations [36,37], or more sophisticated equivalent-linear analyses or fully nonlinear analyses [38,39].

5 References

The user is advised to review each of the following references to determine whether it, a more recent version, or a replacement document is the most pertinent for each application. When alternate documents are used, the user is advised to document this decision and its basis.

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