



ANS

Criteria for Assessing Tectonic Surface Fault Rupture and Deformation at Nuclear Facilities

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**American National Standard
Criteria for Assessing Tectonic Surface
Fault Rupture and Deformation
at Nuclear Facilities**

Secretariat
American Nuclear Society

Prepared by the
**American Nuclear Society
Standards Committee
Working Group ANS-2.30**

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Foreword

(This foreword is not a part of the American National Standard “Criteria for Assessing Tectonic Surface Fault Rupture and Deformation at Nuclear Facilities,” ANSI/ANS-2.30-2015.)

This standard provides criteria and guidelines for assessing permanent ground deformation (PGD) hazard due to tectonic surface fault rupture and deformation at nuclear facilities. Specifically, the purpose of this standard is to provide an outline of procedures and methods for performing probabilistic fault displacement hazard analysis (PFDHA) and probabilistic tectonic deformation hazard analysis (PTDHA).

This standard replaces ANSI/ANS-2.7-1982, “Criteria and Guidelines for Assessing Capability for Surface Faulting at Nuclear Power Plants,” which is obsolete because of changes in the state-of-knowledge, technical methods, public concerns, and regulatory programs. This new standard includes updated information to make it useful for siting/licensing nuclear facilities in the U.S.

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 (R2010), “Categorization of Nuclear Facility Structures, Systems, and Components for Seismic Design.”

Two complementary standards describe procedures for performing site characterization and assessing seismic hazards, respectively: ANSI/ANS-2.27-2008, “Criteria for Investigations of Nuclear Facility Sites for Seismic Hazard Assessments,” and ANSI/ANS-2.29-2008, “Probabilistic Seismic Hazard Analysis.”

This standard might reference documents and other standards that have been superseded or withdrawn at the time the standard is applied.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

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Criteria for Assessing Tectonic Surface Fault Rupture and Deformation at Nuclear Facilities

1 Scope

This standard provides criteria and guidelines for assessing permanent ground deformation (PGD) hazard due to tectonic surface fault rupture and deformation at nuclear facilities. Specifically, the purpose of this standard is to provide an outline of procedures and methods for performing probabilistic fault displacement hazard analysis (PFDHA) for surface rupture hazard and probabilistic tectonic deformation hazard analysis (PTDHA) for surface deformation due to displacements along blind (buried) faults. Probabilistic approaches for assessing surface fault displacement and tectonic deformation hazard are relatively new; thus, criteria and guidelines have not been defined previously. PGD due to fault rupture is a potential hazard for nuclear facilities founded across or near a fault. In this standard, only coseismic PGD hazard related to movement on crustal faults is addressed. Deformation in the form of creep or afterslip and uplift and subsidence during subduction zone earthquakes is not addressed. Non-tectonic deformation, as described in Section 5.1, is not addressed in this standard.

Methods to investigate and characterize surface fault displacement and tectonic deformation hazards have advanced significantly, justifying a new standard. Specifically, it is possible to quantify the expected PGD from surface or near-surface fault rupture due to advances in geologic, geomorphic, and paleoseismic techniques used to identify and quantify the location, rate, and amount of Quaternary deformation as well as empirical observations of PGD resulting from historical earthquakes. Modern engineering practice has developed sufficiently such that the design or retrofit of structures, systems, or components (SSCs) might be able to accommodate or resist certain amounts of earthquake-induced surface rupture or other types of ground deformation. Therefore, characterization of PGD is a critical step during the siting and design of engineered facilities that are to be located in areas where such deformation may occur.

This standard replaces ANSI/ANS-2.7-1982 (withdrawn), “Criteria and Guidelines for Assessing Capability for Surface Faulting at Nuclear Power Plant Sites,” [1]¹ which is obsolete because of changes in technical methods, public concerns, and regulatory programs. This new standard includes updated information to make it useful for siting/licensing nuclear facilities in the U.S.

This standard does not specify methods for estimating the probability of other seismically induced hazards such as soil liquefaction, soil settlement, landsliding, and earthquake-induced flooding. These hazards may be applicable for certain sites and need to be evaluated and included in design requirements.

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

¹ Numbers in brackets refer to corresponding numbers in Sec. 11, “References.”

requirements associated with each nuclear facility, as specified in ANSI/ANS-2.26-2004 (R2010), “Categorization of Nuclear Facility Structures, Systems, and Components for Seismic Design” [2]. As defined in ANSI/ANS-2.26-2004 (R2010) [2], a nuclear facility is a facility that stores, processes, tests, or fabricates radioactive materials in such form and quantity that a significant nuclear hazard to the workers, to the off-site public, or to the environment may exist. These include, but are not limited to, commercial nuclear power plants, 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 an applicable regulatory authority such as the U.S. Nuclear Regulatory Commission (NRC).

The guidelines and requirements provided in this standard are applicable for the design and evaluation of Seismic Design Category (SDC)-3, SDC-4, and SDC-5 facilities. These can also be applied to SDC-1 and SDC-2 or other non-U.S. Department of Energy (DOE) facilities, if, for safety, economic, or other reasons, a site-specific seismic hazard evaluation is necessary.

Two complementary standards describe procedures for performing site characterization and assessing seismic hazards: ANSI/ANS-2.27-2008, “Criteria for Investigations of Nuclear Facility Sites for Seismic Hazard Assessments,” [3] and ANSI/ANS-2.29-2008, “Probabilistic Seismic Hazard Analysis” [4]. ANSI/ANS-2.27-2008 [3] 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; and (4) evaluation of seismic-induced ground failure hazard. ANSI/ANS-2.29-2008 [4] outlines standard criteria and procedures to perform a PSHA for earthquake ground shaking hazard at nuclear facilities.

Appropriate criteria and guidelines are outlined herein to ensure that the current state-of-the-art methodology is being used for completing either PFDHA or PTDHA. The selection of specific techniques and level of detail required to assess seismic-induced hazards are dependent on both the nature of the nuclear facility (i.e., SDC), as defined by ANSI/ANS-2.26-2004 (R2010) [2], and site-specific conditions.

Execution of this standard requires two prior conditions: (1) defining the seismic design category for the facility; and (2) executing a site characterization program following the requirements and guidelines given in ANSI/ANS-2.27-2008 [3] and in Section 5 of this standard.

2 Definitions and acronyms

2.1 Shall, should, and may

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

2.2 Definitions

aleatory uncertainty: The uncertainty inherent in a nondeterministic (i.e., stochastic, random) phenomenon. Aleatory uncertainty, sometimes referred to as “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 uncertainty is called “randomness.”

blind fault: A buried fault or fault zone that does not rupture to the ground surface but can cause surface deformation.

coseismic deformation: Movement of the ground surface due to fault displacement during an earthquake.

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 physical phenomenon is epistemic.

fault/fault zone: A fracture in the earth along which blocks on either side have moved with respect to one another. Faulting may occur along multiple planes (see Fault Displacement) and includes secondary faulting. The area encompassing this faulting is a fault zone.

fault displacement: The relative movement of the two sides of a fault, measured in any chosen direction; also, the specific amount of such movement. As used here, the term applies to either slip or separation as measured or inferred along a fault. *Principal* faulting occurs along a main plane (or planes) that is (are) the locus of release of seismic energy. *Secondary* or distributed faulting is rupture that occurs in the vicinity of the principal faulting, possibly on splays of the main fault or antithetic faults.

frequency of exceedance: The frequency that a specified level of seismic hazard is expected to be exceeded at a site or region during a specified exposure period (e.g., once every 50 years).

hazard curve: Numerical plot that shows the frequency of a certain seismic hazard parameter (e.g., ground motion or fault displacement) being exceeded.

Holocene: The geologic epoch referring to a period of time between the present and approximately 11,700 years before present.

magnitude: A parameter that characterizes the relative size of an earthquake. 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 M). Scales (a), (b), and (c) have limited range and applicability and do not satisfactorily measure the sizes 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; however, 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 evidence for seismic events, determined by analysis of geologic or geomorphic conditions resulting from or affected by prehistoric earthquakes.

permanent ground deformation (PGD): Inelastic movement of the ground surface resulting from displacement on a fault, either expressed at the surface or at depth, including (but not limited to) discrete (or distributed) fault displacement or offset (“faulting”) and simple to complex changes in geometry of surface and near-surface materials (“tilting” or “folding”).

Pleistocene: The geologic epoch between 11,700 and 2,600,000 years before present.

Quaternary: The geologic period between about 2,600,000 years before present and today. The Quaternary period includes the Pleistocene and the Holocene geologic epochs.

recurrence interval: The time period between earthquakes of a given magnitude, fault offset of a given amount, or deformation of a given measure.

return period: The inverse of annual frequency of exceedance; see frequency of exceedance.

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 International Building Code. ANSI/ANS-2.26-2004 (R2010) [2] provides guidance on the assignment of SSCs to SDCs.

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

seismotectonic: The role of seismicity in tectonics, including regionally significant geologic structures generated by earthquakes and the time/space variations in the processes or structures.

structure, system, or component (SSC): A structure is an engineered element or a collection of elements to provide support or enclosure, such as buildings and 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 [5] for SSCs defined at SDC-3 or higher.

uncertainty: See “epistemic uncertainty.”

variability: See “aleatory uncertainty.”

2.3 Acronyms

ANS: American Nuclear Society

ANSI: American National Standards Institute

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

BPT: Brownian Passage Time

CPT: cone penetration test

DEM: digital elevation model

DOE: U.S. Department of Energy

EPRI: Electric Power Research Institute

GIS: geographic information system

GPS: Global Positioning Satellite

InSAR: Interferometric synthetic aperture radar

LiDAR: light detection and radar

NRC: U.S. Nuclear Regulatory Commission

NUREG: NRC publication

PFDHA: probabilistic fault displacement hazard analysis

PGD: permanent ground deformation

PSHA: probabilistic seismic hazard analysis

PTDHA: probabilistic tectonic deformation hazard analysis

QA: quality assurance

SDC: seismic design category

SAR: synthetic aperture radar

SRTM: Shuttle Radar Topography Mission

SSHAC: Senior Seismic Hazard Analysis Committee

USGS: U.S. Geological Survey

3 PFDHA and PTDHA objectives

The purpose of PFDHA and PTDHA is to assess the likelihood or the annual frequency of exceedance of a specified level of PGD at a site in a specified time period. This objective can be met by:

- executing a site characterization program that provides sufficient information on potential fault seismic sources that pass anywhere within 5 km of the facility (NUREG-2117 [6]);
- following guidance for completing the PFDHA and PTDHA consistent with NUREG/CR-6728 [7] and NUREG-2117 [6];
- completing a PFDHA and PTDHA including a full treatment of uncertainties; and
- performing a participatory peer review of the PFDHA and PTDHA.

It is customary to use the inverse of the estimated annual exceedance frequency as a measure of the PGD hazard. This number, expressed in years, is called the return period and is often stipulated as one of the facility design criteria. The return period is selected based on the SDC applicable for the SSCs in the facility (Section 1). The PFDHA and PTDHA each provide the PGD hazard curve that correlates the amount of fault displacement or deformation with return period (Figure 1). These hazard curves shall be used in the design of SSCs.

3.1 PSHA, PFDHA, and PTDHA process

The NRC, DOE, and the Electric Power Research Institute (EPRI) established a committee to develop guidance on how to perform a PSHA. The Senior Seismic Hazard Analysis Committee (SSHAC) guidelines [8] have become the basis for PSHAs for critical facilities. These guidelines are applicable to all levels of analyses. The NRC has recently supplemented these guidelines based on PSHA experience using the SSHAC guidelines (NUREG-2117 [6]). No such guidelines have been developed for PFDHA and PTDHA because these techniques are relatively new to the practice of seismic hazard characterization; however, many of the principles presented in the SSHAC guidelines are applicable to PFDHA and PTDHA and may be used.

Two basic principles underlie the SSHAC approach to PSHAs: (a) the inputs should represent the composite distribution of the informed technical community, and (b) the analyst shall establish ownership of these inputs. The objective of a PSHA is to estimate the composite probability distribution of the inputs to the analysis based on an evaluation and integration of the informed technical community's state of knowledge of earthquake processes and ground motions. To satisfy this objective, the analyst shall conduct an evaluation process that systematically identifies and evaluates the sources and quantifies the epistemic uncertainty in the PSHA (see following discussion).

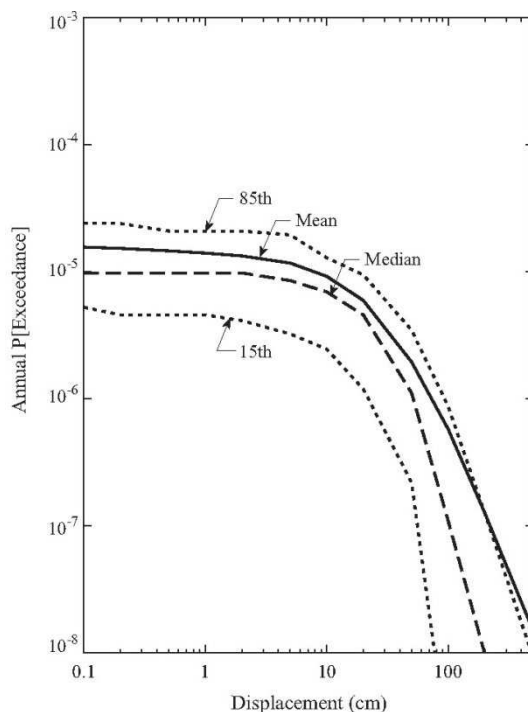


Figure 1 — Example hazard curves for a site at Yucca Mountain (Stepp *et al.*, 2001 [9])

3.2 Uncertainty assessment in PFDHA and PTDHA

Probabilistic hazard analyses, whether PSHA or PFDHA/PTDHA, generally involve significant uncertainties in the state of knowledge of earthquake processes that need to be addressed. For practical reasons, state-of-the-art probabilistic hazard analyses distinguish between two types of uncertainties, epistemic and aleatory. Epistemic uncertainty is the uncertainty that stems from our lack of knowledge concerning the validity of the models and the numerical values of their parameters. As information is collected, epistemic uncertainties can be reduced. An example of epistemic uncertainty is the shape of the magnitude distribution for a given seismic source.

Aleatory uncertainty results from natural variability in physical processes. The size, location, and time of the next earthquake on a fault are examples of quantities considered aleatory. Even with a perfect knowledge of the state of stress of the earth's crust, future earthquakes could still be occurring at a variety of unknown locations with some probability distribution. In current practice, this probability distribution expresses the irreducible aleatory uncertainty. Collection of additional data will not change or reduce the amount of aleatory uncertainty, but it will improve the knowledge of the probability distributions and therefore reduce the epistemic uncertainty.

These two types of uncertainty are treated differently in probabilistic hazard analyses. Aleatory uncertainty is often assessed by closed-form mathematical expressions. Usually, integration is carried out over randomly distributed variables to obtain the probability that some hazard parameter is exceeded, given one assumption on the state of nature. This gives a single hazard curve, whereas uncertainty about this hazard curve, the epistemic uncertainty, is expressed by incorporating multiple assumptions, hypotheses, models, or parameters. These multiple interpretations are propagated through the analysis, resulting in a suite of hazard curves and their associated weights.

3.3 Estimation of deformation hazard

The PGD hazard shall be estimated for all nuclear facility sites that have Quaternary faults within 5 km of the site boundary or facility. Three types of PGD shall be evaluated: principal faulting, distributed faulting, and tectonic deformation. *Principal faulting* occurs along a main plane (or planes) that is (are) the locus of release of seismic energy. Where the principal fault rupture extends to the surface, it may be represented by displacement along a single narrow trace or over a zone that is a few to many meters wide. *Distributed faulting* is rupture that occurs on faults in the vicinity of the principal rupture in response to the principal displacement. Distributed faulting is spatially discontinuous and may occur over a distance of several tens of meters to several kilometers from the principal rupture. A fault that can produce principal rupture may also undergo distributed faulting in response to principal rupture on other faults. *Tectonic deformation* results from slip on a buried fault where the fault and rupture do not extend to the ground surface. Surface or near-surface deformation might result in folding (tilting), permanent uplift, or subsidence of the ground surface and underlying earth materials.

4 General requirements to characterize PGD

For the purpose of characterizing PGD, the geological, seismological, and geotechnical characteristics of a site and its environs shall be investigated according to the requirements and guidance given in ANSI/ANS-2.27-2008 [3] and in Section 5 of this standard. Accordingly, subject matter experts with knowledge and experience should define the program of investigations. Data and other information obtained from prior investigations may be adequate, but it may be supplemented by additional investigations at the specific locations if necessary to ensure that the site characterization of PGD is adequate.

Any known Quaternary fault or fold (generally within 5 km) that could pose a surface deformation hazard at the site 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 rupture characteristics. Faults and folds should be evaluated in the context of their Tertiary-Quaternary history and relationship to the contemporary tectonic regime. All seismic sources with a potential to cause PGD that may affect performance of nuclear facilities at a site shall be identified and characterized as described in Section 5 of this standard. The characterization of sources of PGD shall be performed in a probabilistic framework as described in Sections 6 and 7 of this standard.

5 Detailed requirements to characterize PGD

The scope and degree of detail of investigations to assess PGD hazards shall be based on the:

- (1) highest SDC of the SSCs making up the facilities;
- (2) nature, extent, configuration, and specific performance requirements of the SSCs that may be affected by PGD;
- (3) geological and seismotectonic environment of the site;
- (4) extent of prior knowledge, investigations, and data regarding the site and site region; and
- (5) complexity of the surface and subsurface fault and geologic conditions at the site as inferred from previous information and preliminary site investigation.

Investigations for surface fault rupture and tectonic deformation shall be focused on site-specific characteristics because PGD hazard is proximal to the causative seismic source (in contrast to ground-shaking hazard). Although detailed investigations generally are appropriate for facilities having high SDC levels, investigations of lesser scope and detail may be appropriate when the existing knowledge of the site and region is extensive and has a low degree of epistemic uncertainty. Similarly, although less-detailed investigations generally are commensurate with lower SDC levels, comprehensive investigations may be needed if site hazards are poorly characterized and have a high degree of epistemic uncertainty.

The general requirements provided in this section are applicable for obtaining the detailed site information that is needed for performing a PFDHA/PTDHA. This section provides guidance for characterizing fault rupture-related PGD and is modeled after the general guidance for characterizing seismic sources of strong ground motion provided in NRC Regulatory Guides (RGs) 3.73 [10] and 1.208 [11]. These NRC documents 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 the same terminology to describe areas of investigation. This guidance builds upon the criteria of investigations of nuclear facility sites for seismic hazard assessments (ANSI/ANS-2.27-2008 [3]).

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 and a field reconnaissance of the site and site vicinity. 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 fault-rupture hazard.

5.1 Investigations to support PGD characterization

Per 10 CFR 100.23 [12], NRC requires the evaluation of potential future surface deformation at the site of interest. Geological, seismological, and geophysical investigations to characterize PGD sources shall address parameters and associated uncertainties for location and geometry, expected displacement/deformation, and recurrence. The reader is referred to ANSI/ANS-2.27-2008 [3] for the criteria and guidelines for performing such studies. To characterize the potential for surface fault rupture hazard and other forms of PGD, the geological, seismological, hydrological, and geotechnical characteristics of a site shall be investigated in sufficient scope and detail necessary to support the evaluations required by ANSI/ANS-2.27-2008 [3] and ANSI/ANS-2.29-2008 [4]. Appropriate earth sciences data to support the identification and characterization of active PGD sources shall be collected. Source characterization parameters needed for input for PFDHA include:

- (1) active PGD source location and width within site boundaries, including that of primary and secondary fault strands or fold zones;
- (2) relative distribution of slip on primary and secondary fault strands or fold zones;
- (3) aleatory uncertainty in rupture locations and slip distributions;
- (4) for each zone of PGD, direction (i.e., sense or vergence) and style (e.g., faulting, folding, combination) of displacement;
- (5) fault or fold segment length and proportional distance of the site along the segment;
- (6) maximum earthquake magnitude; and
- (7) earthquake recurrence for various magnitudes.