

IAEA Safety Standards

for protecting people and the environment

Evaluation of Seismic Safety for Nuclear Installations

Specific Safety Guide

No. SSG-89



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International Atomic Energy Agency



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EVALUATION OF SEISMIC SAFETY FOR NUCLEAR INSTALLATIONS



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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".

IAEA SAFETY STANDARDS SERIES No. SSG-89

EVALUATION OF SEISMIC SAFETY FOR NUCLEAR INSTALLATIONS

SPECIFIC SAFETY GUIDE

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2024

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FOREWORD

by Rafael Mariano Grossi
Director General

The IAEA's Statute authorizes it to "establish...standards of safety for protection of health and minimization of danger to life and property". These are standards that the IAEA must apply to its own operations, and that States can apply through their national regulations.

The IAEA started its safety standards programme in 1958 and there have been many developments since. As Director General, I am committed to ensuring that the IAEA maintains and improves upon this integrated, comprehensive and consistent set of up to date, user friendly and fit for purpose safety standards of high quality. Their proper application in the use of nuclear science and technology should offer a high level of protection for people and the environment across the world and provide the confidence necessary to allow for the ongoing use of nuclear technology for the benefit of all.

Safety is a national responsibility underpinned by a number of international conventions. The IAEA safety standards form a basis for these legal instruments and serve as a global reference to help parties meet their obligations. While safety standards are not legally binding on Member States, they are widely applied. They have become an indispensable reference point and a common denominator for the vast majority of Member States that have adopted these standards for use in national regulations to enhance safety in nuclear power generation, research reactors and fuel cycle facilities as well as in nuclear applications in medicine, industry, agriculture and research.

The IAEA safety standards are based on the practical experience of its Member States and produced through international consensus. The involvement of the members of the Safety Standards Committees, the Nuclear Security Guidance Committee and the Commission on Safety Standards is particularly important, and I am grateful to all those who contribute their knowledge and expertise to this endeavour.

The IAEA also uses these safety standards when it assists Member States through its review missions and advisory services. This helps Member States in the application of the standards and enables valuable experience and insight to be shared. Feedback from these missions and services, and lessons identified from events and experience in the use and application of the safety standards, are taken into account during their periodic revision.

I believe the IAEA safety standards and their application make an invaluable contribution to ensuring a high level of safety in the use of nuclear technology. I encourage all Member States to promote and apply these standards, and to work with the IAEA to uphold their quality now and in the future.

THE IAEA SAFETY STANDARDS

BACKGROUND

Radioactivity is a natural phenomenon and natural sources of radiation are features of the environment. Radiation and radioactive substances have many beneficial applications, ranging from power generation to uses in medicine, industry and agriculture. The radiation risks to workers and the public and to the environment that may arise from these applications have to be assessed and, if necessary, controlled.

Activities such as the medical uses of radiation, the operation of nuclear installations, the production, transport and use of radioactive material, and the management of radioactive waste must therefore be subject to standards of safety.

Regulating safety is a national responsibility. However, radiation risks may transcend national borders, and international cooperation serves to promote and enhance safety globally by exchanging experience and by improving capabilities to control hazards, to prevent accidents, to respond to emergencies and to mitigate any harmful consequences.

States have an obligation of diligence and duty of care, and are expected to fulfil their national and international undertakings and obligations.

International safety standards provide support for States in meeting their obligations under general principles of international law, such as those relating to environmental protection. International safety standards also promote and assure confidence in safety and facilitate international commerce and trade.

A global nuclear safety regime is in place and is being continuously improved. IAEA safety standards, which support the implementation of binding international instruments and national safety infrastructures, are a cornerstone of this global regime. The IAEA safety standards constitute a useful tool for contracting parties to assess their performance under these international conventions.

THE IAEA SAFETY STANDARDS

The status of the IAEA safety standards derives from the IAEA's Statute, which authorizes the IAEA to establish or adopt, in consultation and, where appropriate, in collaboration with the competent organs of the United Nations and with the specialized agencies concerned, standards of safety for protection of health and minimization of danger to life and property, and to provide for their application.

With a view to ensuring the protection of people and the environment from harmful effects of ionizing radiation, the IAEA safety standards establish fundamental safety principles, requirements and measures to control the radiation exposure of people and the release of radioactive material to the environment, to restrict the likelihood of events that might lead to a loss of control over a nuclear reactor core, nuclear chain reaction, radioactive source or any other source of radiation, and to mitigate the consequences of such events if they were to occur. The standards apply to facilities and activities that give rise to radiation risks, including nuclear installations, the use of radiation and radioactive sources, the transport of radioactive material and the management of radioactive waste.

Safety measures and security measures¹ have in common the aim of protecting human life and health and the environment. Safety measures and security measures must be designed and implemented in an integrated manner so that security measures do not compromise safety and safety measures do not compromise security.

The IAEA safety standards reflect an international consensus on what constitutes a high level of safety for protecting people and the environment from harmful effects of ionizing radiation. They are issued in the IAEA Safety Standards Series, which has three categories (see Fig. 1).

Safety Fundamentals

Safety Fundamentals present the fundamental safety objective and principles of protection and safety, and provide the basis for the safety requirements.

Safety Requirements

An integrated and consistent set of Safety Requirements establishes the requirements that must be met to ensure the protection of people and the environment, both now and in the future. The requirements are governed by the objective and principles of the Safety Fundamentals. If the requirements are not met, measures must be taken to reach or restore the required level of safety. The format and style of the requirements facilitate their use for the establishment, in a harmonized manner, of a national regulatory framework. Requirements, including numbered ‘overarching’ requirements, are expressed as ‘shall’ statements. Many requirements are not addressed to a specific party, the implication being that the appropriate parties are responsible for fulfilling them.

Safety Guides

Safety Guides provide recommendations and guidance on how to comply with the safety requirements, indicating an international consensus that it

¹ See also publications issued in the IAEA Nuclear Security Series.

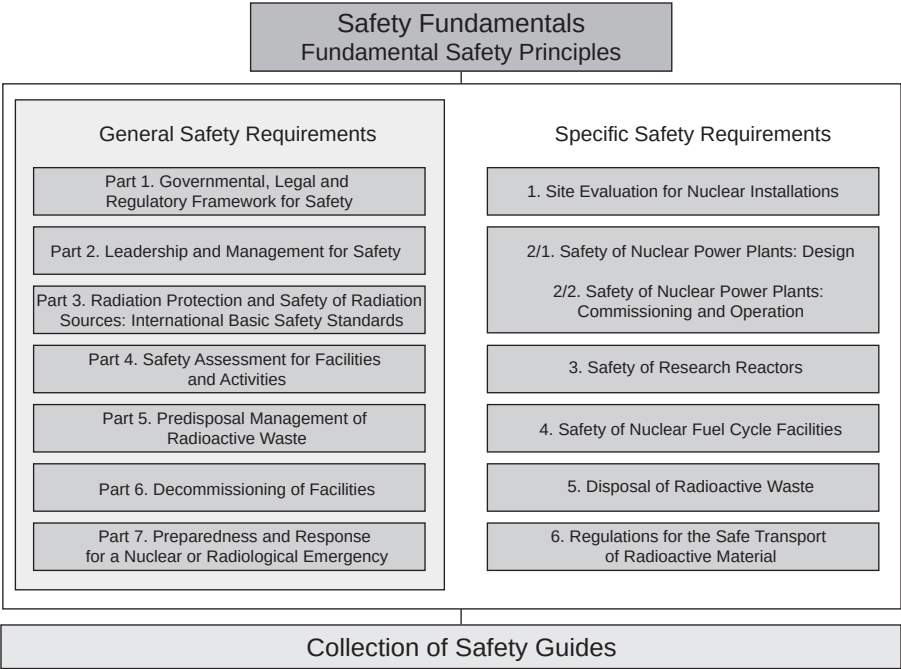


FIG. 1. The long term structure of the IAEA Safety Standards Series.

is necessary to take the measures recommended (or equivalent alternative measures). The Safety Guides present international good practices, and increasingly they reflect best practices, to help users striving to achieve high levels of safety. The recommendations provided in Safety Guides are expressed as ‘should’ statements.

APPLICATION OF THE IAEA SAFETY STANDARDS

The principal users of safety standards in IAEA Member States are regulatory bodies and other relevant national authorities. The IAEA safety standards are also used by co-sponsoring organizations and by many organizations that design, construct and operate nuclear facilities, as well as organizations involved in the use of radiation and radioactive sources.

The IAEA safety standards are applicable, as relevant, throughout the entire lifetime of all facilities and activities — existing and new — utilized for peaceful purposes and to protective actions to reduce existing radiation risks. They can be

used by States as a reference for their national regulations in respect of facilities and activities.

The IAEA's Statute makes the safety standards binding on the IAEA in relation to its own operations and also on States in relation to IAEA assisted operations.

The IAEA safety standards also form the basis for the IAEA's safety review services, and they are used by the IAEA in support of competence building, including the development of educational curricula and training courses.

International conventions contain requirements similar to those in the IAEA safety standards and make them binding on contracting parties. The IAEA safety standards, supplemented by international conventions, industry standards and detailed national requirements, establish a consistent basis for protecting people and the environment. There will also be some special aspects of safety that need to be assessed at the national level. For example, many of the IAEA safety standards, in particular those addressing aspects of safety in planning or design, are intended to apply primarily to new facilities and activities. The requirements established in the IAEA safety standards might not be fully met at some existing facilities that were built to earlier standards. The way in which IAEA safety standards are to be applied to such facilities is a decision for individual States.

The scientific considerations underlying the IAEA safety standards provide an objective basis for decisions concerning safety; however, decision makers must also make informed judgements and must determine how best to balance the benefits of an action or an activity against the associated radiation risks and any other detrimental impacts to which it gives rise.

DEVELOPMENT PROCESS FOR THE IAEA SAFETY STANDARDS

The preparation and review of the safety standards involves the IAEA Secretariat and five Safety Standards Committees, for emergency preparedness and response (EPReSC) (as of 2016), nuclear safety (NUSSC), radiation safety (RASSC), the safety of radioactive waste (WASSC) and the safe transport of radioactive material (TRANSSC), and a Commission on Safety Standards (CSS) which oversees the IAEA safety standards programme (see Fig. 2).

All IAEA Member States may nominate experts for the Safety Standards Committees and may provide comments on draft standards. The membership of the Commission on Safety Standards is appointed by the Director General and includes senior governmental officials having responsibility for establishing national standards.

A management system has been established for the processes of planning, developing, reviewing, revising and establishing the IAEA safety standards.

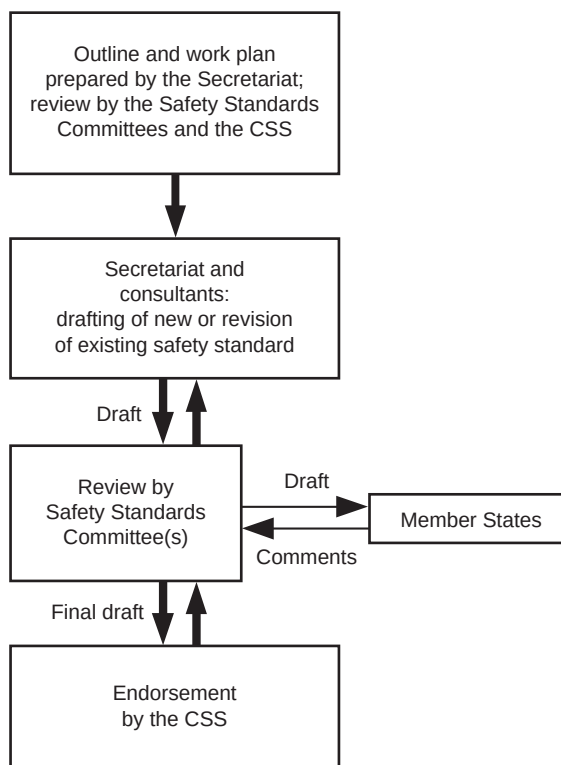


FIG. 2. The process for developing a new safety standard or revising an existing standard.

It articulates the mandate of the IAEA, the vision for the future application of the safety standards, policies and strategies, and corresponding functions and responsibilities.

INTERACTION WITH OTHER INTERNATIONAL ORGANIZATIONS

The findings of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and the recommendations of international expert bodies, notably the International Commission on Radiological Protection (ICRP), are taken into account in developing the IAEA safety standards. Some safety standards are developed in cooperation with other bodies in the United Nations system or other specialized agencies, including the Food and Agriculture Organization of the United Nations, the United Nations Environment Programme, the International Labour Organization, the OECD Nuclear Energy Agency, the Pan American Health Organization and the World Health Organization.

INTERPRETATION OF THE TEXT

Safety related terms are to be understood as defined in the IAEA Nuclear Safety and Security Glossary (see <https://www.iaea.org/resources/publications/iaea-nuclear-safety-and-security-glossary>). Otherwise, words are used with the spellings and meanings assigned to them in the latest edition of The Concise Oxford Dictionary. For Safety Guides, the English version of the text is the authoritative version.

The background and context of each standard in the IAEA Safety Standards Series and its objective, scope and structure are explained in Section 1, Introduction, of each publication.

Material for which there is no appropriate place in the body text (e.g. material that is subsidiary to or separate from the body text, is included in support of statements in the body text, or describes methods of calculation, procedures or limits and conditions) may be presented in appendices or annexes.

An appendix, if included, is considered to form an integral part of the safety standard. Material in an appendix has the same status as the body text, and the IAEA assumes authorship of it. Annexes and footnotes to the main text, if included, are used to provide practical examples or additional information or explanation. Annexes and footnotes are not integral parts of the main text. Annex material published by the IAEA is not necessarily issued under its authorship; material under other authorship may be presented in annexes to the safety standards. Extraneous material presented in annexes is excerpted and adapted as necessary to be generally useful.

1. INTRODUCTION

BACKGROUND

1.1. This Safety Guide provides recommendations on the evaluation of the safety of nuclear installations against the effects generated by earthquakes, in order to meet the applicable safety requirements established in the following publications:

- IAEA Safety Standards Series No. GSR Part 4 (Rev. 1), Safety Assessment for Facilities and Activities [1];
- IAEA Safety Standards Series No. SSR-1, Site Evaluation for Nuclear Installations [2];
- IAEA Safety Standards Series No. SSR-2/1 (Rev. 1), Safety of Nuclear Power Plants: Design [3];
- IAEA Safety Standards Series No. SSR-2/2 (Rev. 1), Safety of Nuclear Power Plants: Commissioning and Operation [4];
- IAEA Safety Standards Series No. SSR-3, Safety of Research Reactors [5];
- IAEA Safety Standards Series No. SSR-4, Safety of Nuclear Fuel Cycle Facilities [6].

1.2. This Safety Guide addresses the requirements for both existing and new nuclear installations. For an existing installation, safety assessments are required to be reviewed periodically and the review may consider potential changes in the characterization of seismic hazards at the site [1, 2, 4–6]. At the design stage of a new nuclear installation, it is required that the design be checked to ensure that it provides for an adequate margin to protect items important to safety against levels of external hazards more severe than those selected for the design basis [3, 5, 6]. In addition, it is required to be checked that the design of nuclear power plants provides for an adequate margin to protect items ultimately necessary to prevent an early radioactive release or a large radioactive release in the event of levels of natural hazards exceeding those considered for the design [3]. Hence, the seismic safety evaluations described in this Safety Guide can be performed either as part of the design development or as a process subsequent to and separate from the design basis cases.

1.3. This Safety Guide is related to a number of other IAEA Safety Guides dealing with seismic hazard and seismic design, including IAEA Safety Standards Series Nos SSG-9 (Rev. 1), Seismic Hazards in Site Evaluation for Nuclear Installations [7]; SSG-67, Seismic Design for Nuclear Installations [8]; and NS-G-3.6, Geotechnical Aspects of Site Evaluation and Foundations for Nuclear

Power Plants [9]. In addition, Ref. [10] provides detailed information relevant to this Safety Guide.

1.4. Guidelines for the seismic safety evaluation of existing nuclear installations — in particular nuclear power plants — have been developed and used in many Member States since the beginning of the 1990s.¹ More recently, the criteria and methods used for the seismic safety evaluation of existing nuclear installations have started being used, with some adaptation, to assess beyond design basis earthquake events for new nuclear installation designs prior to construction. This evaluation of new designs is different from the seismic design and qualification of the installation, which may be performed following the recommendations in SSG-67 [8]. The seismic safety evaluation of a new design is intended to explore beyond design basis events for the new design. Some Member States may have other applicable criteria for seismic safety assessment of new designs for beyond design basis earthquakes.

1.5. The main difference between seismic safety evaluation, and seismic design and qualification is in the evaluation criteria used [8]. Design, as traditionally understood,² uses conservatively defined loads and capacities for structures, systems and components (SSCs) in order to meet the limits given in the design code. Thus, this design approach is aimed at meeting the limits given by the codes for the design basis earthquake in every SSC in order to demonstrate safety. In contrast, in seismic safety evaluation, the aim is to establish the actual capacities of the SSCs in the as-is condition for use in the evaluation of the seismic capacity of the nuclear installation as a whole. Accordingly, the objective of seismic safety evaluations is to be realistic or slightly conservative. The experience from past seismic events, testing and analytical estimates of capacity are used in the seismic safety evaluation, and expert judgement plays a significant role. The as-is condition of the nuclear installation includes its as-built, as-operated, as-modified and as-maintained conditions, and its condition of ageing at the time of the evaluation.

¹ The development and use of guidelines on the seismic safety evaluation of existing nuclear installations started in the United States of America, where the application of such guidelines to all existing nuclear power plants was required by national regulations.

² The final seismic safety evaluation to check that the design provides for an adequate margin to protect items important to safety against levels of external hazards more severe than those selected for the design basis, as required by Refs [3, 5, 6], can now be considered as part of the design process.

1.6. The terms used in this Safety Guide are to be understood as defined in the IAEA Nuclear Safety and Security Glossary [11]. Explanations of terms specific to this Safety Guide are provided in footnotes.

1.7. This Safety Guide supersedes IAEA Safety Standards Series No. NS-G-2.13, Evaluation of Seismic Safety for Existing Nuclear Installations³.

OBJECTIVE

1.8. The objective of this Safety Guide is to provide recommendations on the seismic safety evaluation of nuclear installations in order to meet the applicable safety requirements established in GSR Part 4 (Rev. 1) [1], SSR-1 [2], SSR-2/1 (Rev. 1) [3], SSR-2/2 (Rev. 1) [4], SSR-3 [5] and SSR-4 [6]. For existing installations, such an evaluation may be prompted by a seismic hazard perceived to be greater than that originally established in the design basis, by new regulatory requirements, by new findings on the seismic vulnerability of SSCs or by the need to demonstrate performance for beyond design basis earthquake events, consistent with internationally recognized good practices. For new designs of nuclear installations, the seismic safety evaluation is motivated by the need to demonstrate that the safety margins above the design basis earthquake are sufficient to avoid cliff edge effects⁴ and, in the case of nuclear power plants, sufficient to protect items ultimately necessary to prevent radioactive releases in the event of an earthquake with a severity exceeding that considered for design.

1.9. This Safety Guide is intended for use by regulatory bodies responsible for establishing regulatory requirements; by designers and safety analysts involved in the seismic design of new nuclear installations; and by operating organizations of existing installations directly responsible for conducting seismic safety evaluations and upgrading seismic safety programmes.

³ INTERNATIONAL ATOMIC ENERGY AGENCY, Evaluation of Seismic Safety for Existing Nuclear Installations, IAEA Safety Standards Series No. NS-G-2.13, IAEA, Vienna (2009).

⁴ A cliff edge effect, in a nuclear power plant, is an instance of severely abnormal plant behaviour caused by an abrupt transition from one plant status to another following a small deviation in a plant parameter, and thus a sudden large variation in plant conditions in response to a small variation in an input [3]. In the context of seismic safety, the term ‘plant parameter’ in this definition refers to seismic ground motion at the plant site.

SCOPE

1.10. This Safety Guide addresses all types of new and existing nuclear installation as defined in the IAEA Nuclear Safety and Security Glossary [11], as follows:

- (a) Nuclear power plants;
- (b) Research reactors (including subcritical and critical assemblies) and any adjoining radioisotope production facilities;
- (c) Storage facilities for spent fuel;
- (d) Facilities for the enrichment of uranium;
- (e) Nuclear fuel fabrication facilities;
- (f) Conversion facilities;
- (g) Facilities for the reprocessing of spent fuel;
- (h) Facilities for the predisposal management of radioactive waste arising from nuclear fuel cycle facilities;
- (i) Nuclear fuel cycle related research and development facilities.

Most of the recommendations provided in this Safety Guide apply to all types of nuclear installation and all types of reactor, but aspects such as performance criteria and systems modelling are specific to each installation type. The recommendations for nuclear power plants are also applicable to other nuclear installations through the use of a graded approach.

1.11. For the purposes of this Safety Guide, existing nuclear installations are installations that are either (a) at the operational stage (including long term operation and extended temporary shutdown periods)⁵ or (b) at a pre-operational stage at which the construction of structures, the manufacture, installation and/or assembly of components and systems, and commissioning activities are significantly advanced or fully completed. In existing nuclear installations at the operational or pre-operational stages, a change of the original design bases (e.g. a new seismic hazard at the site) or a change in the regulatory requirements regarding the consideration of seismic hazard and/or seismic design of the installation might lead to important technical modifications.

1.12. For the purposes of this Safety Guide, new nuclear installations are installations whose design has reached a level of development at which a detailed definition of SSCs is available, including the data listed in paras 4.2–4.5. In this

⁵ The operational stage ends with the permanent removal of all radioactive material.

Safety Guide, it is considered that new nuclear installations are not yet constructed or construction is at a very early stage.⁶

1.13. Three assessment methodologies are addressed in detail in this Safety Guide: (a) the deterministic approach, generally represented by seismic margin assessment (SMA); (b) seismic probabilistic safety assessment (SPSA); and (c) a combination of SMA and SPSA known as ‘probabilistic safety assessment (PSA) based SMA’. Variations of these approaches or alternative approaches may also be demonstrated to be acceptable (see Section 3).

STRUCTURE

1.14. Section 2 identifies the safety requirements addressed by this Safety Guide, and describes general concepts and provides general recommendations relating to the seismic safety evaluation of nuclear installations. Section 3 provides recommendations on the selection of the methodology for performing the seismic safety evaluation. Section 4 provides recommendations on the requirements for data collection and investigations for new and existing installations. Section 5 forms the core of this Safety Guide; it focuses on nuclear power plants, providing recommendations on the assessment of seismic hazards, the seismic capability necessary for level 4 of the defence in depth concept, and the implementation of the SMA, SPSA and PSA based SMA methodologies for seismic safety evaluation. Section 6 provides recommendations on applying a graded approach to the seismic safety evaluation of nuclear installations other than nuclear power plants (with reference to Section 5, where appropriate). Section 7 provides recommendations on the use of seismic safety evaluation results, including for potential seismic upgrading. Section 8 provides recommendations on the management system to be established for the performance of all seismic safety evaluation activities and identifies the need for configuration management in future activities to maintain the seismic capacity as evaluated. Sections 1–4 and 6–8 apply (in full or in part) to all nuclear installations. Section 5 is focused on nuclear power plants but can be applied to other nuclear installations through the use of a graded approach, as described in Section 6.

1.15. The Appendix to this Safety Guide presents seismic failure mode considerations for different types of SSC. The annex provides an example of criteria for defining seismic design classes and performance targets in a nuclear installation.

⁶ A new nuclear installation may also be a standard design based on generic site parameters for which the site has not yet been specified.

2. GENERAL CONSIDERATIONS FOR THE EVALUATION OF SEISMIC SAFETY FOR NUCLEAR INSTALLATIONS

SAFETY REQUIREMENTS APPLICABLE TO SEISMIC SAFETY EVALUATION

Safety assessment

2.1. Various safety requirements established in GSR Part 4 (Rev. 1) [1] apply to seismic design robustness and periodic review of seismic safety.

- Requirement 10 of GSR Part 4 (Rev. 1) [1] states that **“It shall be determined in the safety assessment whether a facility or activity uses, to the extent practicable, structures, systems and components of robust and proven design.”**
- Requirement 13 of GSR Part 4 (Rev. 1) [1] states that **“It shall be determined in the assessment of defence in depth whether adequate provisions have been made at each of the levels of defence in depth.”**
- Paragraph 4.48A of GSR Part 4 (Rev. 1) [1] states that (footnote omitted) **“Where practicable, the safety assessment shall confirm that there are adequate margins to avoid cliff edge effects that would have unacceptable consequences.”**
- Requirement 15 of GSR Part 4 (Rev. 1) [1] states that **“Both deterministic and probabilistic approaches shall be included in the safety analysis.”**
- Requirement 24 of GSR Part 4 (Rev. 1) [1] states that **“The safety assessment shall be periodically reviewed and updated.”**

2.2. Similar provisions are required to be applied to research reactors and to nuclear fuel cycle facilities, as established in Requirement 5 of SSR-3 [5] and Requirement 5 of SSR-4 [6], respectively.

Hazard assessment

2.3. With regard to potential changes in the perceived seismic hazard, Requirement 29 of SSR-1 [2] states:

“All natural and human induced external hazards and site conditions shall be periodically reviewed by the operating organization as part of

the periodic safety review and as appropriate throughout the lifetime of the nuclear installation, with due account taken of operating experience and new safety related information.”

Margin provided by the design

2.4. Various safety requirements established in SSR-2/1 (Rev. 1) [3] apply to the seismic margin to be provided by the design of nuclear power plants⁷. Requirement 17 of SSR-2/1 (Rev. 1) [3] states:

“All foreseeable internal hazards and external hazards, including the potential for human induced events directly or indirectly to affect the safety of the nuclear power plant, shall be identified and their effects shall be evaluated. Hazards shall be considered in designing the layout of the plant and in determining the postulated initiating events and generated loadings for use in the design of relevant items important to safety for the plant.”

Paragraph 5.21 of SSR-2/1 (Rev. 1) [3] states (footnote omitted):

“The design of the plant shall provide for an adequate margin to protect items important to safety against levels of external hazards to be considered for design, derived from the hazard evaluation for the site, and to avoid cliff edge effects.”

Paragraph 5.21A of SSR-2/1 (Rev. 1) [3] states:

“The design of the plant shall also provide for an adequate margin to protect items ultimately necessary to prevent an early radioactive release or a large radioactive release in the event of levels of natural hazards exceeding those considered for design, derived from the hazard evaluation for the site.”

2.5. Similar provisions are required to be applied to research reactors and to nuclear fuel cycle facilities, as established in Requirement 19 of SSR-3 [5] and Requirement 16 of SSR-4 [6], respectively.

⁷ Paragraph 1.3 of SSR-2/1 (Rev. 1) [3] states that “It might not be practicable to apply all the requirements of this Safety Requirements publication to nuclear power plants that are already in operation or under construction.” Hence, for the purposes of the present Safety Guide, the requirements quoted here are considered applicable only to new nuclear power plants.

Effects of changes during operation

2.6. Various safety requirements established in SSR-2/2 (Rev. 1) [4] apply to assessing the consequences of changes in the perceived seismic hazard during operation of nuclear power plants. Requirement 12 of SSR-2/2 (Rev. 1) [4] states:

“Systematic safety assessments of the plant, in accordance with the regulatory requirements, shall be performed by the operating organization throughout the plant’s operating lifetime, with due account taken of operating experience and significant new safety related information from all relevant sources.”

Paragraph 4.44 of SSR-2/2 (Rev. 1) [4] states:

“Safety reviews such as periodic safety reviews or safety assessments under alternative arrangements shall be carried out throughout the lifetime of the plant, at regular intervals and as frequently as necessary (typically no less frequently than once in ten years). Safety reviews shall address, in an appropriate manner: the consequences of the cumulative effects of plant ageing and plant modification; equipment requalification; operating experience, including national and international operating experience; current national and international standards; technical developments; organizational and management issues; and site related aspects. Safety reviews shall be aimed at ensuring a high level of safety throughout the operating lifetime of the plant.”

GENERAL CONCEPTS FOR SEISMIC SAFETY EVALUATION OF NUCLEAR INSTALLATIONS

2.7. Well designed and well maintained nuclear installations, especially nuclear power plants, have an inherent capability to resist beyond design basis earthquakes. This inherent capability or robustness — usually described in terms of the seismic margin — is a direct consequence of (a) the conservatism that is present in the seismic design and qualification procedures used according to previous⁸ or current practices in earthquake engineering and (b) the fact that, in

⁸ Previous codes and practices, especially older ones, might not always demonstrate a margin.

the design of nuclear power plants, the seismic loads may not be the governing loads for some SSCs.⁹

2.8. The current criteria for seismic design and qualification applicable to nuclear power plants often introduce substantial seismic design margins that are not fully quantified by the traditional design process. The process by which seismic margins develop through the various stages of analysis, design and construction might lead to large variations in the margins throughout the nuclear installation. The seismic margin typically varies from one location in the installation to another, from one SSC to another and from one part of the same structure to another.¹⁰ Consequently, when evaluating the seismic safety of a nuclear installation, there should be a detailed examination of the actual design methods and, for existing installations, of the as-is condition, in order to understand the sources of conservatism and margins.

2.9. The methodologies presented in this Safety Guide are intended for evaluating and quantifying the seismic margin over the design basis earthquake for a particular nuclear installation. Through understanding the realistic seismic response of the SSCs, in terms of their safety functions, the maximum seismic demand for which there is high confidence that the safety functions will be fulfilled can be determined. The SSC capacities of high confidence derived in this way can be used to assess the seismic safety margin of the installation as a whole.

2.10. The seismic safety evaluation of an existing nuclear installation strongly depends on the actual condition of the installation at the time that the evaluation is performed. This key condition is denoted the ‘as-is condition’, indicating that an earthquake will affect the installation in its current condition, and that the response and capacity of the installation will depend on its current physical and operating configuration. The as-is condition is typically established on the basis of the original design, taking into account design changes during construction and operation, unintended deviations from the design, and ageing. That is why

⁹ The existence of seismic margins has been demonstrated not only through the implementation of SMA and SPSA methodologies for existing nuclear power plants in several Member States, but also by the performance of plants that have experienced large beyond design basis earthquakes and proved their integrity with little or no damage.

¹⁰ One of the main reasons for this variation is that nuclear installations are designed for a wide range of internal and external extreme loads, for example pressure and other environmental loads due to accident conditions, an aircraft crash, a tornado or a pipe break. Therefore, as mentioned in para. 2.7, seismic loads might not be the governing loads for some SSCs. Another reason is the method of equipment qualification, in which envelope type response spectra are generally used.

maintaining up-to-date, as-built design documentation and documentation from the ageing management programme is very important. The as-is condition of the installation should provide the baseline for any seismic safety evaluation.

2.11. Seismic safety evaluations performed on the basis of the as-is condition of the nuclear installation should be pragmatic rather than using extensive complex analyses. Non-linear analyses of relatively simple structural models or the use of higher damping values and ductility factors — provided that they are technically justified and are consistent with allowable deformations considering the as-is condition of the installation — may, however, be particularly helpful in understanding post-elastic behaviour. Numerous field observations and research and development programmes have demonstrated high seismic capacity results when the ductile behaviour of SSCs is able to accommodate large strains.

2.12. When a reliable seismic hazard analysis is available for a particular site (see SSG-9 (Rev. 1) [7]), a realistic definition of the earthquake motion (in terms of amplitude, duration, directivity and frequency) for the selected annual frequency of exceedance should be used for the seismic safety evaluation. When there are several seismic sources that lead to very different motion characteristics (e.g. far field, near field), the feasibility of using several motion characterizations and assessing seismic safety (including safety margins) against each of them should be considered.

REASONS TO PERFORM SEISMIC SAFETY EVALUATIONS

New nuclear installations

2.13. In accordance with the requirements established in GSR Part 4 (Rev. 1) [1], SSR-2/1 (Rev. 1) [3], SSR-3 [5] and SSR-4 [6] (see paras 2.1–2.5 of this Safety Guide), an evaluation of the seismic safety of new nuclear installations is required to be performed as part of the safety assessment, when the design is completed, to verify that the safety margins above the design basis earthquake are sufficient. In addition, in the case of a nuclear power plant, the seismic safety evaluation is required to verify that the margins are sufficient to protect items ultimately necessary to prevent a radioactive release in the event of an earthquake with a severity exceeding that considered for design (see SSR-2/1 (Rev. 1) [3]). This safety evaluation should be reflected in the safety analysis report for the installation (see Safety Standards Series No. SSG-61, Format and Content of the Safety Analysis Report for Nuclear Power Plants [12]). Recommendations on the level of seismic margin to be achieved in a new nuclear installation are provided in SSG-67 [8].

2.14. The design of a new nuclear power plant is required to provide for (a) an adequate seismic margin to protect items important to safety against seismic hazard levels exceeding those considered for design and to avoid cliff edge effects (see para. 5.21 of SSR-2/1 (Rev. 1) [3]) and (b) an adequate seismic margin to protect items ultimately necessary to prevent an early radioactive release or a large radioactive release in the event of levels of natural hazards exceeding those considered for design (see para. 5.21A of SSR-2/1 (Rev. 1) [3]). The seismic margin needed to meet (b) normally applies to a reduced set of SSCs and generally results in larger plant state margins than the seismic margin needed to meet (a).

Existing nuclear installations

2.15. In accordance with the requirements established in GSR Part 4 (Rev. 1) [1], SSR-1 [2], SSR-2/2 (Rev. 1) [4], SSR-3 [5] and SSR-4 [6] (see paras 2.1–2.3 and 2.6 of this Safety Guide), and in line with international practice, an evaluation of the seismic safety of an existing nuclear installation is required to be performed in any of the following cases:

- (a) Evidence of a significant increase in the seismic hazard at the site, arising from new or additional data (e.g. newly discovered seismogenic structures, newly installed seismological networks, new palaeoseismological evidence), new methods of seismic hazard assessment and/or the occurrence of actual earthquakes that affect the installation;
- (b) Regulatory requirements, such as a requirement for periodic safety reviews, that take into account the state of knowledge and the actual condition of the installation;
- (c) Inadequate seismic design, generally due to the very old design of the installation;
- (d) New technical findings, such as vulnerability of selected structures, non-structural elements (e.g. masonry walls) and/or systems or components (e.g. relays);
- (e) New experience from the occurrence of earthquakes (e.g. better recorded ground motion data, observed performance of SSCs);
- (f) A need to address the performance of the installation for beyond design basis earthquake ground motions in order to provide confidence that there is no cliff edge effect — that is, to demonstrate that no significant failures would occur in the installation if an earthquake stronger than the design basis earthquake were to occur;
- (g) A programme of long term operation that extends the lifetime of the plant, if applicable.

2.16. If, for the reasons listed in para. 2.15 or for other reasons, a seismic safety evaluation of an existing nuclear installation is required, the purposes of the evaluation should be clearly established before the evaluation process is initiated. This is because there are significant differences among the available evaluation methodologies and acceptance criteria, depending on the purpose of the evaluation (see Section 3). In this regard, the objectives of the seismic safety evaluation may include one or more of the following:

- (a) To demonstrate the seismic safety margin beyond the original design basis earthquake and to confirm that there are no cliff edge effects.
- (b) To identify weak links¹¹ in the installation and its operations with respect to seismic events.
- (c) To evaluate a group of installations (e.g. all the installations in a region or a State) in order to determine their relative seismic capacity and/or their risk ranking. For this purpose, similar and comparable methodologies should be adopted.
- (d) To provide input for integrated risk informed decision making.
- (e) To identify and prioritize possible upgrades.
- (f) To assess risk metrics (e.g. core and/or fuel damage frequency, large early release frequency) against regulatory requirements, if any.
- (g) To assess installation capacity metrics (e.g. system level and installation level fragilities, high confidence of low probability of failure (HCLPF) capacity¹²) against regulatory expectations.

2.17. The objectives of the seismic safety evaluation of an existing nuclear installation should be established in line with the regulatory requirements and in consultation and agreement with the regulatory body. Consequently, and in accordance with such objectives, the level of seismic input motion, the methodology for capacity assessment and the acceptance criteria to be applied, including the necessary end products, should be defined. In particular, for evaluating seismic safety in the event of an earthquake with a severity exceeding that considered for design, the safety objectives should include the functions to be ensured and the failure modes to be prevented during or after the earthquake's occurrence.

¹¹ In this context, 'seismic weak links' are non-redundant SSCs or identical redundant SSCs (i.e. affected by common cause failure) that have a smaller capacity than the majority of the other SSCs and, as such, could govern the installation level seismic capacity.

¹² The HCLPF capacity is the earthquake motion level at which there is a high confidence of a low probability of failure of SSCs. The HCLPF capacity is a measure of seismic margin (see paras 5.44–5.47).

2.18. The final documentation to be produced at the end of the seismic safety evaluation of an existing nuclear installation should be identified at the outset, in agreement with the regulatory body, and should be consistent with the established purpose of the evaluation programme (see para. 8.6). The end products of the evaluation may be one or more of the following:

- (a) Metrics of the seismic capacity of the nuclear installation in deterministic and/or probabilistic terms;
- (b) Quantification of the seismic risk;
- (c) Identification of SSCs with low seismic capacity, and the associated consequences for installation safety, for use in decision making on seismic upgrade programmes;
- (d) Identification of operational modifications to improve seismic capacity;
- (e) Identification of improvements to housekeeping practices (e.g. storage of maintenance equipment);
- (f) Identification of interactions with equipment and piping, including fire protection systems, high enthalpy lines and utilities;
- (g) Identification of actions to be taken before, during and after the occurrence of an earthquake that affects the installation, including arrangements for operational and management response, analysis of the instrumental seismic records obtained and inspections performed, and the integrity evaluations to be performed as a consequence;
- (h) A framework to provide input to risk informed decision making;
- (i) A framework for the revision of the seismic categorization of SSCs.

CONSIDERATION OF RELEVANT ASPECTS RELATED TO SEISMIC HAZARD

2.19. An initial step of any seismic safety evaluation — in parallel with the collection of relevant data, as indicated in Section 4 — should be to identify the seismic hazards on the basis of which the seismic safety of the installation will be evaluated. In this respect, the seismic hazards specific to the site should be assessed in relation to three main elements¹³:

¹³ In most cases, it is foreseen that a seismic hazard assessment will be available as part of the site investigation or a periodic re-evaluation of the hazards. The available hazard assessments will need to be reviewed to determine if they are adequate for the purposes of the seismic safety evaluation being performed.

- (a) Evaluation of the geological stability of the site [7, 9], with two main objectives pertaining to non-vibratory ground motions:
 - (i) To verify the absence of any capable fault that could produce significant differential ground displacement phenomena underneath or in close proximity to buildings and structures important to safety. If there is evidence that indicates the possibility of a capable fault in the site area or site vicinity, the fault displacement hazard should first be assessed in accordance with the guidance provided in SSG-9 (Rev. 1) [7].
 - (ii) To characterize potential permanent ground deformation phenomena (e.g. liquefaction, slope instability, excessive settlement, subsidence, collapse).
- (b) Characterization of the severity of the seismic ground motion at the site (i.e. assessment of the vibratory ground motion parameters), taking into consideration the full scope of the seismotectonic effects at the four spatial scales of investigation¹⁴ and as recommended in SSG-9 (Rev. 1) [7].
- (c) Evaluation of other concomitant phenomena, such as flooding due to seismically induced failure of dams or water retaining structures, coastal flooding due to tsunamis, and seismically induced slope instabilities.

2.20. In general, the seismic hazard assessment may be performed using a deterministic or a probabilistic approach, depending on the objectives and requirements of the seismic safety evaluation. In either case, both the aleatory and the epistemic uncertainties should be taken into consideration.

2.21. The evaluations recommended in para. 2.19(a) and 2.19(c) of this Safety Guide should be performed in all seismic safety evaluations, regardless of the methodology used and in accordance with SSG-9 (Rev. 1) [7], NS-G-3.6 [9] and IAEA Safety Standards Series No. SSG-18, Meteorological and Hydrological Hazards in Site Evaluation for Nuclear Installations [13]. For evaluating the geotechnical hazards (e.g. liquefaction, slope instability, subsidence, collapse), the most recent available seismic hazard parameters should be used.

2.22. With respect to para. 2.19(b), the recommendations on assessing the seismic hazard at the site are dependent on the objectives of the seismic safety evaluation. A site specific ground motion seismic hazard assessment is generally preferred and should be considered a prerequisite, to be implemented as recommended in

¹⁴ In SSG-9 (Rev. 1) [7], four spatial geographical scales of geological, geophysical and geotechnical investigations are defined: (1) regional (radius typically about 300 km); (2) near regional (radius typically not less than 25 km); (3) site vicinity (radius typically not less than 5 km); and (4) site area (radius typically about 1 km).