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SERIES

# Evaluation of Seismic Hazards for Nuclear Power Plants

SAFETY GUIDE

No. NS-G-3.3

INTERNATIONAL
ATOMIC ENERGY AGENCY
VIENNA

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# EVALUATION OF SEISMIC HAZARDS FOR NUCLEAR POWER PLANTS

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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.*

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# 1. INTRODUCTION

## BACKGROUND

1.1. This Safety Guide was prepared under the IAEA programme for safety standards for nuclear power plants. It supplements the Safety Requirements publication on Site Evaluation for Nuclear Facilities that is planned to supersede the Code on the Safety of Nuclear Power Plants: Siting, Safety Series No. 50-C-S (Rev. 1), IAEA, Vienna (1988). The present publication provides guidelines and recommends procedures for the evaluation of seismic hazards for nuclear power plants. It supersedes Safety Series No. 50-SG-S1 (Rev. 1), Earthquakes and Associated Topics in Relation to Nuclear Power Plant Siting, IAEA, Vienna (1991).

1.2. This publication takes into account the following: the need for hazard curves for the probabilistic safety assessment (PSA) of external events for new and existing nuclear facilities; feedback from IAEA reviews of seismic studies for nuclear facilities performed over the past decade; collective knowledge of the effects of significant recent earthquakes; and new approaches in methods of analysis.

1.3. In the site evaluation for a plant, engineering solutions will generally be available to mitigate, by means of certain design features, the potential vibratory effects of earthquakes. However, such solutions cannot always be demonstrated to be adequate for mitigating the effects of phenomena of permanent ground displacement such as surface faulting, subsidence, ground collapse or fault creep.

## OBJECTIVE

1.4. The main objective of this Safety Guide is to provide recommendations on how to determine the ground motion hazards for a plant at a particular site and the potential for surface faulting, which could affect the feasibility of construction and safe operation of a plant at that site.

## SCOPE

1.5. The guidelines and procedures presented in this Safety Guide can appropriately be used in evaluations of site suitability and seismic hazards for nuclear power plants in any seismotectonic environment. The probabilistic seismic hazard analysis recommended in this Safety Guide also addresses the needs for seismic hazard analysis of external event PSAs conducted for nuclear power plants. Many of the methods and processes described may also be applicable to nuclear facilities other than power plants. Other phenomena of permanent ground displacement (liquefaction, slope instability, subsidence and collapse) as well as the topic of seismically induced flooding are treated in Safety Guides relating to foundation safety [1] and coastal flooding [2].

### STRUCTURE

1.6. Recommendations of a general nature are given in Section 2. Section 3 discusses the acquisition of a database containing the information needed to evaluate and address all hazards associated with earthquakes. Section 4 covers the use of this database for construction of a seismotectonic model. Sections 5 and 6 review ground motion hazards and evaluations of the potential for surface faulting, respectively. Section 7 addresses quality assurance in the evaluation of seismic hazards for nuclear power plants.

## 2. GENERAL RECOMMENDATIONS

2.1. The hazards of ground motion and faulting associated with earthquakes and geological phenomena shall be investigated for every nuclear power plant. Investigations in this area, which form the basis for technical judgements in the site evaluation for a plant, are treated in this Safety Guide for all levels of exposure to seismic hazards.

2.2. The geological, geophysical and seismological characteristics of the region around the site and the geotechnical characteristics of the site area should be investigated and evaluated as described in this Safety Guide.

2.3. Where necessary, the site region should include areas extending beyond national borders and, for sites located near a coastline, the relevant offshore area. In other words, the database should be homogeneous for the entire region to the extent possible, or, at a minimum, should be sufficiently complete for characterizing, from a seismotectonic point of view, features relevant to the site that are located in other States or in offshore areas.

2.4. The size of the region to be investigated, the type of information to be collected and the scope and detail of the investigations should be determined according to the nature and complexity of the seismotectonic environment.

2.5. In all cases, the scope and detail of the information to be collected and investigations to be undertaken should be sufficient to determine the ground motion and fault displacement hazards.

2.6. Regardless of any lower apparent exposure to seismic hazard, and as a good safety practice, a minimum of 0.1g peak horizontal ground acceleration should be adopted for all plants as a value to scale the appropriate response spectra which corresponds to the seismic level 2 (SL-2) earthquake, as determined in Section 5 (see Ref. [3]).

2.7. The general approach to seismic hazard evaluation should be directed towards reducing the uncertainties at various stages of the process. Experience shows that the most effective way of achieving this is to collect a sufficient amount of reliable and relevant data. There is generally a trade-off between the effort needed to compile a detailed, reliable and relevant database and the degree of uncertainty that the analyst should take into consideration at each step of the process.

2.8. The ultimate purpose of the data compilation and seismic hazard analysis described here is to determine the ground motion and fault displacement hazards for a nuclear power plant site. Every aspect of the identification, analysis and characterization of seismic sources and estimation of ground motion hazards may involve substantial subjective interpretation by experts. Particular care should be taken to avoid bias. Experts should not promote any one hypothesis or model but should evaluate all viable hypotheses and models using the available data, and then develop an integrated evaluation which incorporates both knowledge and uncertainties.

## 3. NECESSARY INFORMATION AND INVESTIGATIONS (DATABASE)

### OVERVIEW

3.l. A comprehensive and integrated database should be acquired which incorporates in a coherent form the information needed to evaluate and resolve issues relating to all hazards associated with earthquakes.

3.2. It should be ensured that each element of every practical database has been investigated as fully as possible before integration of the various elements is attempted. The integrated database should include all relevant information; that is, not only geological, geophysical, geotechnical and seismological data, but also any other information that is relevant to evaluating the ground motion, faulting and geological hazards at the site.

3.3. Investigations should be conducted on four scales — regional, near regional, site vicinity and site area — thus leading to progressively more detailed investigation, data and information. The detail of these data is determined by the different scales. The first three scales of investigation lead primarily to progressively more detailed geological and geophysical data and information. The site area investigations are aimed at developing the geotechnical database. In order to achieve consistency in the presentation of information, data should be compiled in a geographical information system (GIS) whenever possible and all data, evaluations and interpreted products should be displayed on a consistent scale to facilitate comparison.

3.4. The compilation of the seismological database will normally be less dependent on the regional, near regional and site vicinity scales. That is, the scope and detail of the information to be compiled will be largely independent of scale for the entire region of the site. However, seismogenic structures in the near region and in the site vicinity will normally be more important for seismic hazard evaluation, depending on the rates of activity, maximum magnitude and regional attenuation. Particularly for intraplate tectonic settings, attention should be paid to compiling seismological data for more distant sources that may be beyond the typical boundaries of the region. In offshore regions, adequate geophysical investigations should be carried out in order to compensate for any lack of, or deficiency in, seismological data.

## GEOLOGICAL, GEOPHYSICAL AND GEOTECHNICAL DATABASE

### Regional investigations

3.5. The objective of obtaining data on a regional scale is to provide knowledge of the general geodynamic setting of the region and to identify and characterize those geological features that may influence or relate to the seismic hazard at the site. The most relevant among those geological features are structures that show potential for displacement and/or deformation at or near the ground surface; that is, capable faults. The data will usually be obtained from any type of published and unpublished geological and geophysical sources (for example, data derived from existing galleries, road cuts or water boreholes) and should be presented on maps with appropriate cross-sections. The size of the relevant region will vary depending on the geological and tectonic setting, and its shape may be asymmetric in order to include distant significant sources of earthquakes. Its radial extent will typically be 150 km or more.

3. 6. In the particular case of investigations into the potential for tsunamis (see Ref. [2]), the investigations may need to consider sources at very great distances from the site.

3.7. Where existing data are inadequate for the purpose of delineating seismogenic structures, in terms of location, extent and rate of ongoing tectonism, it may be necessary to verify and complete the database by acquiring new geological and geophysical data. This may involve investigations at the scale (detail) of the near region and site vicinity to assess the potential seismogenic features located outside the near region. Identification of the ground effects of past earthquakes on the geological–geomorphological environment (that is, the palaeoseismology; see para. 4.17) is also useful for this purpose.

3.8. The data are typically presented on maps at a scale of 1:500 000 and with appropriate cross-sections.

### Near regional investigations

3.9. Near regional studies should include a geographical area typically not less than 25 km in radius, although this dimension should be adjusted to reflect local conditions. The objectives are:

- to define the seismotectonic characteristics of the near region on the basis of a more detailed database than that obtained from the regional study;
- to determine the latest movements of faults and, for the faults of importance for seismic hazard assessment, the amount and nature of displacements, rates of activity and evidence of segmentation.

3.10. To supplement the published and unpublished information on near regional areas, specific investigations should typically include a definition of the stratigraphy, structural geology and tectonic history of the near region. The tectonic history should be very well defined for the current tectonic regime; for example, Upper Pleistocene–Holocene may be adequate for interplate regions, and Pliocene–Quaternary for intraplate regions. Age dating, by any applicable method, should be performed. In addition to field mapping, various sources of data should be used, for example:

- Subsurface data derived from geophysical investigations (such as seismic reflection and refraction, and gravimetric, electric and magnetic techniques), to characterize spatially the identified structures considered to be relevant for the seismic hazard at the site in terms of their geometry, extent and rate of tectonism. Use of heat flow data may be also necessary. These data are of primary importance in dealing with offshore areas (for sites located on or near a coastline).

- Surface data derived from studies of Quaternary formations or landforms, such as terrace analysis and pedological and sedimentological studies. Use should be made of aerial and satellite photographs and/or images for this task.
- For understanding the ongoing rate and type of tectonism, use should also be made of data derived by recently developed technological means, such as global positioning system data and interferometry data, and data from strain rate measurements.

3.11. For some relevant structures identified in the near regional investigations, it may be necessary to conduct additional geological and geophysical studies at the site vicinity level in order to obtain the desired detail of characterization (see also para. 4.17).

3.12. Investigations should be made in sufficient detail so that the causes of each recent (in terms of the pertinent time window for the specific local tectonic environment) geological and geomorphological feature that is relevant — for example, linear topographic or structural features as found in photographs, remote sensing imagery or geophysical data — can be properly included in a reasonable model of the recent geological evolution of the area.

3.13. The data are typically presented on maps at a scale of 1:50 000 and with appropriate cross-sections.

### Site vicinity investigations

3.14. Site vicinity studies should cover a geographical area typically 5 km in radius. In addition to providing a yet more detailed database for this smaller area, the objective of these investigations is to define in greater detail the neotectonic history of faults, especially for determining the potential for surface faulting at the site (fault capability), and to identify conditions of potential geological instability of the site area.

3.15. Investigations of the site vicinity should typically include geomorphological–geological mapping, geophysical prospecting, boreholes and trenching (see also para. 4.17), and should provide the following data:

- a geological map with cross-sections;
- age, type and amount of displacement of all the faults located in the area;

- identification and characterization of locations exhibiting potential hazards induced by natural phenomena (for example, Karst, subsidence, landslide) and by human activities. Special attention should be paid to the potential for induced seismicity resulting from the impoundment of large dams or reservoirs, or from extensive fluid injection into or extraction from the ground.

3.16. The data are typically presented on maps at a scale of 1:5000 and with appropriate cross-sections.

### Site area investigations

3.17. Site area studies should include the entire area covered by the plant, which is typically one square kilometre. The primary objective of these investigations is to obtain detailed knowledge of the potential for permanent ground displacement and to provide information on the dynamical properties of foundation materials (such as P and S wave velocities), to be used in site response analysis.

3.18. The database should be developed from detailed geological, geophysical and geotechnical studies complemented by in situ and laboratory testing.

3.19. The following investigations of the site area should be performed, using geological, geophysical, seismological and geotechnical techniques:

(1) Geological and geotechnical investigations: Investigations using boreholes or test excavations (including in situ testing), geophysical techniques and laboratory tests should be conducted to define the stratigraphy and structure of the site area and to determine the thickness, depth, dip, and static and dynamic properties of the different subsurface layers as may be required by engineering models (Poisson's ratio, Young's modulus, shear modulus, density, relative density, shear strength, consolidation and swelling characteristics, grain size distribution).

(2) Hydrogeological investigations: Investigations using boreholes and other techniques should be conducted to define the geometry, physical and chemical properties, and steady state behaviour (recharge, transmissivity) of all aquifers in the site area, with the specific purpose of determining how they interact with the foundation.

(3) Investigations of site effects: The dynamic behaviour of the rock and soil at the site should be assessed, using available historical and instrumental data as a guide.

3.20. All the data required for assessing the dynamic soil–structure interaction (see Ref. [1]) should be acquired in the course of these investigations. For completeness and efficiency, the investigations described in para. 3.19 should be integrated with the investigations required for the dynamic soil–structure interaction as described in Ref. [1].

3.21. The data are typically presented on maps at a scale of 1:500 and with appropriate cross-sections.

## SEISMOLOGICAL DATABASE

3.22. Data shall be collected for all recorded earthquakes that have occurred in the region.

### Historical earthquake data

3.23. All 'pre-instrumental' historical earthquake data (that is, for events for which no instrumental recording was possible) shall be collected, extending as far back in time as possible. Palaeoseismological information on historical earthquakes should also be taken into account (see para. 4.17).

3.24. To the extent possible, the information on each earthquake should include:

- date and time of the event;
- location of the macroseismic epicentre;
- estimated focal depth;
- estimated magnitude;
- maximum intensity and, if different, intensity at the macroseismic epicentre, with a description of local conditions;
- isoseismal contours;
- estimates of uncertainty for all of the above parameters;
- intensity of the earthquake at the site, together with any available details of effects on the soil;
- an assessment of the quality and quantity of data from which the above parameters have been estimated.

The intensity scale used in the catalogue should be specified, since levels can vary depending on the scale used. The magnitude and depth estimates for such earthquakes should be based on relevant empirical relationships between instrumental data and macroseismic information, which may be developed from the data described in para. 3.23. When the catalogue of relevant historical earthquake data has been compiled, its completeness and reliability should be assessed.

3.25. When the catalogue of historical and instrumental earthquake data has been compiled, the assessment of completeness of the information it contains, particularly in terms of macroseismic intensity, magnitude, date, location and focal depth, will be fundamental to a properly conducted seismic hazard evaluation. In general, the catalogues are incomplete for small magnitude events owing to the threshold of recording sensitivity, and for large magnitude events owing to their long recurrence intervals (and the comparatively short period of coverage of the catalogues). Appropriate methods should be used to take account of this incompleteness.

### Instrumental earthquake data

3.26. All available instrumental earthquake data shall be collected. The information to be obtained for each earthquake includes:

- time of origin;
- location of epicentre and hypocentre;
- all magnitude determinations, including those on different scales, and any information on seismic moment or stress drop;
- dimensions and geometry of the fore-shock and aftershock zones;
- other information that may be helpful in understanding the seismotectonic regime, such as focal mechanism, stress drop and other source parameters;
- estimates of uncertainty for each of the above parameters;
- macroseismic details as discussed in para. 3.24.

When the catalogue of relevant instrumental earthquakes has been compiled, its reliability and completeness should be assessed.

3.27. It should be noted that, in addition to catalogues maintained by individual States or neighbouring States, worldwide instrumental earthquake catalogues are maintained by various organizations such as the International Seismological Centre, the United States National Earthquake Information Center and the European–Mediterranean Seismological Centre in France.

### Site specific instrumental data

3.28. To supplement the available data on earthquakes with more detailed information on potential seismic sources, it is often useful to operate a network of sensitive seismographs having a recording capability for micro-earthquakes. The minimum monitoring period necessary to obtain meaningful data for seismotectonic interpretation is several years for regions of high seismicity, and may be longer for regions of low seismicity.

3.29. Earthquakes recorded within and near such a network should be carefully analysed in connection with seismotectonic studies of the near region.

3.30. Wherever possible, recordings of regional strong ground motion should be collected and used for deriving appropriate seismic wave attenuation functions and in developing the response spectra as discussed in Section 5.

3.31. Strong motion accelerographs should be installed permanently within the site area and maintained so as to operate continuously and record small and large events (see Ref. [3]).

# 4. CONSTRUCTION OF A REGIONAL SEISMOTECTONIC MODEL

## INTRODUCTION

4.1. The link between the database and any calculational model for deriving hazard levels is a regional seismotectonic model which should be based on a coherent merging of the regional databases. In the construction of such a model, all existing interpretations of the seismotectonics of the region that may be found in the available literature should be taken into account. Above all, a sound database is essential in the construction of a reliable seismotectonic model. It should be noted that the most sophisticated methods will not yield good models if the database is poor or insufficient.

4.2. The standard procedure is to integrate the elements of the seismological, geophysical and geological databases (see Section 3) in order to construct a coherent seismotectonic model (or alternative models) consisting of a discrete set of seismogenic structures.

4.3. The seismogenic structures identified may not explain all the observed earthquake activity. This is because seismogenic structures may exist without recognized surface or subsurface manifestations and because of the timescales involved; for example, fault displacements may have long recurrence intervals with respect to seismological observation periods.

4.4. Consequently, any seismotectonic model consists, to a greater or lesser extent, of two types of seismic sources:

- — those seismogenic structures which can be identified by using the available database;
- — diffuse seismicity (consisting usually, but not always, of small to moderate earthquakes) which is not attributable to specific structures identified by using the available database.

4.5. The identification, evaluation and characterization of seismogenic structures is described in Section 3. Evaluation and characterization of both these types of seismic sources involve assessments of uncertainty. However, the second type, diffuse seismicity, is a particularly complex problem in seismic hazard evaluation and generally will involve greater uncertainty because the sources of the earthquakes are not well understood. A complete definition of these sources involves expert interpretations that are uncertain. The uncertainty in the interpretations should be properly assessed in order to incorporate it into the evaluation of the ground motion hazard at the site. This assessment should typically involve alternative interpretations and the weighting of each alternative according to the interpreted degree of support that it has in the data.

4.6. Although attempts should be made to define all the parameters of each element in a seismotectonic model, the construction of the model should be data driven, and any tendency to interpret data only in a manner that supports some preconception should be avoided.

4.7. When it is possible to construct alternative models which explain the observed seismological, geophysical and geological data sufficiently well, and the differences cannot be resolved by means of additional investigations within a reasonable time-frame, the final hazard evaluation should take into consideration all such models, with appropriate weights, in order to fully express the uncertainty contained in the seismotectonic model.

## SEISMOGENIC STRUCTURES

### Identification

4.8. The need to identify seismogenic structures is ultimately due to their significance for determining the ground motion or surface faulting hazard at the site.

4.9. Regarding the ground motion hazard, the concern lies with those seismogenic structures whose combination of location and earthquake potential could affect ground motion levels at the site.

4.10. Regarding the surface faulting hazard, the concern lies with those seismogenic structures close to the site that have a potential for relative displacement at or near the ground surface (that is, capable faults; see Section 6).

4.11. The identification of seismogenic structures is made on the basis of geological, geophysical and seismological data providing direct or indirect evidence that these structures have been the source of earthquakes under current tectonic conditions. The correlation of historical and instrumental recordings of earthquakes with geological and geophysical features is particularly important in identifying seismogenic structures. A lack of correlation does not necessarily indicate that a structure is not seismogenic.

4.12. Whenever the investigations described in Section 3 show that an earthquake hypocentre or a group of earthquake hypocentres can be potentially associated with a geological feature, the rationale for the association should be developed by considering the characteristics of the feature, its geometry and geographical extent, and its structural relationship to the regional tectonic framework.

4.13. Other available seismological information, such as hypocentral uncertainties, focal mechanisms, stress environments and fore-shock and aftershock distributions, should also be used in considering any association of earthquake hypocentres with geological features.

4.14. When specific data are lacking or sparse, detailed comparison of any given geological feature with other features in the region in terms of their age of origin, sense of movement and history of movement is essential.

4.15. The incorporation of seismogenic structures into a seismotectonic model should be firmly based on the available data and should incorporate uncertainties in the definition of these structures. Unsupported assumptions as to associations between earthquakes and geological features should not be considered an appropriate assessment of uncertainty, particularly when the geological feature in question is distant from the site.

### Characterization

4.16. For seismogenic structures that have been identified to be pertinent to determining the exposure of the site to earthquake hazards, as discussed earlier, the associated characteristics should be determined. The dimensions of the structure, amount and direction of displacement, maximum historical earthquake, palaeoseismological data, earthquake data and comparisons with similar structures for which historical data are available should be used in this determination.

4.17. Earthquakes produce effects on the environment which are also described in the intensity scales. Some of these effects (for example, faulting, liquefaction, coastline uplift), or their cumulative effect, can be used to recognize past earthquakes. The study of the geological record of past earthquakes is referred to as palaeoseismology. Palaeoseismological studies may be useful in areas where historical earthquake records are lacking. Palaeoseismological studies should be performed using the database described in Section 3 for the following purposes:

- Identification of seismogenic structures based on the recognition of effects of past earthquakes in the region.
- Improvement of the completeness of earthquake catalogues for large events, using identification and age dating of fossil earthquakes, mainly by trenching; for instance, trenching across the identified capable faults may be useful in estimating displacement magnitudes (for example, from the thickness of colluvial wedges) and recurrence (using age dating of the encountered sediments).
- Estimation of the maximum seismic potential of a given seismogenic structure, typically on the basis of the displacement per event (trenching) as well as of the cumulative effect (seismic landscape).
- Calibration of probabilistic hazard analyses, using the recurrence intervals of large earthquakes.

4.18. When sufficient information about the seismological and geological history of the movement of a fault or structure (such as segmentation, average stress drop and fault width) is available to allow estimates to be made of the maximum rupture dimensions and/or displacements of future earthquakes, direct empirical relationships can be used for evaluating the potential maximum magnitude.

4.19. In the absence of suitably detailed data, the potential maximum magnitude of a seismogenic structure can be estimated from its total dimensions. However, to use this approach, a fraction of the total length of the structure which can move in a single earthquake should be used. The fraction to be used will depend on the characteristics of the fault, in particular on its segmentation.

4.20. In the application of either of the two approaches, it should be remembered that earthquake magnitude is a function of both source dimensions and stress drop. Stress drop will usually not be known, but reasonable estimates based on available published studies may be used.

4.21. Other approaches are available for estimating potential maximum magnitudes on the basis of statistical analysis of the magnitude–frequency recurrence relationships for earthquakes associated with a particular structure. These approaches assume an association between the structure and all the earthquake data used. In all cases the results of these methods should be consistent with the derived data.

4.22. Regardless of the approach or combination of approaches used, the determination of the maximum earthquake magnitude is significantly uncertain, and the uncertainty should be fully described. The result should be consistent with geological and geomorphological evidence.

4.23. Earthquake recurrence should be evaluated for each seismogenic structure contained in the seismotectonic model for the site. In addition to the maximum earthquake magnitude, this evaluation should include the rate of earthquake activity and the recurrence relationship. The appropriate recurrence model for any seismotectonic structure and the model parameters will involve interpretations of uncertainties which should be assessed and included in the determination of the ground motion hazard for the site.

4.24. The appropriateness of a recurrence model often depends on the type of seismic source. A recurrence model may be more appropriate for structure specific or for fault specific seismic sources.

4.25. For seismic sources that have moderate to high rates of earthquake recurrence, the rate of earthquake activity can usually be determined directly by using the instrumental or historical earthquake catalogue. The rate of activity for these sources can be determined with reasonable confidence (low uncertainty).

4.26. In addition to the rate of earthquake activity of a seismic source, the distribution parameter for the recurrence model should be determined. As in the case of the rate of earthquake activity, for seismic sources that have high rates of earthquake activity this parameter and its uncertainty can normally be determined by using the earthquake catalogue.

## ZONES OF DIFFUSE SEISMICITY

### Identification

4.27. Seismotectonic provinces may be defined in a seismotectonic model to represent diffuse seismicity for the purpose of seismic hazard evaluation, with each seismotectonic province being assumed to encompass an area having equal seismic potential. Alternatively, a non-uniform distribution may be used provided that the available data support this assumption.

4.28. In the performance of seismic hazard evaluations, knowledge about the depth from which the diffuse seismicity originates should be incorporated. Estimates about the maximum depth of foci can be made on the basis of the fact that earthquakes are known to originate in the brittle to ductile transition zone of the Earth's crust.

4.29. Significant differences in rates of seismicity may suggest different tectonic conditions and may be used in defining boundaries. Significant differences in hypocentral depth (for example, crustal versus deeper) may be used to differentiate between zones.

### Characterization

4.30. The maximum potential earthquake not associated with identified seismogenic structures should be evaluated on the basis of historical data and the seismotectonic characteristics of the zone. Comparison with similar regions for which extensive historical data are available may be useful, but considerable judgement should be used in the evaluation. Often this value will have significant uncertainty owing to the relatively short period covered by historical data with respect to the processes of ongoing tectonism. This uncertainty should be described by a representative distribution or by assuming an appropriately conservative value, depending on whether a probabilistic or deterministic hazard assessment is used.

4.31. A determination of the rate of earthquake activity for seismic sources that have few earthquakes, as may be encountered in intraplate tectonic regions, may have considerable uncertainty. For these sources, determination of the slope parameter may involve a different approach which may include adopting a value that represents the regional tectonic setting of the seismic source, for example, a stable continental tectonic setting. This approach may be considered viable because the slope parameter (the b value) has been shown to vary only over a narrow range within a tectonic setting. Regardless of the approach used to determine the slope parameter of the recurrence distribution, uncertainty in the parameter should be appropriately assessed and incorporated into the seismic hazard analysis.

4.32. Earthquake recurrence should be evaluated for each zone of diffuse seismicity. This evaluation should include determination of the appropriate earthquake recurrence model and model parameters, and an assessment of the uncertainty in the model and parameters. The Poisson exponential model is generally more appropriate for zones of diffuse seismicity. For either type of seismic source, however, alternative recurrence models may be used with appropriate weightings to express the evaluator's uncertainty.

# 5. EVALUATION OF GROUND MOTION HAZARD

## INTRODUCTION

5.1. This section presents guidelines and procedures regarding the levels and characteristics of ground motion hazard. Guidance on the appropriate level of ground motion — seismic level 1 or seismic level 2 (SL-1 or SL-2) — to be assumed for the design of each particular structure, system and component of the plant is given in Ref. [3], which also recommends the loading combinations applicable for the design basis ground motion levels. Determination of the ground motion hazard shall be based on the seismotectonic model derived as described in Section 4.

5.2. In taking decisions relating to the levels of ground motion hazard as discussed in paras 5.3–5.8 and to the parameters used to characterize the ground motion, close consultations should be held between the seismic hazard analyst and the design engineer.

## LEVELS OF GROUND MOTION HAZARD

5.3. Typically, two levels of ground motion hazard (SL-1 and SL-2) are evaluated for each plant. The application of these levels in plant design is explained in Ref. [3].[1]

5.4. The SL-2 level corresponds directly to ultimate safety requirements. This level of ground motion shall have a very low probability[2] of being exceeded during the lifetime of the plant and represents the maximum level of ground motion to be assumed for design purposes. Its determination shall be based on the seismotectonic evaluation and a detailed knowledge of the geology and engineering parameters of the strata beneath the site area.

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[1] In some States, licensing authorities require only an evaluation of level SL-2.

[2] In some States, SL-2 corresponds to a level in excess of a mean frequency of $1 \times 10^{-3}$ to $1 \times 10^{-4}$ per year.

5.5. Regardless of the exposure to seismic hazard, a design basis ground motion corresponding to the level SL-2 earthquake should be adopted for every plant. The recommended minimum level is a horizontal peak ground acceleration of 0.1g corresponding to the zero period of the design response spectrum.

5.6. The SL-1 level corresponds to a less severe, more likely[3] earthquake which has different safety implications from those of SL-2. The factors which may influence decisions on the level of ground motion chosen to represent SL-1 are:

- Seismotectonic evaluation: the relative exposure of the site to multiple sources of seismicity; the frequency of earthquakes from each such source with respect to the lifetime of the plant.
- Design considerations: the safety implications of the required loading combinations and stress limits; the plant type.
- The post-earthquake situation: the implications of the agreed required action following SL-1; the regional need for the plant to continue to operate safely after an earthquake which may have damaged other electricity generating plants.
- Plant inspection considerations: the cost and safety implications of designing and/or constructing the plant to a higher level of SL-1, compared with the possibility of more frequent inspections for a lower level of SL-1.

5.7. Regardless of the method used to evaluate the ground motion hazard, both SL-1 and SL-2 should be defined by means of appropriate response spectra and time histories. The motion is defined for free field conditions at the surface of the ground, at the level of the foundation or on bedrock. The ground motion for reference bedrock conditions should be given, provided that a good database is available. Motions at the foundation level and at the surface are then computed, with account taken of the transfer functions of the surface layers. Consideration should be given to the appropriate interfacing of the defined reference ground motion and the site response analysis.

5.8. For both SL-1 and SL-2, the characteristics of the ground motion should be defined to allow calculation of the behaviour of the plant according to the methods chosen for the design. Ground motions having different characteristics may need to be defined according to the various types of earthquakes that can affect the site.

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[3] In some States, SL-1 corresponds to a level in excess of a mean frequency of $1 \times 10^{-2}$ per year.

METHODS FOR THE DETERMINATION OF GROUND MOTION

5.9. Ground motion is typically characterized by response spectra for three orthogonal directions and several damping values and corresponding time histories. Site specific response spectra should be calculated directly for both SL-1 and SL-2. An alternative is to choose a standard spectrum shape scaled to a prescribed level of free field acceleration (or velocity, or displacement).

5.10. The method used for any one region should make full use of the available database (for example, the relative predominance of historical earthquake data or strong motion recordings).

5.11. The assessment of appropriate ground motion levels for SL-1 and SL-2 may involve analyses based on deterministic and/or probabilistic methods.

### Use of data on intensity and magnitude

5.12. In addition to providing seismotectonic information concerning the seismogenic structures and zones of diffuse seismicity in the region, data on intensity and magnitude are relevant for estimating the characteristics of ground motions: attenuation, response spectra and duration.

5.13. Intensity data may be used to estimate the magnitude of earthquakes that occurred before seismological instruments were operating systematically. They can also be used to estimate attenuation relations for ground motion in those regions of the world where strong motion recording instruments have not been in operation for a long enough period of time to provide instrumental attenuation data. By comparing any derived attenuation relation with those obtained in regions where intensity data and strong ground motion records are available, improved relations can be obtained for ground motion.

### Deterministic methods

5.14. The assessment of SL-2 by deterministic methods includes:

(1) Dividing the seismotectonic model into seismotectonic provinces corresponding to zones of diffuse seismicity and seismogenic structures.
(2) Identifying the maximum potential earthquake associated with each seismogenic structure and with each seismotectonic province.

(3) Performing the evaluation as follows:

   (a) For each seismogenic structure, the maximum potential earthquake should be assumed to occur at the point of the structure closest to the site area, with account taken of the physical dimensions of the source. When the site is within the boundaries of a seismogenic structure, the maximum potential earthquake should be assumed to occur beneath the site. In this case, special care should be taken to demonstrate that the seismogenic structure is not capable (see Section 6).
   (b) The maximum potential earthquake in a zone of diffuse seismicity which includes the site should be assumed to occur at some identified specific distance from the site, on the basis of investigations which ensure that there are no seismogenic structures within this distance and that therefore the related probability of earthquakes occurring therein is negligibly low. This distance may be in the range of a few to about 20 kilometres and will depend on the best estimate of the focal depth of the earthquakes in that seismotectonic province. In selecting a suitable distance, the physical dimensions of the source should be taken into account.
   (c) The maximum potential earthquake associated with zones of diffuse seismicity in each adjoining seismotectonic province should be assumed to occur at the point of the province boundary closest to the site.
   (d) An appropriate attenuation relation should be used to determine the ground motion that each of these earthquakes would cause at the site, with account taken of local conditions at the site.
   (e) Ground motion characteristics should be obtained using the recommendations given in paras 5.19–5.35.

### Probabilistic methods

5.15. Probabilistic methods have advanced in practice to the extent that they can be effectively used to determine the ground motion hazard. Results of probabilistic seismic hazard analyses are necessary for the external event PSAs that are being conducted for nuclear power plants. Generally, seismic hazard curves that are used as input to seismic PSA studies need to extend to lower frequency per year levels than those used for the design. This should be taken into consideration.

5.16. Probabilistic computations should make use of all the elements and parameters of the seismotectonic model. Zones of diffuse seismicity may be modelled as sources of uniform seismicity, with allowances made for the full range of earthquake magnitudes associated with each seismogenic source, that is, zone or structure.

Recently developed probabilistic methods integrate all the variables and parameters of the seismotectonic model. The method allows for uncertainties in the parameters of the seismotectonic model as well as alternative interpretations of models to be explicitly included in the hazard analysis and propagated through to the hazard results. Alternative models may be proposed by different experts or expert groups and may be formally included in the probabilistic hazard computation. When this is the case, the results of international practice in the application of such multiple evaluations for probabilistic seismic hazard analysis should be reviewed and taken into account.

5.17. Application of the probabilistic method includes the following steps:

(1) Evaluation of the seismotectonic model for the site region in terms of seismic sources, including uncertainty in source boundaries.
(2) For each source, evaluation of the maximum earthquake magnitude, rate of earthquake recurrence and earthquake recurrence model, together with the uncertainty associated with each evaluation.
(3) Evaluation of the attenuation of earthquake ground motion for the site region, and assessment of the uncertainty in both the mean attenuation and the variability of the motion about the mean as a function of earthquake magnitude and source distance.

5.18. Results of ground motion hazard analyses are typically displayed as the mean annual frequency of exceedance, often referred to as annual probability, of measures of ground shaking that represent the range of periods important for plant structures (for example, peak acceleration and an appropriate range of response spectral accelerations for both horizontal and vertical motions). The mean, 15th, 50th and 85th percentile hazard curves are typically presented to display the hazard uncertainty for each measure of ground motion. With these hazard results, uniform hazard spectra (that is, spectral amplitudes that have the same annual exceedance frequency for the range of structural periods of interest) can be constructed for any selected target hazard level (annual frequency of exceedance).

5.19. To assist in determining the ground motion characteristics at a site, it is often useful to de-aggregate the probabilistic seismic hazard analysis. Such de-aggregation should be carried out for a target annual frequency of exceedance, typically the value selected for determining the design basis ground motion at the site. The de-aggregation should be performed for at least two response spectral frequencies, normally 1 Hz and 10 Hz. The de-aggregation may be used to identify the mean magnitude and distance of earthquakes that control the ground motions at these response spectral frequencies.

## Ground motion characteristics

5.20. The characteristics of the ground motions corresponding to SL-1 and SL-2 should be expressed in terms of response spectra for a range of damping values and compatible time histories, with due account taken of the reference conditions (see para. 5.7).

### *Response spectra*

5.21. The response spectral characteristics of the ground motion are determined according to the relative influences of the seismogenic source characteristics and the attenuation characteristics of the geological strata which transmit the seismic waves from the hypocentres to the site area. In strata above the base rock, the seismic waves are modified according to the response characteristics of those strata as a function of the strain level induced by seismic waves.

5.22. In addition to the uniform hazard spectra resulting from the probabilistic seismic hazard analysis (para. 5.18), response spectra can be generated by several methods.

### *Standard response spectrum*

5.23. A standardized response spectrum may be used when the contribution of multiple seismic sources needs to be represented by an envelope. The prescribed shape of the standard response spectrum is obtained from various response spectra derived on the basis of earthquake records. This standard response spectrum is scaled to the relevant site specific value of ground acceleration, velocity and/or displacement. It is possible to have a low to moderate magnitude near field earthquakes that have a relatively rich high frequency content and short duration, and which may produce peak accelerations that exceed the zero period value of the standard response spectrum. In such cases, these response spectra should be separated for design purposes.

### *Site specific response spectrum*

5.24. A site specific response spectrum may be developed from time histories of strong motion recorded at the site. Usually, however, an adequate sample of time histories of strong motion cannot be obtained at the site for a practical timescale. Therefore, response spectra obtained at places having similar seismic, geological and soil characteristics and experiencing similar types of ground motion are necessary in order to establish a response spectrum appropriate to the site.

### *Uniform confidence response spectrum*

5.25. The uniform confidence approach makes use of the results of regression studies of the attenuation of the ordinates of response spectra corresponding to different vibration periods, for the purpose of obtaining a response spectrum having ordinates which possess the same confidence values for all periods considered.

5.26. Regardless of which approach is adopted for specifying the response spectrum, account should be taken of the uncertainties associated with the spectral ordinates.[4]

### *Time histories*

5.27. Time histories should satisfactorily reflect all of the prescribed ground motion parameters, including duration. The number of time histories to be used in the detailed analyses and the procedure used in generating these time histories will depend on the type of analysis to be performed. Good co-ordination with the plant designer should be established in order to understand and respond to the needs of the particular type of analysis [3].

5.28. The duration of earthquake ground motion is determined mainly by the length and velocity of the fault rupture. Site effects and, in particular, trapped waves in deep basins can also enhance the duration of ground motion. Duration can also be correlated with magnitude. A consistent definition of duration should be used throughout the evaluation. For example, the duration of acceleration may be defined in several ways such as:

- the time interval between the onset of ground motion and the time when the acceleration has declined to 5% of its peak;
- the time interval between the 95th and 5th percentiles of the integral of the mean square value of the acceleration;
- the time interval for which the acceleration exceeds 5% of g.

5.29. In determining the length of time histories, due weighting should be given to any empirical evidence provided by the regional database. For some sites, relatively low amplitude motions from distant, large earthquakes may pose a liquefaction hazard. When this condition applies, time histories used for liquefaction should include such low amplitude time histories over an appropriate duration.

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[4] In many States, when deterministic methods are used, the specified spectral ordinates are equal to their median plus one standard deviation.

5.30. The generation of time histories may be based on a variety of data, such as:

- artificial time histories using spectral matching techniques that take account of phase characteristics of the seismic wave;
- strong motion records obtained in the site vicinity, or adequate modifications thereof, obtained by scaling the peak acceleration, applying appropriate frequency filters or combining records;
- strong motion records obtained at other places having similar seismic, geological and soil characteristics; in some cases, these records may also require amplitude and frequency modifications to make them appropriate;
- artificial time histories, which should be generated for several values of damping in order to reflect satisfactorily the ground motion characteristics.

Significant progress has been made recently in the theoretical simulation of ground motion including source, propagation and site effects (for example, by use of an empirical Green's function). Ground motions thus obtained for regions where pertinent parameters are available can be employed to complement the above mentioned methods. These new approaches should be applied carefully, especially when large non-linearities are expected in the surface layers of the site strata.

5.31. Regardless of the procedure used to generate time histories, the design response spectra and the time histories should be compatible. In using power spectral density functions, it should be ensured that the time histories include the appropriate energy content of the ground motion that has been evaluated, and that acceptable levels of deviation are indicated.

### *Ratio of motion in vertical and horizontal directions*

5.32. If no specific information is available on the peak acceleration of vertical ground motion in the site vicinity, it may be reasonable to assume a prescribed ratio between peak acceleration in the vertical and horizontal directions (for example, 2/3). Empirical evidence has shown that this ratio typically varies from 1/2 to 1 and may be largest in the near field, depending on the characteristics of the source and the site, among other factors.

5.33. Response spectra and time histories corresponding to vertical ground motion should be evaluated using the same procedure as for the horizontal spectra and time histories. When available, records of vertical time histories should form the basis of this evaluation.

*Time histories for base isolated structures*

5.34. The methodology for deriving the ground motion hazard (levels SL-l and SL-2) has been developed for fixed base plant structures. For structures that utilize base isolation systems for seismic protection, additional considerations may be necessary. These concern especially the long period effects which may cause excessive residual displacements in the elements of the base isolation system. For plant structures for which a base isolation system is envisaged, time histories should be examined and, if necessary, modified to take these effects into account (see also Ref. [3]).

5.35. For buried structures such as ducts and piping, appropriate response spectra and time histories should be developed in co-operation with the designer (see also Ref. [3]).

# 6. POTENTIAL FOR SURFACE FAULTING AT THE SITE

## INTRODUCTION

6.l. This section gives guidelines and procedures for assessing the potential for surface faulting (capability) which may jeopardize the safety of the plant. It also describes the scope of the investigations that are necessary to permit such an assessment to be made.

6.2. It should be taken into consideration that surface faulting may also occur without being associated with significant releases of seismic energy. For instance, seismic fault creep may be important along some segments of major strike slip faults — it is relatively common in volcano-tectonic environments and, for normal faults, it is sometimes induced by the extraction of underground fluids. Fault creep has typically been observed in areas characterized by high tectonic activity and seismicity. Stable sliding, seismic fault ground rupture and seismogenic surface faulting can be considered modes of fault displacement that may occur both in time and in space along capable faults.

## CAPABLE FAULTS

6.3. The main question with regard to surface faulting is whether a fault (buried or outcropping) at or near the site is capable. The basis for answering such a question should be the database (see Section 3) as incorporated in the seismotectonic model (see Section 4), together with such additional specific data as may be needed.

6.4. On the basis of geological, geophysical, geodetic or seismological data, a fault shall be considered capable:

- If it shows evidence of past movement or movements (such as significant deformations and/or dislocations) of a recurring nature within such a period that it is reasonable to infer that further movements at or near the surface may occur. In highly active areas, where both earthquake data and geological data consistently reveal short earthquake recurrence intervals, periods of the order of tens of thousands of years may be appropriate for the assessment of capable faults. In less active areas, it is likely that much longer periods are appropriate.
- If a structural relationship with a known capable fault has been demonstrated such that movement of the one fault may cause movement of the other at or near the surface.
- If the maximum potential earthquake associated with a seismogenic structure, as determined in Section 4, is sufficiently large and at such a depth that it is reasonable to infer that, in the geodynamic setting of the plant, movement at or near the surface may occur.

## INVESTIGATIONS NECESSARY TO DETERMINE CAPABILITY

6.5. Sufficient surface and subsurface related data should be obtained from the investigations in the region, near region, site vicinity and site area (see Section 3) to show the absence of faulting at or near the site, or, if faults are present, to describe the direction, extent and history of movements on them and to estimate reliably the age of the most recent movement.

6.6. As stated in Section 3, particular attention should be paid to those geological and geomorphological features at or near the site which may be particularly useful for distinguishing faulting and which may be useful in ascertaining the age of fault movements.

6.7. When faulting is known or suspected to be present, investigations of site vicinity scale and type should be made which include very detailed geological–geomorphological mapping, topographical analyses, geophysical surveys (including geodesy, if necessary), trenching, boreholes, age dating of sediments or fault rocks, local seismological investigations and any other appropriate techniques to ascertain when movement last occurred.

6.8. Consideration should be given to the possibility that faults that have not demonstrated recent near surface movement may be reactivated by large reservoir loading, fluid injection, fluid withdrawal or other phenomena.

6.9. Where reliable evidence shows that there may be a capable fault with the potential to affect the safety of a plant at the site, the feasibility of construction and safe operation of a plant at this site should be re-evaluated and, if necessary, an alternative site should be considered.

## 7. QUALITY ASSURANCE

7.1. A quality assurance programme shall be established and implemented to cover all the data collection and data processing activities, field and laboratory investigations, analyses and evaluations that are within the scope of this Safety Guide. See Ref. [4] for further recommendations and guidance on quality assurance.

7.2. Owing to the variety of investigations carried out (field, laboratory, office) and the need for using expert judgement in the decision making process, technical procedures that are specific to the project should be developed in order to facilitate the execution and verification of these tasks, and a peer review of the process should be conducted.

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# GLOSSARY

**capable fault.** A fault that has a significant potential for relative displacement at or near the ground surface.

**free field ground motion.** The motion that would occur at a given point of the ground owing to an earthquake if vibratory characteristics were not affected by structures and facilities.

**ground response.** The behaviour of a rock or soil column at a site under a prescribed ground motion load.

**intensity (of an earthquake).** An indicator of the physical effects of an earthquake on humans, or structures built by humans, and on the Earth's surface. The indicator comprises a set of numerical indices that is based on subjective judgements, not instrumental records.

**macroseismicity.** Seismicity to a level that implies significant, coherent, sustained tectonic activity.[5]

**seismogenic structures.** Structures that display earthquake activity, or that manifest historical surface rupture or effects of palaeoseismicity. Seismogenic structures are those considered likely to generate macro-earthquakes within a period of concern.

**surface faulting.** The permanent offsetting or tearing of the ground surface by differential movement across a fault during an earthquake.

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[5] Macroseismicity usually refers to the seismicity of larger earthquakes as opposed to micro-earthquakes. However, such seismicity might have different aspects in different areas. A determination of what level of seismicity constitutes macroseismicity in a given region is made after consideration of the overall seismicity in that region.

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