

IAEA SAFETY STANDARDS SERIES

Seismic Design and Qualification for Nuclear Power Plants

SAFETY GUIDE

No. NS-G-1.6



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IAEA SAFETY RELATED PUBLICATIONS

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SEISMIC DESIGN AND QUALIFICATION FOR NUCLEAR POWER PLANTS

IAEA NS-G-1.6 2003

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The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

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FOREWORD

by **Mohamed ElBaradei**
Director General

One of the statutory functions of the IAEA is to establish or adopt standards of safety for the protection of health, life and property in the development and application of nuclear energy for peaceful purposes, and to provide for the application of these standards to its own operations as well as to assisted operations and, at the request of the parties, to operations under any bilateral or multilateral arrangement, or, at the request of a State, to any of that State's activities in the field of nuclear energy.

The following bodies oversee the development of safety standards: the Commission on Safety Standards (CSS); the Nuclear Safety Standards Committee (NUSSC); the Radiation Safety Standards Committee (RASSC); the Transport Safety Standards Committee (TRANSSC); and the Waste Safety Standards Committee (WASSC). Member States are widely represented on these committees.

In order to ensure the broadest international consensus, safety standards are also submitted to all Member States for comment before approval by the IAEA Board of Governors (for Safety Fundamentals and Safety Requirements) or, on behalf of the Director General, by the Publications Committee (for Safety Guides).

The IAEA's safety standards are not legally binding on Member States but may be adopted by them, at their own discretion, for use in national regulations in respect of their own activities. The standards are binding on the IAEA in relation to its own operations and on States in relation to operations assisted by the IAEA. Any State wishing to enter into an agreement with the IAEA for its assistance in connection with the siting, design, construction, commissioning, operation or decommissioning of a nuclear facility or any other activities will be required to follow those parts of the safety standards that pertain to the activities to be covered by the agreement. However, it should be recalled that the final decisions and legal responsibilities in any licensing procedures rest with the States.

Although the safety standards establish an essential basis for safety, the incorporation of more detailed requirements, in accordance with national practice, may also be necessary. Moreover, there will generally be special aspects that need to be assessed on a case by case basis.

The physical protection of fissile and radioactive materials and of nuclear power plants as a whole is mentioned where appropriate but is not treated in

detail; obligations of States in this respect should be addressed on the basis of the relevant instruments and publications developed under the auspices of the IAEA. Non-radiological aspects of industrial safety and environmental protection are also not explicitly considered; it is recognized that States should fulfil their international undertakings and obligations in relation to these.

The requirements and recommendations set forth in the IAEA safety standards might not be fully satisfied by some facilities built to earlier standards. Decisions on the way in which the safety standards are applied to such facilities will be taken by individual States.

The attention of States is drawn to the fact that the safety standards of the IAEA, while not legally binding, are developed with the aim of ensuring that the peaceful uses of nuclear energy and of radioactive materials are undertaken in a manner that enables States to meet their obligations under generally accepted principles of international law and rules such as those relating to environmental protection. According to one such general principle, the territory of a State must not be used in such a way as to cause damage in another State. States thus have an obligation of diligence and standard of care.

Civil nuclear activities conducted within the jurisdiction of States are, as any other activities, subject to obligations to which States may subscribe under international conventions, in addition to generally accepted principles of international law. States are expected to adopt within their national legal systems such legislation (including regulations) and other standards and measures as may be necessary to fulfil all of their international obligations effectively.

EDITORIAL NOTE

An appendix, when included, is considered to form an integral part of the standard and to have the same status as the main text. Annexes, footnotes and bibliographies, if included, are used to provide additional information or practical examples that might be helpful to the user.

The safety standards use the form 'shall' in making statements about requirements, responsibilities and obligations. Use of the form 'should' denotes recommendations of a desired option.

The English version of the text is the authoritative version.

CONTENTS

1.	INTRODUCTION	1
	Background (1.1–1.5)	1
	Objective (1.6)	2
	Scope (1.7–1.12)	2
	Structure (1.13)	3
2.	GENERAL SAFETY CONCEPTS	4
	Scope (2.1–2.2)	4
	Design basis earthquake (2.3–2.10)	4
	Seismic categorization for structures, systems and components (2.11–2.26)	6
	Combination of earthquake loads with operating condition loads (2.27–2.30)	10
	Seismic capacity (2.31–2.38)	12
	Considerations for beyond design basis events (2.39–2.40)	14
	Content of the safety analysis report (2.41)	15
3.	SEISMIC DESIGN	15
	Selection of an appropriate plant layout (3.1–3.5)	15
	Geotechnical parameters (3.6)	16
	Civil engineering structures (3.7)	16
	Earth structures (3.8–3.10)	18
	Piping and equipment (3.11–3.13)	19
	Selection of appropriate design standards (3.14–3.17)	20
	Periodic safety review (3.18–3.20)	21
4.	GENERALITIES ON SEISMIC QUALIFICATION (4.1–4.10) ..	22
5.	QUALIFICATION BY ANALYSIS	25
	Modelling techniques (5.1–5.39)	25

1. INTRODUCTION

BACKGROUND

1.1. This Safety Guide was prepared under the IAEA's programme for safety standards for nuclear power plants. It supplements the Safety Requirements publication on Safety of Nuclear Power Plants: Design [1].

1.2. The present Safety Guide supersedes the Safety Guide on Seismic Design and Qualification for Nuclear Power Plants issued in 1992.¹ A Safety Guide on seismic design was originally issued in 1979 as Safety Series No. 50-SG-S2², which extended the seismic considerations in relation to the siting of nuclear power plants into the areas of design and qualification. The present Safety Guide on seismic design makes reference to a Safety Guide [2]³ which gives guidance on how to determine the seismic hazard for a nuclear power plant at a given site.

1.3. The Safety Guide on Seismic Design and Qualification for Nuclear Power Plants issued in 1992¹ was revised in 1999–2000 to incorporate new recommendations arising from recent operational experience, the analysis of damage caused to industrial facilities by recent earthquakes, and new scientific evidence on analytical approaches and their reliability. The text was also revised for compatibility with other revised Safety Guides [2, 3] as a consequence of a reorganization of the coverage of hazard evaluation issues and design issues (for foundations and superstructure).

1.4. Other Safety Guides that support the Safety Requirements publication on Safety of Nuclear Power Plants: Design [1] present recommendations in relation to external events and to this extent are complementary to the present Safety Guide. In particular, since Ref. [4] deals with general procedures for design against external events, the present Safety Guide is intended to present

¹ INTERNATIONAL ATOMIC ENERGY AGENCY, Seismic Design and Qualification for Nuclear Power Plants, Safety Series No. 50-SG-D15, IAEA, Vienna (1992).

² INTERNATIONAL ATOMIC ENERGY AGENCY, Seismic Analysis and Testing of Nuclear Power Plants, Safety Series No. 50-SG-S2, IAEA, Vienna (1979).

³ Reference [2] supersedes INTERNATIONAL ATOMIC ENERGY AGENCY, Earthquakes and Associated Topics in Relation to Nuclear Power Plant Siting, Safety Series No. 50-SG-S1 (Rev.1), IAEA, Vienna (1991).

a more specific instance of that more general approach, which should be considered a reference framework for safety aspects. Reference [3] deals with the design of foundations and presents recommendations and guidance on the evaluation of the effects of soil–structure interactions and soil liquefaction.

1.5. Other Safety Guides present recommendations relating to the earthquake scenario, but in the framework of the design of specific plant systems: Ref. [5] deals with the reactor coolant system, Ref. [6] with the containment system, Ref. [7] with the emergency power system, and Ref. [8] with instrumentation and control systems.

OBJECTIVE

1.6. The purpose of this Safety Guide is to provide recommendations on a generally accepted way to design a nuclear power plant so that an earthquake motion at the site determined according to Ref. [2] will not jeopardize the safety of the plant. It also gives guidance on a consistent application of methods and procedures for analysis, testing and qualification of structures and equipment so that they meet the safety requirements established in Ref. [1]. Reference [1] covers the design of nuclear power plants, safety assessments for the design and the regulatory issues concerned with the licensing of plants.

SCOPE

1.7. This Safety Guide is applicable to the design of land based stationary nuclear power plants with water cooled reactors to withstand site specific earthquakes regardless of the severity of the earthquake ground motion or the risk posed to individual plant items, provided that the recommendations of Ref. [2] concerning site exclusion criteria in relation to the hazard are met.

1.8. It is recognized that simplified procedures may be available for some of the recommended methods of design and verification. The adequacy of such procedures for achieving the safety objective should be determined for the individual circumstances and should be adequately evaluated in terms of safety.

1.9. It is recognized also that there is generally more than one possible engineering solution to a problem, and the approach adopted for one nuclear power plant may result in significant differences in design between that plant and another plant for which a different approach has been adopted.

The present Safety Guide is based on the general practices in Member States. A recommended framework for the assessment of seismic safety in plant design is presented in Ref. [9].

1.10. Probabilistic assessment of the seismic capacity of a nuclear power plant is beyond the scope of this Safety Guide. Relevant requirements and recommendations are presented in Refs [1, 9]. This Safety Guide is intended to be applied to the design and construction of new nuclear power plants and in general it should not be applied in the seismic re-evaluation of existing plants. The assessment of the seismic margin of an existing plant is beyond the scope of this Safety Guide; such an assessment should follow the generic procedures outlined in Ref. [10].

1.11. The recommendations of this Safety Guide may also be applied to reactor types other than water cooled reactors in stationary nuclear power plants. However, engineering judgement should be used to assess their applicability, in accordance with the specific safety objectives defined for the plant type concerned.

1.12. The technical recommendations in this Safety Guide concerning modelling and item qualification may also be applicable in part to the design of the plant against vibrational phenomena induced by sources other than earthquakes, such as explosions in industrial facilities, aircraft crashes, explosions in quarries or accidents with high speed rotating machinery [4]. However, such an extension should be done with care and engineering judgement should be used, particularly in relation to the frequency of the induced vibration, its duration, its direction and the mechanism of its impact on the plant. It should also be noted that the design to resist such loads may take different forms, such as sacrificial walls, or may encompass different failure modes, such as scabbing or spalling for impact loads. These particular engineering provisions are not considered in this Safety Guide.

STRUCTURE

1.13. Section 2 discusses the safety implications of the design process and the relevant acceptance criteria required for different safety classes. In Section 3 the design principles for the achievement of the protection objective are recommended and the concept of periodic safety review is discussed in relation to the design issues. Guidance on an appropriate selection of methods for seismic qualification is provided in Section 4, recommendations for qualification by analysis are provided in Section 5, and qualification by test and

experience is discussed in Section 6. Section 7 presents guidance on recommended seismic instrumentation, and suitable monitoring procedures and their relation to design assumptions.

2. GENERAL SAFETY CONCEPTS

SCOPE

2.1. This section makes recommendations on categorizing the structures, systems and components (SSCs) of a nuclear power plant in terms of their importance to safety in the event of a design basis earthquake, in accordance with the requirements established in Safety of Nuclear Power Plants: Design [1]. Recommendations are also made concerning the application of standards for design to guarantee an appropriate safety margin in the design.

2.2. A quality assurance programme is required to be established and implemented to cover items, services and processes that affect safety and are within the scope of this Safety Guide (Ref. [1], paras 3.14–3.16). The quality assurance programme is required to be implemented to ensure that data collection, data processing, studies, analyses and qualification, code validation (software) and verification, and other activities necessary to meet the recommendations of this Safety Guide are performed correctly [11, 12].

DESIGN BASIS EARTHQUAKE

2.3. According to Ref. [2], two levels of ground motion hazard should be evaluated for each plant sited in a seismic area. Both hazard levels should generate a number of design basis earthquakes grouped into two series, seismic level 1 (SL-1) and seismic level 2 (SL-2), following the procedures outlined in Ref. [2] and according to the target probability levels defined for the plant design⁴.

⁴ In some States, SL-2 corresponds to a level with a probability of being exceeded in the range 1×10^{-3} to 1×10^{-4} (mean values) or 1×10^{-4} to 1×10^{-5} (median) per reactor per year and SL-1 corresponds to a level with a probability of being exceeded of 1×10^{-2} (mean value) per reactor per year.

2.4 In the plant design SL-2⁵ is associated with the most stringent safety requirements, while SL-1 corresponds to a less severe, more probable earthquake level that normally has different safety implications. In general, SL-1 is used for load combinations (when, for reasons related to probabilities, other events are combined with an earthquake at lower intensity), post-accident inspection and national licensing requirements⁶. For low levels of seismic hazard, SL-1 is usually not associated with safety requirements but is related to operational requirements only. Safety classified items should be designed with reference to either SL-1 or SL-2 according to their safety function (usually associated with SL-2) and to operational requirements for operability or licensing, for example⁷ (usually associated with SL-1).

2.5. Where a deterministic approach has been selected for the hazard evaluation or directly for the design basis specification, an estimation of the associated return period should be made, at least to allow a comparison with national standards for the design of industrial facilities. This value should then be assessed in the safety assessment phase, as recommended in Ref. [9].

2.6. It is common practice to have more than one design basis earthquake associated with each hazard level, SL-1 and SL-2, each one representative of a potential seismogenic area. All of these should be considered in the design, and appropriate enveloping should be carried out on the results.

2.7. Regardless of the exposure to seismic hazard, an SL-2 design basis earthquakes should be adopted for every nuclear power plant for the design of safety classified items. The minimum level should correspond to a peak ground acceleration of 0.1g (zero period of the design response spectrum), to be considered at the free field. A unified, site compatible spectrum should be associated with this peak ground acceleration value. In this case SL-1 may be assumed to be coincident with SL-2.

⁵ This level corresponds to an earthquake level often denoted as a safe shutdown earthquake. The term design basis earthquake is sometimes used to refer to a standard or unified safe shutdown earthquake that is site independent.

⁶ See Ref. [13] for a general discussion on operating limits and conditions and their correlation with design safety.

⁷ In some States some items are still designed with reference to both an SL-2 and a lower level hazard, often termed the operating base earthquake. However, in this Safety Guide operational requirements are not established together with safety requirements as they relate to different objectives. The SL-1 (or the operating base earthquake) is addressed in this Safety Guide only in relation to its application in safety analysis and design.

2.8. The design basis earthquake for any hazard level should be defined with account taken of the frequency distribution of the potential associated ground motions, their duration and their power spectral density. Particular care should be taken when two or more sources are identified as major contributors to the hazard. In this case enveloping for different ground motions (or response spectra) originated by different physical mechanisms (e.g. far field and near field mechanisms) associated with the same hazard level should be performed with care. Owing to the potential differences in seismic demands on SSCs, it may be appropriate to perform a separate capacity evaluation for the different ground motions.

2.9. Seismic input motion is normally defined in the free field, at the surface of the ground or on the bedrock [2]. Seismic input can be defined in terms of spectral acceleration, velocity or displacement as a function of the frequency of ground motion.

2.10. When the seismic input is needed for the foundation level, a deconvolution–convolution process may be required for its evaluation, as explained in Ref. [3].

SEISMIC CATEGORIZATION FOR STRUCTURES, SYSTEMS AND COMPONENTS

2.11. Any major effects to be expected at a site from an earthquake would be related to the vibrations induced in the SSCs through the structures of the plant. Vibrations can affect the plant safety functions directly or by indirect interaction mechanisms such as mechanical interaction between items, release of hazardous substances, fire or flooding induced by an earthquake, impairment of operator access and unavailability of evacuation routes or access routes.

2.12. All items experience any seismic loading that occurs, and the performance required in the event of an earthquake is not necessarily related to the reference safety function considered in the safety classification (Ref. [1], paras 5.1 and 5.2), which is based on the most demanding of all the safety functions required by all the design basis conditions (postulated initiating events). For a safety oriented approach to design, therefore, in addition to the safety classification, SSCs may be grouped into four or more categories in terms of their importance to safety during and after an earthquake.

2.13. In the event that an external event categorization is available, as defined in Ref. [4], the seismic categorization⁸ as proposed here should be consistent with it. However, a seismic categorization should also be defined in the absence of a general external event classification, owing to the peculiarity of the seismic design, and the seismic categorization is therefore redefined here. Other classification methods would be acceptable provided that they met the same acceptance criteria as defined below.

2.14. A seismic category 1 should be established for the plant. Items in this category should be designed to withstand the consequences of ground motions associated with earthquakes of level SL-2. Seismic category 1 usually coincides with the highest categories identified for safety and covers all items important to safety. In particular, seismic category 1 should include the following items as well as all the structures that support them:

- (a) Items whose failure could directly or indirectly cause accident conditions as a consequence of an earthquake of level SL-2;
- (b) Items required for shutting down the reactor, maintaining the reactor in a shutdown condition, removing residual heat over the required period and monitoring parameters essential to these functions;
- (c) Items that are required to prevent or mitigate non-permissible radioactive releases (limits for which should be established by the regulatory body) in the event of any postulated initiating events considered in the design, regardless of their probability of occurrence.

2.15. The selection of items under item (c) above is related to the defence in depth approach: in the event of an earthquake of level SL-2, all levels of defence are required to be available at all times (Ref. [1], para. 4.4)⁹. The physical barriers designed to protect the plant from external events other than seismic events should maintain their integrity and functionality during an earthquake.

⁸ Seismic categorization is the process by which a plant item is assigned to a seismic category in accordance with its required performance during and after an earthquake, in addition to other classifications such as safety, quality assurance and maintenance classifications. The relevant acceptance criterion associated with the item is part of the categorization.

⁹ In the framework of the defence in depth approach, protection against all external events is part of level 1 of defence in depth.

2.16. Nuclear power plant items of seismic category 1 should be designed, installed and maintained in accordance with the most stringent national practices for nuclear applications: the safety margin¹⁰ should be higher than the safety margin used in facilities at conventional risk. For any item in seismic category 1, an appropriate acceptance criterion¹¹ should be established (such as the value of a design parameter indicating functionality, leaktightness or maximum distortion) in accordance with the required safety function. However, in some cases the acceptance criteria for the physical barriers may be reduced for load combinations including an earthquake of level SL-2 (Ref. [1], para. 5.7), provided that the effects on the plant's safety functions are evaluated in detail.

2.17. A seismic category 2 should be established for the plant. Among all plant items, including those that are not items important to safety [1], seismic category 2 includes:

- (1) Items that may have spatial interactions (e.g. due to collapse, falling or dislodgement) or any other interactions (e.g. via the release of hazardous substances, fire or flooding, or earthquake induced interactions) with items in seismic categories 1 and 3. It should be demonstrated that the potential effects due to, and the damage caused to, items in seismic category 2 would affect neither the safety related functions of any of the items in seismic categories 1 and 3 (para 2.20) nor any safety related operator action.
- (2) Items not included in seismic category 1 (particularly items under (b) and (c) in para. 2.14) that are required to prevent or mitigate plant accident conditions (originated by postulated initiating events other than earthquakes) for a period long enough that there is a reasonable likelihood that an SL-2 earthquake may occur during that period.

¹⁰ In this context, the safety margin is the result of special provisions in design, material selection, construction, maintenance and quality assurance.

¹¹ Acceptance criteria are specified bounds on the value of a functional or condition indicator used to assess the ability of a structure, system or component to perform its design function. Acceptance criteria as used here means specified bounds on the value of a functional or condition indicator for a structure, system or component in a defined postulated initiating event (e.g. an indicator relating to functionality, leaktightness or non-interaction).

- (3) Items related to the accessibility of the site and items necessary for the implementation of the emergency evacuation plan.

2.18. In particular, when, as a result of an earthquake, any interaction is expected on the basis of analysis, testing or experience to occur, and this could jeopardize the functioning of items in seismic category 1 or 3 (including operator action), one of the following measures should be taken:

- (a) Such an item in seismic category 2 should be reclassified to seismic category 1 or 3 and designed accordingly.
- (b) Such items in seismic category 2 should be qualified against SL-2 in order not to adversely affect items in seismic category 1 or 3.
- (c) The endangered items in seismic category 1 or 3 should be suitably protected so that their functioning is not jeopardized by the interaction with items in seismic category 2.

2.19. Items in seismic category 2 should follow the practice for design, installation and maintenance for nuclear applications. However, in the hypothesis in para. 2.18 (b) (interacting items), lower intrinsic safety margins than those specified in nuclear standards can be applied when the probability of interaction with items in seismic category 1 or 3 is considered very low.

2.20. A seismic category 3 should be established for the plant. Seismic category 3 should include all items that could pose a radiological hazard but that are not related to the reactor (e.g. the spent fuel building and the radioactive waste building). In some States these items are required to have safety margins consistent with their potential for radiological consequences, which are expected to be different from the potentials associated with the reactor, as they would be in general related to different release mechanisms (e.g. leakage from waste, failure of spent fuel casks).

2.21. A seismic category 4 should be established for the plant. Seismic category 4 should include all items that are not in seismic category 1 or seismic category 2 or 3.

2.22. Nuclear power plant items in seismic category 4 should be designed as a minimum in accordance with national practice for non-nuclear applications, and therefore for facilities at conventional risk. For some items of this seismic category important to the operation of the plant, it may be reasonable to choose more stringent acceptance criteria based only on operational targets. Such an approach would minimize the need for plant

shutdown, inspection and relicensing, thus allowing the plant to continue to operate.

2.23. The inclusion of an item in a seismic category should be based on a clear understanding of the functional requirements that should be ensured for safety during or after an earthquake. According to their different functions, parts of the same system may belong to different categories. Tightness, degree of damage (e.g. fatigue, wear and tear), mechanical or electrical functional capability, maximum displacement, degree of permanent distortion and preservation of geometrical dimensions are examples of aspects that should be considered.

2.24. Seismic loads should be considered for all possible operational modes of the plant. In seismic design, consideration should be given to the categorization of the items being designed.

2.25. The seismic categorization depends on the reactor type (e.g. pressurized water reactor and boiling water reactor), on the regulations and standards of the regulatory body of the State concerned, and on site specific boundary conditions (e.g. the availability of cooling water resources).

2.26. As part of the design process, a detailed list of all items should be produced with the associated acceptance criteria. Sample lists are given in the Appendix.

COMBINATION OF EARTHQUAKE LOADS WITH OPERATING CONDITION LOADS

2.27. Design loads are grouped as follows:

- L1 Loads during normal operation,
- L2 Additional loads during anticipated operational occurrences,
- L3 Additional loads during accident conditions.

2.28. Seismic loads should be calculated for the specific location of the item under consideration, with account taken of the characteristics of the soil and plant structures, including mass and stiffness, and the distribution of equipment within the plant. It should be ensured that the bounding loading combinations are considered.

2.29. For seismic design, loads from earthquakes should be combined with plant process loads as follows (Table I):

- (a) For items in seismic categories 1 and 3, L1 loads should be combined with the design basis earthquake, according to their categorization.
- (b) For items in seismic categories 1 and 3, L1 and L2 or L3 loads should be combined with the design basis earthquake if the L2 or L3 loads are caused by the earthquake and/or have a high probability of coinciding with the earthquake loads (which may be the case, for example, for L2 loads that occur sufficiently frequently, independently of an earthquake¹²).

TABLE I. LOAD COMBINATIONS WITH SEISMIC LOADS

Seismic category	L1	L2	L3	SL-2 ^a	Safety margin
1	×			×	According to design codes for facilities at higher risk (nuclear code).
b	×	×		×	Same as above.
b	×		×	×	Same as above.
2	×			×	According to design codes for facilities at higher risk (nuclear code) or lower risk ^c .
b	×	×		×	Same as above.
b	×		×	×	Same as above.
3	×			×	According to design codes for facilities at risks different from (usually lower than) those for nuclear power plants.
b	×	×		×	Same as above.
b	×		×	×	Same as above.
4	×			×	According to design codes for facilities at conventional risk.

^a SL-1 may be used in some load combinations, other than those with SL-2, if supported by probabilistic arguments.

^b To be considered only if there is either a causal dependence on SL-2 or a high probability of coincidence.

^c Lower safety margins may be considered if a low probability of interaction can be demonstrated.

¹² Typical L2 loads induced by a seismic event could be loads created by tripping of the reactor or by a pressure peak in the primary system due to a tripped turbine in a boiling water reactor with a small steam bypass capacity to the condenser.