Authority for Nuclear Safety and
Radiation Protection

Seismic Design and Qualification for Nuclear Power Plants

(revised version of IAEA standard NS-G-1.6, 2010)

1 Foreword

The ANVS (the Authority for Nuclear Safety and Radiation Protection) has published the Guidelines on the Safe Design and Operation of Nuclear Reactors “ANVS Guidelines on Design and Operation” [1] for short DSR. They are available to download from the website of the ANVS (www.anvs.nl). The DSR provide insight into the best technology available in 2015 for ensuring the safety of new nuclear reactors.

In the context of the preparation of an application for a licence for the construction of a new reactor the DSR provide insight into what the ANVS considers to be the best available technology. Although the Safety Guidelines do not have the status of (ministerial) Regulations and do not therefore define any legal requirements, licence applications will be assessed on the basis of the safety requirements described in the Safety Guidelines. A licensee of an existing nuclear installation also has a legal (and social)responsibility to continuously improve nuclear safety. That implies that, following their publication, the DSR should also be used for guidance on the best nuclear technology currently available until no later than the next periodic evaluation. Evaluation of a nuclear reactor’s safety in the light of the best technology currently available may warrant action to improve nuclear safety, insofar as such action may reasonably be expected.

So the DSR describe the best technology available in 2015 for ensuring the safety of nuclear reactors and should be used as a guidance document for new and existing nuclear reactors. The DSR are goal oriented and at level of abstraction.
The document describes subjects like the fundamental safety objectives, the technical safety concepts and requirements and postulated operation conditions and event. For the application of the DSR also other documents such as guidelines of the IAEA are useful. However these IAEA documents do not use completely the same systematic and nomenclature as the DSR which are based on the Dutch legislation and for example WENRA documents. That is why ANVS decided to adept several IAEA documents to reach a better consistency with the DSR.

One of these documents is the attached IAEA safety standard NS-G-1.6 “Seismic Design and Qualification for Nuclear Power Plants” (2010). This document provides guidance and recommends procedures for the evaluation of seismic hazards for nuclear reactors and other nuclear installations and the revised version has got the name ”ANVS Guidelines on Seismic Design and Qualification for Nuclear Reactors (revised version of IAEA standard NS-G-1.6, 2010)”. These ANVS guidelines should be used in the same way indicated above for the DSR for both new as existing nuclear reactors.

Contents

2 Introduction

Background

2.1. This Safety Guide supplements the Dutch "ANVS Guidelines on the Safe Design and Operation of Nuclear Reactors" (DSR) [1] and is based on the IAEA Safety Guide NS-G-1.6 "Seismic Design and Qualification for Nuclear Power Plants".

2.2. This Safety Guide on "Seismic Design and Qualification for Nuclear Reactors" makes reference to the ANVS Guidelines on Seismic Hazards in Site Evaluation for Nuclear Installations (revised version of IAEA standard SSG-9, 2010), May 2017 [2] which gives guidance on how to determine the seismic hazard for a nuclear reactor at a given site.

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

Objective

2.4. The purpose of this Safety Guide is to provide recommendations on a generally accepted way to design a nuclear reactor so that an earthquake motion at the site determined according to Ref. [2] will not jeopardize the safety of the reactor. It also gives guidance on a consistent application of methods and procedures for analysis, testing and qualification of structures and equipment so that they meet the safety requirements established in the DSR.

Scope

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

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

2.7. It is recognized also that there is generally more than one possible engineering solution to a problem, and the approach adopted for one nuclear reactor may result in significant differences in design between that reactor and another reactor for which a different approach has been adopted. A recommended framework for the assessment of seismic safety in reactor design is presented in Ref. [9].

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

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

2.10. The technical recommendations in this Safety Guide concerning modelling and item qualification may also be applicable in part to the design of the plant against vibrational phenomena induced by sources other than earthquakes, such as explosions in industrial facilities, aircraft crashes, explosions in quarries or accidents with high speed rotating machinery [4]. However, such an extension should be done with care and engineering judgement should be used, particularly in relation to the frequency of the induced vibration, its duration, its direction and the mechanism of its impact on the plant. It should also be noted that the design to resist such loads may take different forms, such as sacrificial walls,

103103_Seismic Design_V2.indd 5 12-06-17 12:10

or may encompass different failure modes, such as scabbing or spalling for impact loads. These particular engineering provisions are not considered in this Safety Guide.

Structure

2.11. Section 3 discusses the safety implications of the design process and the relevant acceptance criteria required for different safety classes. In Section 4 the design principles for the achievement of the protection objective are recommended and the concept of periodic safety review is discussed in relation to the design issues. Guidance on an appropriate selection of methods for seismic qualification is provided in Section 5, recommendations for qualification by analysis are provided in Section 6, and qualification by test and experience is discussed in Section 7. Section 8 presents guidance on recommended seismic instrumentation, and suitable monitoring procedures and their relation to design assumptions.

3 General safety concepts

Scope

3.1. This section makes recommendations on categorizing the structures, systems and components (SSCs) of a nuclear reactor in terms of their importance to safety in the event of a design basis earthquake, in accordance with the requirements established in the DSR. Recommendations are also made concerning the application of standards for design to guarantee an appropriate safety margin in the design.

3.2. The quality assurance programme is required to be implemented to ensure that data collection, data processing, studies, analyses and qualification, code validation (software) and verification, and other activities necessary to meet the recommendations of this Safety Guide are performed correctly.

Design basis earthquake

3.3. According to Ref. [2], two levels of ground motion hazard should be evaluated for each plant sited in a seismic area.

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

3.5. It is common practice to have more than one earthquake associated with each of the two hazard level, the operation base earthquake and the design basis earthquake. These earthquakes should be representative of the corresponding seismogenic areas. All of them should be considered in the design, and appropriate enveloping should be carried out on the results.

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

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

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

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

Seismic categorization for structures, systems and components

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

3.11. All items experience any seismic loading that occurs, and the performance required in the event of an earthquake is not necessarily related to the reference safety function considered in the safety classification (Ref. DSR 3.1 (5) and 3.5 (1)), which is based on the most demanding of all the safety functions required by all the design basis conditions (postulated initiating events). For a safety oriented approach to design, therefore, in addition to the safety classification, SSCs may be grouped into four or more categories in terms of their importance to safety during and after an earthquake.

3.12. In the event that an external event categorization is available, as defined in Ref. [4], the seismic categorization[1] as proposed here should be consistent with it. However, a seismic categorization should also be defined in the absence of a general external event classification, owing to the peculiarity of the seismic design, and the seismic categorization is therefore redefined here. Other classification methods would be acceptable provided that they met the same acceptance criteria as defined below.

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

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

3.14. The selection of items under item (c) above is related to the defence in depth approach: in the event of a design basis earthquake, all levels of defence are required to be available at all times (Ref. DSR 2.1 (9))[2]. The physical barriers designed to protect the plant from external events other than seismic events should maintain their integrity and functionality during an earthquake.

3.15. Nuclear power plant items of seismic category 1 should be designed, installed and maintained in accordance with the most stringent national practices for nuclear applications: the safety margin[3] should be higher than the safety margin used in facilities at conventional risk. For any item in seismic category 1, an appropriate acceptance criterion[4] should be established (such as the value of a design parameter indicating functionality, leaktightness or maximum distortion) in accordance with the required safety function. However, in some cases the acceptance criteria for the physical barriers may be reduced for load combinations including the design basis earthquake (Ref. DSR 2.1 (1)), provided that the effects on the plant's safety functions are evaluated in detail.

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

---

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

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

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

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

(1) Items that may have spatial interactions (e.g. due to collapse, falling or dislodgement) or any other interactions (e.g. via the release of hazardous substances, fire or flooding, or earthquake induced interactions) with items in seismic categories 1 and 3. It should be demonstrated that the potential effects due to, and the damage caused to, items in seismic category 2 would affect neither the safety related functions of any of the items in seismic categories 1 and 3 (para. 3.19) nor any safety related operator action.
(2) Items not included in seismic category 1 (particularly items under (b) and (c) in para. 3.13) that are required to prevent or mitigate plant accident conditions (originated by postulated initiating events other than earthquakes) for a period long enough that there is a reasonable likelihood that design basis earthquake may occur during that period.
(3) Items related to the accessibility of the site and items necessary for the implementation of the emergency evacuation plan.

3.17. In particular, when, as a result of an earthquake, any interaction is expected on the basis of analysis, testing or experience to occur, and this could jeopardize the functioning of items in seismic category 1 or 3 (including operator action), one of the following measures should be taken:
(a) Such an item in seismic category 2 should be reclassified to seismic category 1 or 3 and designed accordingly.
(b) Such items in seismic category 2 should be qualified against the design basis earthquake in order not to adversely affect items in seismic category 1 or 3.
(c) The endangered items in seismic category 1 or 3 should be suitably protected so that their functioning is not jeopardized by the interaction with items in seismic category 2.

3.18. Items in seismic category 2 should follow the practice for design, installation and maintenance for nuclear applications. However, in the hypothesis in para. 3.17 (b) (interacting items), lower intrinsic safety margins than those specified in nuclear standards can be applied when the probability of interaction with items in seismic category 1 or 3 is considered very low.

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

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

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

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

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

3.24. The seismic categorization depends on the reactor type (e.g. pressurized water reactor and boiling water reactor) and on site specific boundary conditions (e.g. the availability of cooling water resources).

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

Combination of earthquake loads with operating condition loads

3.26. Design loads are grouped as follows:

- Level 1 – Loads during normal operation,
- Level 2 – Additional loads during anticipated operational occurrences,
- Level 3a – Additional loads due to postulated single initiating events,
- Level 3b – Additional loads due to postulated multiple failure events,
- Level 4 – Additional loads due to postulated core melt accidents.

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

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

(a) For items in seismic categories 1 and 3, Level 1 loads should be combined with the design basis earthquake, according to their categorization.

(b) For items in seismic categories 1 and 3, Level 1 and Level 2 or Level 3 loads should be combined with the design basis earthquake if the Level 2 or Level 3 loads are caused by the earthquake and/or have a high probability of coinciding with the earthquake loads (which may be the case, for example, for Level 2 loads that occur sufficiently frequently, independently of an earthquake[5]).

(c) For items in seismic category 2 which have been identified to interact with items in seismic categories 1 and 3, the same combinations of seismic category 1 or 3 should be applied, possibly associated with different safety margins.

(d) For items in seismic category 4, combinations according to national practice should be applied to the relevant design basis loads.

3.29. For the seismic design of SSCs, external events such as floods or fires assumed to occur at the site as a consequence of an earthquake should be taken into account. They should be defined on the basis of probabilistic considerations. These loadings as a consequence of an earthquake should be combined with either operation base earthquake or design basis earthquake loadings, with due account taken of event timing and duration.

Table 1. Load combinations with seismic loads

Seismic category	Level 1	Level 2	Level 3	DBE[a]	Safety margin
1	X			X	According to design codes for facilities at higher risk (nuclear code).
[b]	X	X		X	Same as above.
[b]	X		X	X	Same as above.
2	X			X	According to design codes for facilities at higher risk (nuclear code) or lower risk[c].
[b]	X	X		X	Same as above.
[b]	X		X	X	Same as above.
3	X			X	According to design codes from facilities at risk different from (usually lower than) those for nuclear reactors.
[b]	X	X		X	Same as above.
[b]	X		X	X	Same as above.
4	X			X	According to design codes for facilities at conventional risk.

a Operation basis earthquake may be used in some load combinations, other than those with design basis earthquake, if supported by probabilistic arguments.
b To be considered only if there is either a causal dependence on design basis earthquake or a high probability of coincidence.
c Lower safety margins may be considered if a low probability of interaction can be demonstrated.

5 Typical Level 2 loads induced by a seismic event could be loads created by tripping of the reactor or by a pressure peak in the primary system due to a tripped turbine in a boiling water reactor with a small steam bypass capacity to the condenser.

Seismic capacity

3.30. Acceptance criteria for load combinations, including the effects of design basis earthquake with Level 1 or Level 2 loads, or Level 3 loads, should be the same as those adopted in related practices for Level 3 loads acting without an earthquake.

3.31. Structures in seismic categories 1 and 3 may be designed to exhibit non-linear behaviour (by choice of material and/or geometry) provided that their acceptance criteria (as expressed in terms of the value of a design parameter such as elasticity, maximum crack opening, absence of buckling or maximum ductility) are met with a safety margin consistent with the seismic categorization. The incidence of irreversible structural behaviour (e.g. in relation to limited ductility of joints) should be compatible with the expected frequency of occurrence of the associated seismic scenarios. In any case, the specific acceptance criteria (e.g. leaktightness, maximum relative displacement and functionality) should be assessed explicitly, according to the seismic categorization.

3.32. Structures in seismic category 2 may also be designed to exhibit non-linear behaviour. Detailing of structural members, particularly joints and connections, should be consistent with the ductility level required by the acceptance criteria.

3.33. Material properties should be selected according to characteristic values supported by appropriate quality assurance procedures. Appropriate ageing evaluation should be carried out to guarantee the long term safe performance of materials and SSCs (Ref. DSR 3.1 (2)).

3.34. Specific evaluations should be carried out concerning the acceleration of degradation mechanisms by seismic events. If such mechanisms are responsible for any reduction in seismic capacity over the lifetime of the plant, additional safety margins should be adopted to guarantee the required safety level in the design after any seismic event.

3.35. To ensure adequate seismic safety, ductile design should be effected and gradual and detectable failure modes should be incorporated. The following measures are a sample, indicative of what should be considered at the design stage:
- In reinforced concrete structures, brittle failure in shear and/or bond or in the compressive zones of concrete should be prevented.
- An appropriate minimum compressive strength of the concrete should be determined to ensure that the ultimate strength of the structural members is governed by the reinforcement.
- For reinforcement, an appropriate minimum ratio of the ultimate tensile stress to the yield tensile strength should be defined, to ensure a minimum ductility.
- Structural joints, particularly in reinforced concrete structures, should be designed to provide a high ductility and a capability to accommodate large displacements and rotations; this provision should be consistent with the acceptance criteria specified in the seismic categorization, but is intended also to take into account considerations relating to beyond design basis events.
- At least for the main coolant loops, it should be demonstrated that any ‘reasonable’ defect that inspections may fail to detect will not propagate during the plant lifetime and will also remain stable during an earthquake.
- Appropriate consideration should be given to ageing in order to provide a basis for the assumption of ‘long term’ geometric configurations (e.g. against creep and settlement) and ductile material properties (e.g. against radiation embrittlement).

3.36. A particular case is represented by the application of the leak before break concept[6]: in cases where this criterion is applied, a specific evaluation of the seismic contribution to crack propagation should be carried out by analysis or by testing, with procedures that are compatible with the required accuracy.

6 The leak before break concept is a general approach that affects design, material selection, construction, quality assurance, monitoring and inspection. It has major effects on some design assumptions such as the transient load to be considered for the design of fuel assemblies, the transient load for the design of the coolant pressure boundary (the need for consideration of a double ended guillotine break is avoided) and the pipe whip load from a pipe break scenario. However, the approach has been developed in many different versions in various States (including different ranges of application: from the primary loop only to all safety related piping) and there can be no general discussion in this Safety Guide.

3.37. The acceptance criteria for seismic category 4 should at least follow applicable national standards and codes for conventional risk facilities.

Considerations for beyond design basis events

3.38. Seismic design should be carried out in accordance with the general recommendations outlined in the previous paragraphs and the design recommendations given in Section 4 to provide margins for seismic events that are beyond the design basis and to prevent potential small deviations in plant parameters from giving rise to severely abnormal plant behaviour ('cliff edge' effects)[7]. These margins should be quantified. For specific items for which general principles of seismic design cannot be observed owing to highly non-linear behaviour (e.g. behaviour induced by unilateral restraints installed to meet other design criteria such as thermal loads), sensitivity studies should be performed and appropriate strengthening measures should be taken to enhance safety margins.

Content of the safety analysis report

3.39. The derivation of the design basis, general assumptions in design, the final evaluation of the safety margin and the logic of the seismic monitoring should be described in the safety analysis report (SAR). Technical reports should be referenced and made available in order to ensure the traceability of the procedures for analysis and testing followed for seismic qualification. Recommendations and guidance on the content of the SAR are given in Ref. [13].

7 A cliff edge effect is the effect of an abrupt transition from one status to another: a discontinuity in the first derivative of the response to a small deviation in a plant parameter.

4 Seismic design

Selection of an appropriate plant layout

4.1. In the early stages of the design of the plant, a preliminary layout of the main facilities should be prepared; this should be periodically reviewed to achieve the most suitable solution for the seismic design. All procedures for seismic design should be firmly based on a clear appreciation of the consequences of past destructive earthquakes, and this knowledge should be adopted and realistically applied. In this preliminary work, the considerations mentioned in this section should be taken into account to reduce the effects of earthquakes on SSCs.

4.2. In the preliminary design stages, seismic effects (in terms of forces and undesired torsional or rocking effects) should be minimized by the appropriate selection of a structural layout applying certain general criteria, such as:
(a) Locating the centre of gravity of all structures as low as practicable;
(b) Selecting a plan and elevation that are as simple and regular as practicable, and also avoiding different embedment depths;
(c) Avoiding protruding sections (i.e. lack of symmetry) as far as practicable;
(d) Locating the centre of rigidity at the various elevations as close as practicable to the centre of gravity;
(e) Avoiding rigid connections between structures or equipment of different categories and dynamic behaviour as far as practicable.

4.3. To reduce undesirable differential movements between structures, consideration should be given to locating the structures, to the extent practicable, on a common foundation structure, or at least avoiding different embedment depths. In siting the plant, having significant differences in soil properties below the foundation structure should be avoided. All individual footings or pile foundations should be tied within the structural floor plan.

4.4. Regular layouts and simple connections between structures should be adopted to facilitate the seismic analysis and to improve the seismic behaviour of piping and equipment appended to buildings. In crossing structural boundaries (e.g. with expansion or construction joints), in making connections between buildings or in bringing services to and from a building through underground conduits, care should be taken to avoid damage or failure due to differential movements.

4.5. A specific approach could also be applied to the whole design or to parts of it through the use of antiseismic systems and devices such as base isolators. This technique should be integrated with special provisions in the design of a more complicated foundation system and special operational procedures for the periodic inspection and maintenance of the isolation devices; these additional efforts can be largely compensated for by a significant reduction in seismic demand on SSCs. The increased relative displacement field may give rise to concerns for the design of structural interfaces and connections, and it should be explicitly addressed in the design. Moreover, the effects of using seismic isolators should be evaluated in relation to the response to other loads where the response may be worsened.

Geotechnical parameters

4.6. Information on site specific soil properties should be available from site investigation campaigns, laboratory analyses and engineering syntheses, as described in Ref. [3], in which guidance is also given on the extension of the campaigns and their requirements. Their accuracy should be compatible with the overall reliability required in the design process. Procedures for soil modelling are discussed in Section 6.

Civil engineering structures

4.7. Particular attention should be paid to the following issues in the design and design review of structures:
(a) The adequacy of the supporting soil [3].
(b) The suitability of types of foundation supports or of different types of foundations under interconnected structures (e.g. it should be avoided that part of the foundations of one building is supported on piles or rock and part is set directly onto soil).

(c) A balanced and symmetrical arrangement of structural frames and shear walls to achieve optimum stiffness and distribution of loads and weight with minimum torsional effects.
(d) The need to prevent collisions between adjacent buildings (pounding) as a consequence of their dynamic deformations (this phenomenon may also occur in weakly coupled structures).
(e) The adequacy of the connections of annexes and appendages to the main structure (see also item (d)).
(f) The need to ensure sufficient resistance of essential structural elements, especially resistance to lateral shear forces.
(g) The need to ensure sufficient ductility and to avoid brittle failure by shear or compression; for example, by ensuring that there is an adequate amount of reinforcement steel, and in particular that there are enough hoop ties for columns (i.e., adequate confinement) to prevent the premature buckling of compression bars located in plastic regions.
(h) The arrangement and distribution of steel reinforcement: too high a concentration of rebars may cause cracking of concrete along the lines of the rebars.
(i) The need for joints between structural elements and anchorages of items cast into concrete to be designed so as to ensure ductile failure modes (e.g. anchor lengths should be sufficiently long to avoid pull-out and adequate reinforcement with transverse ties should be provided) and, to the extent practicable, for connections between members to be made as strong and as ductile as the members that they connect.
(j) An evaluation of the non-linear bending moments induced by the vertical forces and the horizontal translation in the event of an earthquake (the so-called 'P–D' effect).
(k) The additional effect of groundwater buoyancy on the foundation.
(l) The possibility of lateral sliding of structures on waterproofing material (especially if wet) in an earthquake.
(m) The dynamic effect of 'non-structural' elements, such as partition walls, on structural elements.
(n) The detailed design of construction joints and thermally induced stresses in large integrated monolithic structures designed to resist differential earthquake motions.
(o) The effects of the transfer of forces in cases where the stiffness of a containment vessel is greater than that of the surrounding concrete structures, and where they are interconnected or may interact so that the earthquake loads on the concrete structures may be transferred to the containment vessel. Owing to the complexity of the interactions of such structures, it is difficult to evaluate such forces, and such structures should be decoupled above the foundation level to the extent possible.
(p) The adequacy of the anchorages of mechanical components to civil structures.
(q) The need to strengthen non-structural walls or steelworks to prevent them or parts of them from falling on safety related items.

Earth structures

4.8. The following safety related earth structures may be encountered at nuclear reactor sites:
- Ultimate heat sinks: dams, dykes and embankments;
- Site protection: dams, dykes, breakwaters, sea walls, revetments;
- Site contour: retaining walls, natural slopes, cuts and fills.

4.9. These earth structures should be designed in accordance with their seismic categorization with adequate seismic capacity and for the following seismic related effects:
(1) Slope failure induced by design basis vibratory ground motions, including liquefaction;
(2) Sliding of structures on weak foundation materials or materials whose strength may be reduced by liquefaction;
(3) Failure of buried piping or seepage through cracks induced by ground motions;
(4) Overtopping of the structure due to tsunamis on coastal sites or seiches in reservoirs, earth slides or rock falls into reservoirs, or failure of spillway or outlet works;
(5) Overturning of retaining walls.

Piping and equipment

4.10. Specific provisions should be made with regard to the seismic design of equipment and piping supports:
(a) Care should be taken in the design of the supports to ensure that all joints are designed to behave as assumed in the analysis for the support and to transmit the full range of loads determined in the members connected to them. In particular, if restraints on six degrees of freedom are used, they should be designed, manufactured and installed so as to minimize the potential for any unexpected failure or crack initiated in the supporting element to propagate to the functional parts, such as the pressurized shell or the primary piping.

(b) Care should be taken in the design of devices for anchoring equipment, for example, in the possible use of hook shaped or end plate anchor bolts, to ensure that all potential forces and moments are fully evaluated and that anchoring materials are suitable for their purpose. It should be ensured that baseplates are sufficiently stiff to avoid prising effects and that anchor bolts are adequately tightened to avoid rocking effects, lowered frequencies, increased response levels, loads higher than the design loads and increased risk of loosening, pull-out or fatigue. Oversized or redundant anchors, pre-loaded to close to their yield point on installation, should be used.

4.11. The following points should be taken into account to improve the resistance to earthquake induced vibration:
(1) Equipment support legs should be braced unless their dimensions warrant departure from this recommended practice. Resonance should be avoided and, in some cases (e.g. for core internals for which it is difficult to avoid resonance by means of modifying the design), the vibration characteristics of the reactor building's internal structure itself may be modified to prevent resonance effects. If systems are made stiffer, the effects of thermal stresses, other dynamic loads and differential motions of the supporting points should be considered.
(2) Resonance of equipment such as piping, instrumentation and core internals at the frequency of the dominant modes of supporting structures should be avoided as far as is practicable. In some cases, where the response of equipment, although significant, cannot in practice be reduced by other means, the damping of the system may be increased by means of suitable design modifications.
(3) To provide seismic restraints for piping and components and at the same time allow freedom for thermal deformations, dampers or motion limiting stops may be used. Excessive use of snubbers should be avoided owing to the implications of these in relation to operation and maintenance. Realistic damping values to define seismic design inputs should be used, since overdesign for seismic loads can reduce the design margins for thermal loads (through the restraint of free displacement).
(4) Particular attention should be paid to the possibility of collision between adjacent components, or between components and adjacent parts of a building, as a consequence of their dynamic displacement. Allowance should also be made for the flexibility of connections between such components, between components and building penetrations, and between components and underground connections to buildings, as well as between buildings.
(5) Piping support should be arranged so that loads transferred to the equipment are at a minimum.

4.12. Such measures should also be taken with reference to all possible sources of vibration (e.g. aircraft crash, operational vibrations and explosions), as their effect may be different from the effects induced by seismic vibrations.

Selection of appropriate design standards
4.13. Consistency of the standards applied for design, material selection and construction quality should be ensured for the different disciplines (mechanical, civil and electrical). An early assessment of the consistency of the respective safety margins and relevant uncertainty levels and of their agreement with the general safety requirements for the project should be carried out in the different design tasks.

4.14. Such an assessment may in fact affect the management of the project and the entire quality system required for the design assessment and the construction phase, by ensuring that the design assumptions in terms of global plant safety are realized in the design.

4.15. If a licensee decides to follow other seismic design standards in addition to the applicable national nuclear standards, the compatibility and suitability of the following options should be evaluated:
- National 'non-nuclear' seismic standards (for facilities presenting a conventional risk);
- International nuclear seismic design standards (for installations potentially posing a higher risk for workers, the public and the environment);
- International nuclear design standards that do not include seismic design standards;
- National non-nuclear and non-seismic design standards.

Safety margins, design procedures and requirements for quality assurance throughout the entire design process, from the site data to the calculation of material capacity, should be compared in the evaluation. Mixing design standards is not good practice and should be avoided owing to the consequent intrinsic difficulty of evaluating the global safety margin of the design.

4.16. The overall safety margins provided by the design should then be evaluated in the safety assessment phase, in accordance with the procedures recommended in Ref. DSR 5 (4).

Periodic safety review

4.17. As required in the DSR, periodic safety reviews of the plant should be carried out on a ten-year basis. In addition, reviews of the seismic design should be performed whenever evidence is gained of a significant modification of any design assumption. Adequate long term configuration control and monitoring (Section 8) should be put in place to support periodic safety reviews of this kind adequately.

4.18. In such a review the original design assumptions should be assessed against new site evaluations (e.g. reflecting the occurrence of new events or the availability of new evidence of the local tectonics), modern standards for design and qualification, and newly available methods of design.

4.19. Upon the completion of a periodic safety review, the ongoing validity of the seismic qualification of equipment should be ensured. The need to maintain the seismic qualification status of equipment should be reflected in the procedures for controlling changes to the plant, including changes to its operating procedures. In this framework, beyond the normal good housekeeping standards expected for a nuclear installation, areas adjacent to seismically qualified SSCs should be maintained free from interaction hazards.

5 Generalities on seismic qualification

5.1. Seismic qualification of items important to safety[8] can be performed by the use of one or more of the following approaches:
- Analysis;
- Testing;
- Earthquake experience;
- Comparison with already qualified items (similarity).
  It is also possible to use combinations of these methods, as shown in Fig. 1.

5.2. Seismic qualification generally includes qualification of structural integrity as well as qualification for operability or functionality. Seismic qualification is made directly on actual or prototype items; or indirectly on a reduced scale model, a reduced scale prototype or a simplified item; or by means of similarity where this can be established between a candidate item and a reference item and direct qualification has been performed on the latter. Whatever the method selected, it should accurately represent the actual performance of the component or structure when it is subjected to the prescribed effects.

5.3. Care should be taken to ensure that consistent levels of sophistication in modelling apply for all the items to be qualified.

5.4. Any qualification programme requires that the boundary conditions applying for this item in the plant during an earthquake are correctly or conservatively simulated, or that any departure from them will not significantly influence the result. Among these conditions, the most important are: excitation conditions, support conditions, environmental conditions and operational conditions.

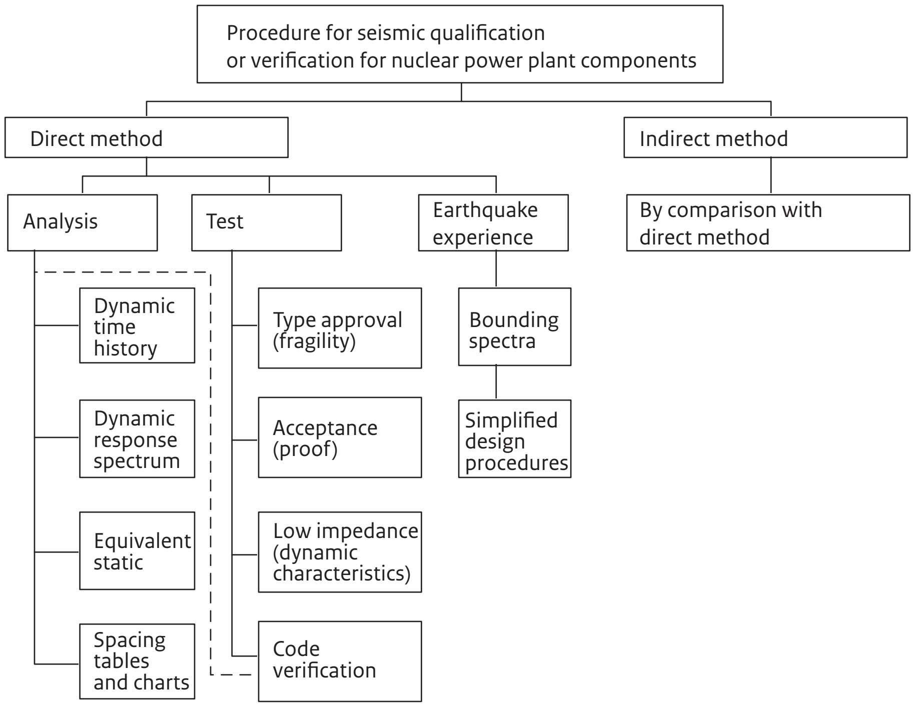
5.5. A combination of analysis and testing should be considered to guarantee an adequate reliability level for the results, particularly for testing on prototypes. In general:

In the case of testing:
- Analysis should inform the location of sensors for a test.
- Analysis should inform the definition of test range and test programme.
- Analysis should inform the processing of data from a test.

In the case of analysis:
- Testing should validate the constitutive law selected for material modelling.
- Testing should validate the identification of the failure mode.

8 Investigation or modelling of soils, together with structures and foundation media, is largely outside the scope of this Safety Guide. This subject is treated comprehensively in Ref. [4].

Fig. 1. Summary of seismic qualification or verification methods.



5.6. Seismic qualification by analysis should be used for items without a functional safety requirement that are unique and that are of a size or scale to preclude their qualification by testing. Civil engineering structures, tanks, distribution systems and large items of equipment are usually qualified by analytical methods after the modelling requirements discussed above have been fulfilled.

5.7. The continuing increase in analytical capabilities has allowed the use of highly sophisticated non-linear constitutive laws to model materials in conjunction with very finely detailed numerical models. This has enabled validating results to be derived from alternative software, thus enhancing confidence in the appropriateness and correctness of the results. However, as all analytical techniques have limits of applicability, an appropriate validation phase of methods and software verification should be carried out by means of either an independent analysis or a test.

5.8. For equipment, a systematic evaluation of the possible modes of failure related to earthquakes should be carried out with reference to the acceptance criteria assigned by the safety classification. This should be carried out by means of specific tests. However, as sophisticated techniques of analysis by computer simulation are improving, even the performance of 'active' equipment (e.g. pumps, valves and diesel generator sets) under earthquake conditions may be predicted with some confidence by means of analysis. The operability of active components may be qualified by analysis only when their potential failure modes can be identified and described in terms of stress, deformation (including clearances) or loads. Otherwise, testing or earthquake experience should be used for the qualification of active components.

5.9. In general, it should be understood that a high level of analytical sophistication still requires a number of assumptions to be made and produces at best only an indication of seismic behaviour. Data from testing or experience should always be used to validate analytical results, particularly with regard to functionality.

5.10. In addition to the methods described above, seismic qualification of items in seismic category 2 should be carried out by means of dedicated expert walkdown, in which all potential interaction mechanisms should be evaluated: mechanical interaction or interaction by the release of hazardous substances, fire and flood (earthquake induced), and the prevention of safety related operator action through the impairment of access.

Seismic qualification by means of analysis is treated in Section 6. The other three means form the subject matter for Section 7.

6 Qualification by analysis

Modelling techniques

Modelling of seismic input

6.1. The dynamic input motions used to qualify items are conservatively but realistically defined by either time histories or response spectra. In the case of response spectra, the spectrum shape, the peak ground acceleration and the duration of the motion should be derived consistently with the hazard definition, as discussed in Ref. [2].

6.2. It is common practice to apply the horizontal and vertical components of the seismic input simultaneously to the numerical model. In this case the components should be statistically independent. When the input components are applied individually, the corresponding structural responses should be suitably combined to account for the statistical independence of the two components of the input.

General modelling techniques for structures and equipment

6.3. Nuclear reactors can be modelled in many different ways according to their structural characteristics (e.g. lumped mass models, one dimensional models, axisymmetric models, two or three dimensional finite element models). The most suitable and reliable numerical technique should be used in order to minimize the contribution of the modelling techniques used to the uncertainties in the results. The continuing increase in the speed of computation and the progress in the graphical display of results have enabled the use of greatly refined structural and material models.

6.4. Typical models for the structures and equipment of nuclear reactors are shown in Figs 2 and 3. These figures are included to demonstrate the wide range of complexity possible in the way analytical models may be constructed. While simple conceptual models are capable of capturing the global pattern of response in complex structural or mechanical systems, local patterns of stresses or deformations are best obtained from detailed models.

6.5. The use of simple lumped mass models for structural components or rigid mass models with spring supports to represent foundation–structure interactions should be restricted to the purpose of checking the accuracy of calculations made with more detailed models.

Fig. 2. Examples of various models associated with dynamic or static analysis

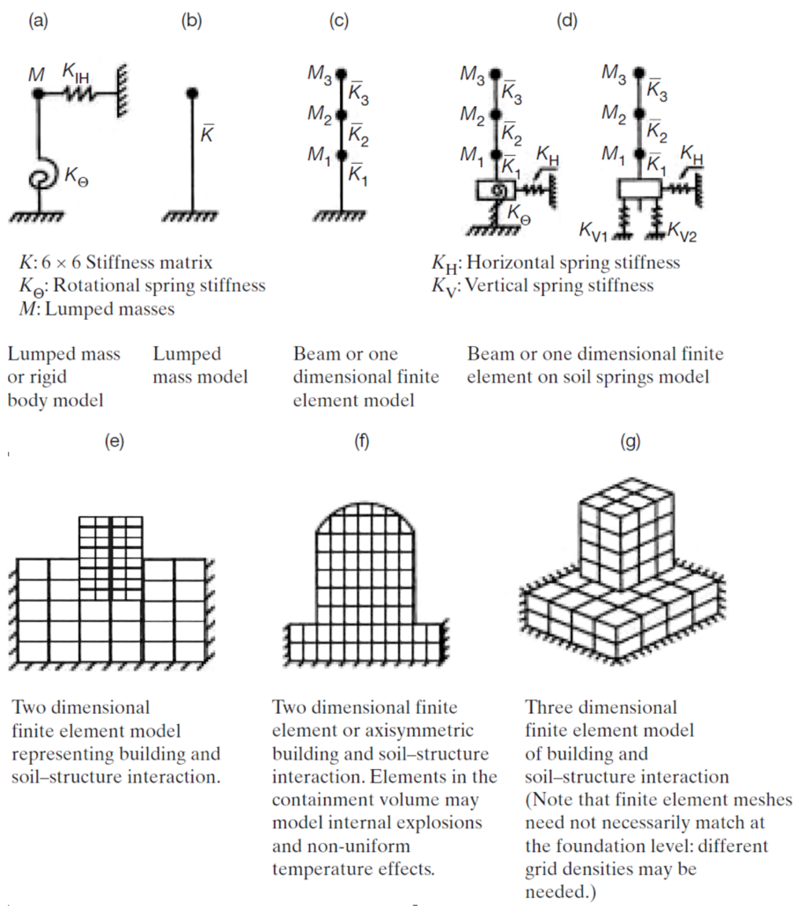
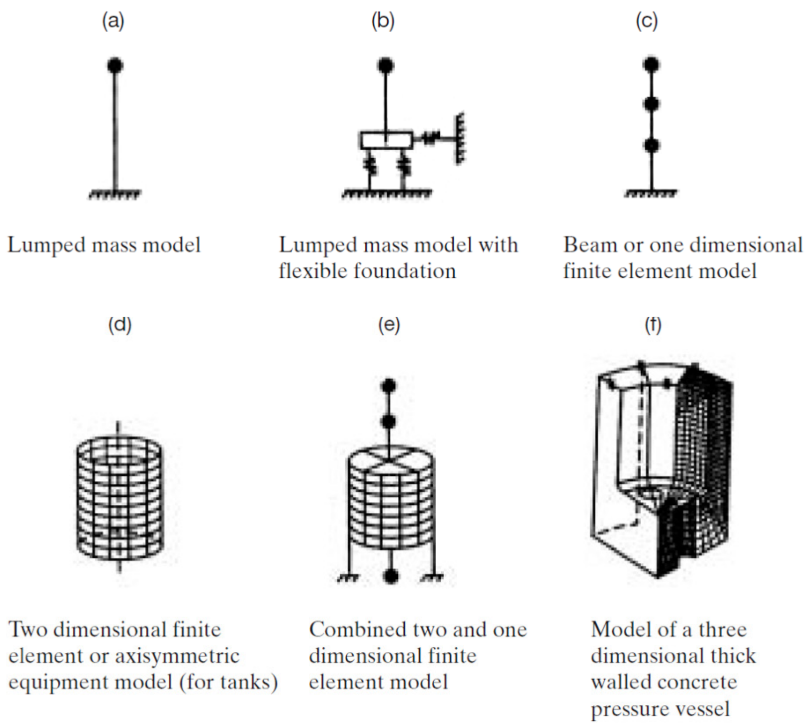


Fig. 3. Examples of various equipment models associated with dynamic or static analysis



6.6. There are sufficient grounds to attribute confidence to the outcome of models that have many thousands of degrees of freedom and that exploit sophisticated soil modelling techniques if these analytical tools have been benchmarked against experimental or theoretical results on the basis of methods generally accepted by experts. The validation of codes used (i.e. the intrinsic accuracy of the code) and the verification (i.e. the use of the code in a specific application) should be addressed in the safety related documentation (Ref. DSR (5) 7).

6.7. The mass characteristics of the structural systems should be adequately incorporated into the analytical models. Modelled mass should include suitable contributions from operational loads (including the live loads): Quasi-permanent loads should be treated as permanent loads (100 %). For tanks, a fluid level of 80 % should be assumed. Other variable actions (e.g. area loads on platforms or loads during outages) may be accounted for with ¼ of their actual value.

6.8. More than one model should be developed if there is uncertainty about the response of some parts of the structure. A sensitivity analysis should be made to provide the basis for this decision and this should also help in the choice of the size, type and number of finite elements if this modelling technique is used. Models should be validated by means of testing or by comparison with numerical models with different formulations in order to resolve possible uncertainties.

6.9. The selection of an adequate number of degrees of freedom is often straightforward, for example in the calculations for a conventional building with floors. In other cases, for example for shell or beam type structures, the selection is not obvious and will depend on the number of modes needed for the seismic analysis. The detail of the model should be consistent with the objectives of the required qualification and should be able to represent the corresponding local modes. A practical way to ensure that a sufficient number of modes (missing mass) are included in the analysis is to add a rigid body or a zero period acceleration mode, which corrects for the highest frequency modes that may otherwise not be included in the evaluation. An evaluation of the missing mass should be carried out as a final confirmation of the cut-off. It should also be ensured that correct reactions at supports are computed, within the limits of the finite element model.

Decoupling criteria

6.10. Nuclear power plant structures may be very complex and a single complete model of the entire structure would be too cumbersome or possibly ill conditioned. The analysis should therefore identify the substructures by defining main systems and subsystems.

6.11. Major structures that are considered in conjunction with foundation media to form a soil–structure interaction model should constitute the main systems. Other SSCs attached to the main systems should constitute the subsystems.

6.12. Criteria should be used to decide whether a particular subsystem should be taken into account in the analysis of the main system. Such decoupling criteria should define limits on the relative mass ratio and on the frequency ratio between the subsystem and the supporting main system; special care should be taken to determine whether there is a possibility of resonance between the subsystem and the main system.

6.13. If the decoupling criteria are not satisfied, a suitable model of the subsystem should be included in the model of the main system. For a subsystem having all its resonant frequencies (with the flexibility of the support taken into account) higher than the amplified frequencies (above 15 Hz for the usual design basis earthquakes), only the mass should be included in the model of the main system.

6.14. For detailed analysis of subsystems, the seismic input, including the motion of differential supports or attachments, should be obtained from the analysis of the main model. When coupling is significant, the model of the subsystem should be included in the analysis of the main system. The subsystem model should have at least the same natural frequencies and modal masses as the detailed model of the subsystem in the frequency range of interest.

Material properties

6.15. Modelling of reinforced concrete structures is usually undertaken by assuming that sections are uncracked. However, the effects of reduced section properties, equivalent to some degree of cracking, should also be evaluated in a sensitivity analysis.

6.16. The selection of soil properties, frequencies and strain dependences should be adequately documented. Methods of investigation and testing procedures are discussed in Ref. [3]. In this design context, a range of variation in soil properties should be defined to take account of uncertainties in geotechnical parameters, as suggested in Ref. [3]. The effect of such variation may envelop the variation in structural properties (e.g. due to a cracked section): this aspect should be explicitly addressed in the safety evaluation.

6.17. The structural damping used in the qualification analysis should be conservatively but realistically defined. To this extent, experimentally determined damping for a material or a structural system should be evaluated with care since it might not be representative of the actual structural behaviour of the component installed in the plant.

6.18. Damping values used in seismic analysis should be mean or median centred.

6.19. The value of (geometrical and material related) damping for soil that is to be used in the seismic analysis should be obtained by conservatively applied engineering judgement. Variation of damping factors with the frequency and amplitude of motion may be taken into account if this is warranted on the basis of the experimental data.

6.20. Particular care should be taken with the numerical modelling for the parts of the model with different damping values (e.g. soil, structure and components).

Interactions with soil, fluid and other structures

6.21. In the modelling of buildings or large ground founded tanks, the soil–structure interaction should be taken into account and explicitly modelled. With consideration of embedment, depth to water table, and locally modified properties of soil, input ground motions defined for surface conditions should be deconvolved to prescribed levels of the soil–structure complex, typically at the foundation level [3]. This process should include the rotational input. In the event that high reduction of input ground motion is obtained, it should be carefully justified.

6.22. Effects of soil–structure interaction should be evaluated by appropriate modelling of the soil–structure complex. With growing confidence in analytical procedures utilizing robust material laws, this task can be accomplished relatively easily even for very detailed models. However, simplified methods may be applied if it is demonstrated that they are conservative. The appropriate range of values applied for soil properties, and the way they are modelled, should be thoroughly documented. Special attention should be given to the modelling of the soil boundaries, which should account for radiative effects of seismic waves in unbounded media.

6.23. Lateral earth pressure induced on underground portions of structures or foundations by ground motion should be evaluated in accordance with Ref. [3].

6.24. The liquefaction potential of saturated granular soil layers, the potential for a loss of bearing capacity and the potential for settlement should be evaluated for the design basis earthquake and the existence of appropriate safety margins should be demonstrated, as explained in Ref. [3].

6.25. The following effects of an earthquake on buried independent structures (e.g. buried pipes, ducts and well casings) should be taken into account:

- Deformations imposed by the surrounding soil during and after the earthquake;
- Differential displacements or loads at end connections to buildings or other structures;
- Effects of contained fluids (impulsive loads, hydrostatic pressure and sloshing effects).

Recommendations for a seismic design of buried structures are provided in Ref. [3].

6.26. Adjacent buildings or components on the same foundation structure should be included in the same model when the relative displacement can affect a specified acceptance criterion (such as the value of a design parameter indicating elasticity, maximum crack opening, absence of buckling or maximum ductility).

6.27. The adequacy of the gap dimension in structural joints between adjacent structural parts or between adjacent buildings should be checked to avoid pounding and hammering, with account taken of the need for an adequate safety margin.

6.28. Subsystems that may exhibit inertial effects from the liquid contained in tanks and pools should be taken into account in the modelling of the structures. In particular, the vertical motion due to the breathing mode of vertical flexible tanks should be evaluated and carefully considered.

6.29. Moreover, sloshing liquid can generate significant impulsive loads and impact loads up and down as well as cyclic loads on structures or parts of them. In particular, such impulsive loads can cause the failure of tank roofs and of attachments to the walls of tanks and pools in their path. Impulsive loads, when detected, should be modelled with dedicated procedures.

6.30. Where appropriate, simplified models built up of combinations of equivalent masses and springs should be considered to ensure that the sloshing response can be correctly captured for the required frequency range.

6.31. The damping coefficient for the sloshing mode should be very low[9], since the damping associated with the impulse mode of vibration is typically associated with the container material, the connections and the anchorage used. However, if the vertical component of the acceleration at the free water surface is expected to be greater than 1.0g, additional waves at the free surface could be generated. In such cases, non-linear damping effects should be considered in the response.

General modelling techniques for mechanical and electrical components

6.32. Mechanical and electrical components other than primary loop items are usually represented in the analysis by a single mass or a multimass system attached to the supporting building. Their dynamic coupling to the main building can usually be neglected, provided that they meet the general decoupling criteria discussed above.

6.33. The modelling of equipment is typically divided into several categories, as shown in Fig. 3. For components not modelled together with the supporting structure, the input for analysis is the floor response, expressed in terms of either design floor time histories[10] or design response spectra.

6.34. The quantity of insulation, the size, location and number of support gaps, the connection type (e.g. flanged), the frequency of response, and the use of yielding or energy absorbing support devices may all have an effect on the damping which is to be considered in the design of the components. This effect should be carefully checked and adequately modelled.

6.35. For vessels and tanks that contain liquids, the effects of sloshing and impulsive loads, including frequency effects, should be considered. The effects of liquid motion or pressure changes on submerged structures should also be considered. These effects may involve hydrodynamic loads from the fluid and a reduction of functional capability (e.g. loss of shielding efficiency of fuel pools or disturbance of instrument signals).

General modelling techniques for distribution systems

6.36. The response of distribution systems (piping, cable trays and cable conduits) to earthquake excitations tends to be quite non-linear. Computations of stresses and support reactions by means of linear elastic analyses provide approximate indications of stresses and support loads that are suitable for comparison with acceptance criteria to determine the adequacy of the design, but such computations should not be applied for deriving accurate values of actual stresses and support reactions. Nominally fixed supports for distribution systems with some limits on deflections may be considered rigid for modelling purposes.

6.37. The flexibility or stiffness of elements of piping systems such as elbows, tees and nozzles should be considered in the model. Spring hangers may be ignored in the seismic analysis of piping. If there is a pump or a valve in the piping system, its contribution to the response should be evaluated. All additional masses, including their eccentricities, such as valve actuators, pumps, liquid inside pipes and thermal insulation, should be taken into account.

9 The damping coefficient for the sloshing mode should typically be taken as 0.5% or less.

10 The design floor time history is a record of the floor motion with time for the structure under consideration derived from the design basis ground motion, with account taken of the variability of and uncertainty in the input ground motion and the characteristics of the building and the foundation.

6.38. When distribution systems are connected to two or more points having different movements and applicable response spectra, a single response spectrum of a particular support point should be applied with care. To account for inertial effects, either an envelope spectrum or multiple spectra should be applied. However, the results are not always conservative and engineering judgement should be used in their evaluation. In the event that results are unreliable, methods should be used in which multisupport excitation is considered in conjunction with modal analysis.

6.39. In addition to inertial effects, careful consideration should be given to the effects of differential motions between supports, since experience of earthquakes has demonstrated that this phenomenon can be a major contributor to the seismically induced failure of piping systems.

Analytical techniques

Analytical methods for structures

6.40. When the output of the numerical analysis is requested in terms of floor response spectra[11], maximum relative displacements, relative velocities, absolute accelerations and maximum stresses during an earthquake, linear dynamic analysis (e.g. direct time integration, modal analysis, frequency integration and response spectrum) is generally adequate for most models. Alternatively, non-linear dynamic analysis should be used where appropriate or necessary (e.g. structural lift-off, non-linear load dependent support, properties of foundation materials in soil–structure interaction problems or interactions between solid parts).

6.41. The trade-off between linear and non-linear solutions is governed by the conditions in each individual case: the latter usually require better defined input parameters, where these introduce uncertainties. The decision should therefore be informed by conducting parametric studies.

6.42. Simplified methods, such as the equivalent static, should be restricted to use for assessment purposes.

6.43. In the response spectrum method, the maximum response of each mode should be calculated by direct use of the design response spectrum. The maximum response in each principal direction should be determined by an appropriate combination of the modal maxima, such as the square root of the sum of the squares of each modal response, or by the complete quadratic combination procedure. For closely spaced modal frequencies, a conservative procedure should be applied by taking the sum of the absolute values of each closely spaced modal and rigid response. The missing mass as a function of the modelling detail, cut-off frequencies and modal participation factors used in the analysis should also be carefully assessed and documented.

6.44. Responses due to input acceleration in the three different directions should be combined by taking the square root of the sum of the squares of individual responses. It is also possible to define horizontal input motion as the resultant in one of the two reference horizontal orthogonal directions and combine it with the vertical motion to determine the worst case response.

6.45. In the time history[12] method, the structural response of the system should be calculated as a function of time either directly or after a transformation to modal co-ordinates (for linear models only). The input motion should be represented by a set of natural or artificial time histories of acceleration at ground level or a specific floor level, suitably chosen to represent the design response spectrum and the other characteristics of seismic hazard (e.g. duration).

6.46. An appropriate time integration step should be chosen, consistent with the level of detail required in the results and with the general modelling assumptions (e.g. grid density).

6.47. For non-linear analysis, the linear combination of the results from different load combinations is no longer valid. In such cases, conservative enveloping procedures should be used, after suitable validation.

11 The floor response spectrum is the response spectrum for floor motion at a particular elevation of a building for a given input ground motion.

12 The time history is a record of earthquake motion over time or an earthquake response motion with time for a particular floor or at a particular level for a structure resting on the ground.

6.48. For items in seismic categories 1 and 3, methods relying on ductility factors applied either to internal forces, evaluated linearly, or to the input spectra should be used for checking purposes only. For items in seismic categories 2 and 4, simplified procedures using ductility factors can be followed where appropriate, but an adequate justification of their values should be provided, carried out either by testing or by analysis.

Evaluation of floor response spectra

6.49. The floor response spectra, typically used as the seismic input for equipment, should be obtained on the basis of the structural response to the design basis ground motion. Natural or artificial time history motions that can be shown to generate response spectra at least as conservative as the response spectra for the design basis ground motion should be used as input to the structural analysis.

6.50. Alternatively, direct methods may be used to calculate design floor response spectra[13], on the basis of simplified engineering assumptions about the relation between the free field ground motion and the floor response spectra. However, the conservatism of the resulting floor response spectra should be compared with that provided by the time history solution.

6.51. A critical review of the calculated floor response spectra should be made, on the basis of sound engineering judgement, in which their shape and the relation between the vibration characteristics of the building and the supporting foundation materials should be considered.

6.52. The calculated floor response spectra should be broadened to account for possible uncertainties in the evaluation of the vibration characteristics of the building's components[14]. The extent of broadening may be reduced if parametric studies are performed to account for uncertainties relating to the soil modelling. Alternatively, segments of broadened spectra can be used sequentially to analyse the components. For systems having closely spaced frequencies, the use of such segmented response spectra can help to avoid undue conservatism.

6.53. Consideration should be given to the modification of input for the floor response spectra for equipment attached to very flexible structural members (for vertical amplification due to floor flexibility), or when significant torsional motion of the building occurs. When the centre of stiffness and centre of mass of the building are significantly different, and when this has not been considered in the modelling of the building structure, either items located away from the centre of stiffness should be analysed according to non-linear procedures or the floor response spectra should be modified to take account of the torsional response of the support structure.

6.54. Concurrently, appropriate modifications should be made to the floor response spectra if significant incursion into the range of non-linear structural response occurs. The value of ductility associated with any item should be consistent with its structural detailing.

Analytical methods for equipment

6.55. The calculated stresses and reaction loads in the equipment and equipment supports should be a direct output of either dynamic or static analysis. It should be noted that electrical equipment, exclusive of anchorage or support, is generally only evaluated for operability by means of testing or by using experience data. For this reason, analysis of these components should assume an elastic response of the electrical cabinet, panel or rack structure, in their loaded configuration, to calculate in-cabinet transfer functions and to evaluate support loads or anchorage loads.

Analytical methods for distribution systems

6.56. For distribution systems (e.g. piping, cable trays, conduits, tubing and ducts and their supports), modal response spectrum analysis may be used for the seismic design of large bore (diameter greater than 60 mm) piping of safety classified systems, while the static method is usually applied for the analysis of small bore piping. Spacing tables and charts based on generic analysis or testing are also used in the evaluation of small bore piping and are typically used to evaluate cable trays,

13 The design floor response spectrum is the response spectrum for floor motion at a particular elevation of a building and is obtained by modifying one or more floor response spectra to take into account the variability of and uncertainty in the input ground motion and the characteristics of the building and the foundation.

14 Typical values in use are ±10 to ±15%.

conduits, tubing and ducts. Simplified analytical or design procedures based on data drawn from experience of earthquakes may also be used. All such simplified techniques should be fully validated to show their degree of conservatism in comparison with more refined modelling techniques and they should be suitably documented.

6.57. A variation of the static method for small bore piping of 60 mm or less in diameter can also be used. The maximum acceleration of the design basis response spectrum in the frequency range between 0.5ff and 2.0ff (where ff is the fundamental frequency of the equipment) is taken as the design acceleration. A suitable amplification factor, typically chosen as 1.0–1.5 depending on the number of supports, is then applied. Such an approach should be validated with rigorous analytical or experimental methods before application.

7 Seismic qualification by means of testing, earthquake experience and indirect methods

Seismic qualification by means of testing

Type of testing and typical application fields

7.1. A method of direct seismic qualification of items is the testing of the actual item or prototype. A test can be carried out to prove its capability or to assist directly or indirectly in qualifying the item.

7.2. Types of testing include:
- Type approval test (fragility test);
- Acceptance test (proof test);
- Low impedance test (dynamic characteristic test);
- Code verification test.

7.3. Test qualification of items in seismic categories 1 and 3 should be carried out when failure modes cannot be identified or defined by means of analysis or earthquake experience. Direct qualification by testing makes use of type approval and acceptance tests. Low impedance (dynamic characteristic) tests should be limited to identify similarity or to verify analytical models. Code verification tests should be used for the generic verification of analytical procedures, which typically use computer codes. The methods of testing depend on the required input, weight, size, configuration and operational characteristics of the item, plus the characteristics of the available test facility.

7.4. The type approval (fragility) test should be used for standard electrical components and mechanical components when design margins to failure, damage or non-linear response and identification of the lower bound failure mode have to be evaluated. Such testing is typically carried out by means of a shaking table. The fragility test should be able to detect unexpected failure modes or potential malfunctions, because the test conditions typically cover a wider spectrum of loading than that required for the design basis, providing information also on the behaviour in beyond design basis conditions.

7.5. The acceptance (proof) test is also used for electrical and mechanical components to demonstrate their seismic adequacy. It is typically performed by manufacturers to demonstrate compliance with procurement specifications and should not be used in the evaluation of seismic margins or the analysis of failure modes. Such testing is typically carried out by means of a shaking table.

7.6. The code verification test is important for reliable analytical work. Computer codes should be verified before their application by means of analyses made using an adequate number of test results or results obtained from other appropriate computer codes or analytical procedures. A number of test results that cover the range of interest should be correlated with the analytical results [11].

Testing devices

7.7. Type approval and acceptance tests are usually carried out in a laboratory. One or more of the following facilities should be available:

- A shaking table (one or more degrees of freedom);
- A hydraulic actuator (large and stiff reaction walls are usually required);
- An electric actuator;
- A mechanical actuator (unbalanced mass type);
- An impact hammer;
- A blast actuator.

7.8. In case low impedance (dynamic characteristic) tests are carried out on items in situ, items are typically tested by means of mechanical actuation, impact, blast and other low energy exciters as well as ambient excitation. These tests should not be used for direct seismic qualification of the item but can be used to define dynamic characteristics, including support, which can then be used in analysis or in other tests to qualify the item of interest.

Test planning

7.9. Conducting a meaningful test with the purpose of assessing the integrity or functional capability of an item requires that the conditions existing for this item in the plant during an earthquake are correctly or conservatively simulated or that any departure from these conditions will not significantly influence the results. Among these conditions, the most important are:

- Input motions;
- Boundary (support) conditions;
- Environmental conditions (e.g. of pressure and temperature);
- Operational conditions (if functional capability has to be assessed).

7.10. In a test, the item should be subjected to conservatively derived test conditions in order to produce effects at least as severe as those of the design basis seismic event concurrently with other applicable operating or design conditions. Deviations should be evaluated on a case by case basis.

7.11. Tests may be conducted either on the site or in a laboratory. On-site testing of equipment and components should be limited to a few qualification aspects since it often conflicts with accessibility. It represents a reliable strategy for the evaluation of real support, boundary conditions and ageing effects. On-site testing of structures is often the only means of capturing the actual properties of materials, global structural seismic behaviour and the effects of soil–structure interactions, and it should be carried out whenever feasible to provide results as a reference for similar structures.

7.12. The input motion should be consistent with the seismic categorization of the item to be tested, to provide confidence in the required safety margin.

7.13. The functional testing and integrity testing of complex items such as control panels containing many different devices should be performed either on the prototype of the item itself or on individual devices with the seismic test input scaled to allow for the location and attachment of the device within the item or on the item (via the in-cabinet transfer function).

7.14. Account should be taken of ageing effects, which may cause deterioration or otherwise alter the characteristics of the item during its service life.

7.15. Seismic tests may be performed on the item itself or on a full scale model or, where appropriate, on reduced scale models. However, for qualification purposes, the component itself or a full scale model should be tested without any simplification; if there is no other practical alternative, the careful use of a reduced scale model may be permitted for qualification purposes. Such tests include:

(a) Functional tests intended to ensure the performance of the required safety function of the component or the absence of transient malfunctioning during and after an earthquake;

(b) Integrity tests aimed at proving the mechanical strength of the component.

7.16. When reduced scale testing is performed, the setting of similarity criteria associated with indirect methods of seismic qualification should be considered.

7.17. Any test result should be accompanied by a detailed evaluation of the reliability of the measurements (usually obtained by means of statistical analysis), evaluation of the signal to noise ratio and sensitivity evaluations, with a clear identification of the numerical (from data processing) and physical (from assumptions in the modelling) sources of uncertainties.

Conduct of tests

7.18. The number of repetitions of testing or cycles of loading per test is dependent on the application, but the accumulation of damage of various types associated with fatigue or ratcheting phenomena should be taken into account for the evaluation of the results and to permit qualification for the service life of the item.

7.19. For components whose functional capability should be demonstrated by means of testing under earthquake conditions, excitation in one direction at a time can be considered adequate if either of the following conditions applies:

(a) If the component design review and visual inspection or exploratory tests clearly demonstrate that the effects of excitation in three directions on the component are sufficiently independent of each other.

(b) If the severity of shaking table tests can be increased in such a way as to take into account the interaction effects of simultaneous excitation in three directions (e.g. the amplitude of excitation can be increased in one direction to envelop the response due to coupling effects in another direction).

Otherwise, simultaneous multidirectional inputs should be applied.

7.20. If random vibration or multifrequency input motion is used, appropriate procedures should be followed. The duration of the input motion should be decided on the basis of the anticipated duration of the earthquake [2].

7.21. A sinusoidal or sinusoidal beat motion can be used for the qualification testing of stiff systems at a frequency significantly lower than the first mode frequency of the system. This should result in a test response spectrum that envelops the reference response spectrum required to qualify the item. If no adequate shaking device is available, a sinusoidal motion can be used at resonance to obtain the necessary qualifying level of response of the item.

7.22. When the system has one or more vibrational resonances in the frequency range of interest, the test input motion should have a response spectrum not smaller than the required design basis response spectrum. This can be achieved by using a time history input whose test response spectrum envelops the reference response spectrum required to qualify the item.

7.23. When the natural frequencies of the item are well separated, independent tests can be made, for example with a suitably scaled[15] sinusoidal input at the given frequency with a half-sine or other time envelope of interest. However, such tests should be made with two or more time histories or natural time histories whose response spectra are not lower than the required design basis response spectrum. The use of several different time histories helps to overcome any deficiencies that could arise from the peculiarities of a single time history.

7.24. Natural frequencies and other vibrational characteristics of the components may generally be assessed by means of a test for the characteristics of low impedance vibrations (for which a low level input, in the range of 0.01g to 0.05g, can be used).

7.25. It should be noted that the results of the low impedance test or excitation level test may differ from those for the test carried out under higher seismic levels for non-linear systems. To be of use in seismically qualifying equipment, low impedance tests require the response of the equipment to be essentially linear up to potential failure mode levels of excitation so as to be able to determine design margins.

15 'Suitably scaled' means that the amplitude of the test spectrum at the frequency of interest should be higher than the amplitude of the required spectrum.

7.26. In general functional requirements should be established for active items (i.e. those items that move or otherwise change state) in advance, as part of the test procedure. In most cases active items are required to perform their active function after the earthquake excitation has ceased. However, if they have to perform such active functions during the earthquake excitation or during potential aftershocks, this should be considered in establishing functional test requirements. Care should also be taken that functionality tests are consistent with the required safety functions in service[16].

7.27. The functional requirements for a computer used for control or data evaluation are of particular concern. The seismic resistance of such equipment is very complicated and the detection of a malfunction or failure may be difficult. Dedicated procedures should be developed, including specification of the functional tests to be carried out during and after the test.

7.28. The following actions should be carried out in accordance with dedicated quality assurance procedures:
(a) All test equipment should be calibrated and a calibration dossier should be maintained.
(b) All software used to control test equipment should be supplied with a verification dossier.

Seismic qualification by means of earthquake experience

7.29. The direct seismic qualification of items by means of the use of experience from strong motion seismic events has had limited but growing application. Only in recent years have data from strong motion earthquakes generally been collected in the quality and detail necessary to provide the information necessary for direct application to individual items.

7.30. The level of seismic excitation experienced during a real earthquake by an item identical to the item being qualified should effectively envelop the seismic design motion at the item's point of installation in the building's structure. The item being qualified and the item that underwent the strong motion should be of the same model and type or should have the same physical characteristics and have similar support or anchorage characteristics. For active items it should be shown that the item performed the same functions during and following the earthquake, including any aftershock effects, as would be required of items in seismic category 1 or 3.

7.31. In general the quality and detail of the information used to qualify individual items directly on the basis of data from experience should not be less than are required for direct qualification by analysis or testing. As is the case for direct qualification by analysis or testing, earthquake experience may be used as a basis for qualification by the indirect method also.

Seismic qualification by means of indirect methods

7.32. The indirect method of qualification relies on establishing the similarity of a candidate item to a reference item previously qualified by means of analysis, testing or earthquake experience. To some degree, large quantities of data from earthquake experience, in particular those applicable to the seismic qualification of distribution systems, have been used to justify simplification of the analytical evaluation and seismic qualification of such systems[17]. Seismic qualification of cable trays is an example of a simplified analytical evaluation based on data from earthquake experience.

7.33. The seismic input used to qualify the candidate item should envelop the design spectra for that item and the seismic input used for the reference item; it should also equal or exceed those required for the candidate item. Proper similitude relationships should be considered in input to scale models. The physical and support conditions, the functional characteristics for active items and the requirements for the candidate item should closely resemble those for the reference item.

7.34. The reliable application of indirect methods depends on the appropriate formulation and application of rigorous and easily verifiable similarity criteria. The validation of such criteria and a qualified training of the review team are key issues for the process and should be explicitly recorded in the safety documentation.

16 For example, the lighting of a warning lamp as a result of a few milliseconds of relay chatter during an earthquake would be inappropriate if a minimum 20 ms opening of the relay would be necessary for the circuit to change state.

17 The use of a factor of three times the dead weight capacity with respect to normal acceptance criteria is applicable to cable trays with ductile supports (which permit large lateral movements without failure).

7.35. Where indirect methods are applied to items in seismic category 2, the application of similarity criteria should be verified through an expert walkdown. In particular, because of the large number of potential seismic induced interactions of all kinds (through contact, release of hazardous substances, or fire or flood, or earthquake interaction) and the importance of the adequate anchorage and support of structures, equipment and distribution systems, all seismically qualified items in the nuclear power plant should be subjected to walkdown by structural engineers qualified in seismic design and with earthquake experience prior to operation.

7.36. The goal of this approach to qualification is to ensure that the 'as installed' items are capable of withstanding the design basis seismic effects without loss of structural integrity, with account taken of anchorage effects and seismic interaction[18] effects (on items and operators).

7.37. The training records for the engineers who conduct the seismic walkdown and the evidence that appropriate criteria have been met should be collected in the safety documentation for the qualification in accordance with the applicable quality assurance procedures.

18 A seismic interaction is an interaction initiated by an earthquake that leads to influences between items or between an item and the operator that could impair their capability to perform their assigned safety function. Interactions may be mechanical (hammering, impact, wear and explosion), chemical (release of toxic or asphyxiant substances), radiological (an increase in dose) or by means of an earthquake induced fire or flood.

8 Seismic instrumentation

Introduction

8.1. According to Annex 2 of DSR seismic instrumentation shall be installed at the site. This instrumentation has the following purposes:

(a) For structural monitoring: to collect data on the dynamic behaviour of SSCs of the nuclear power plant and to assess the degree of validity of the analytical methods used in the seismic design and qualification of the buildings and equipment.

(b) For seismic monitoring: to provide alarms for alerting operators of the potential need for a plant shutdown depending on post-earthquake inspections.

8.2. The amount of seismic instrumentation to be installed, its safety classification and its seismic categorization should be decided on the basis of the relevance of the postulated seismic initiating event for system design and, in general, on the basis of the instrumentation's significance for the emergency procedures for the plant. Seismic monitoring should be properly safety classified and adequate redundancy should be provided.

8.3. The seismic instruments installed at the nuclear power plant should be calibrated and maintained in accordance with written maintenance procedures.

Seismic structural monitoring

8.4. A minimum amount of seismic instrumentation should be installed at any nuclear power plant site as follows:

- One triaxial strong motion recorder installed to register the free field motion;
- Two triaxial strong motion recorders installed to register the motion of the basemat of the reactor building;
- One triaxial strong motion recorder installed on the most representative floor of the reactor building.

8.5. The collection and analysis of data should be carried out on a regular basis to support the periodic safety review of the plant.

Seismic monitoring

8.6. The operator plays an important part in the decisions on post-earthquake actions and therefore should be adequately trained for this contingency.

8.7. The lower trigger level (alert) should be close to the operation base earthquake, at which significant damage to safety related items is not expected. If the overall seismic capacity of the plant is lower than the operation base earthquake (e.g. during the seismic re-evaluation), the lower trigger level should be referred to the actual seismic capacity of the plant.

8.8. The control panel of the seismic instrumentation should be located in the control room for easy access by the operator.

Data processing

(1) Post-earthquake operator actions should be based upon a proper set of parameters derived from the recorded data and suitably processed, to provide an indicator of damage for comparison with the assumptions made at the seismic design phase.

8.9. This goal could be achieved by applying appropriate software using a combination of the signals from different locations and directions (spurious signals could be filtered out), with appropriate filtering of the frequencies in the signal (in order to remove the contribution of the non-damaging part of the signal) and the evaluation of cumulative damage parameters, substantiated by means of plant walkdowns.

8.10. Cumulative damage parameters should mainly be based on the integration of the velocity record, thus providing a more representative parameter of earthquake induced damage in the safety related equipment. Such global values should be compared with values of the same quantities derived from the free field dsign basis earthquake and with data from earthquake experience. Analogous comparisons should be made in other plant locations since they could provide good support for the post-earthquake walkdown and therefore for the decision on the restarting of plant operation.

Post-earthquake actions

8.11. Post-earthquake actions should be planned for any nuclear reactor.

8.12. The control room operator should be informed of the occurrence of an earthquake by means of the installed seismic instrumentation. Subsequent responses should include an evaluation of recorded earthquake motion in comparison with the specific design of safety related items, a walkdown evaluation of the damage to the plant and an evaluation to determine the readiness of the plant for the resumption (or continuation) of operation following the occurrence of an earthquake.

8.13. The list of items to be inspected in such a walkdown should be consistent with the safety and seismic categorization of plant items. The nature, extent and location of tests to be carried out after an earthquake should be clearly defined and directly related to the damage expected due to an earthquake. For practical reasons the tests might be limited to the visual inspection of accessible items and to a validated comparison with the seismic behaviour of all other safety related items.

8.14. Different levels of such inspections could be defined according to the level of earthquake damage experienced (measured in terms of appropriate analytical parameters): different responsibilities should be identified accordingly among the operators, the technical support staff in the plant and external specialized teams.

8.15. The immediate notification of the regulatory body and its involvement in the restarting of the plant should be specified in appropriate procedures.

8.16. Recommendations and guidance on operational procedures following an earthquake, including the timing of, responsibilities for and tracking of the necessary actions, are provided in Ref. [12].

Appendix

Samples of seismic categorization

A.1. This is a sample list for items in seismic category 1 (this list is not comprehensive):

(a) Process systems:
- the primary coolant system,
- the main steam and feedwater system,
- the primary heat removal system,
- the control rod drive system,
- the safety injection system.

(b) Electrical systems:
- the emergency power supply, including diesel generators, auxiliaries and distribution systems.

(c) Instrumentation and control systems:
- reactor protection and control systems required for safe shutdown functions,
- monitoring instrumentation to measure important parameters of the safety functions,
- control rooms required for safe shutdown.

(d) Structures and buildings which house or support systems for safe shutdown, power systems, and instrumentation and control systems (including the containment).

(e) Dams or dykes for site protection.

A.2. Examples of items in seismic category 2 that may influence the safety functions of items in seismic category 1 or 3 or safety related operator actions are:
- the turbine building,
- the vent stack,
- cooling water intake structures,
- access roads.

A.3. Seismic induced collapse, falling, dislodgement or spatial response of structures and equipment in seismic category 2 may generate or cause, for example, the following:
- debris loading,
- missiles due to failure of rotating machinery,
- pressure waves due to bursting tanks,
- blocking of emergency cooling lines,
- flooding,
- fire,
- release of hazardous substances.

A.4. Examples for items in seismic category 3 are:
- the spent fuel building,
- the radioactive waste building.

A.5. Examples of items in seismic category 4 are:
- storage and workshop buildings,
- the canteen building,
- the administration building.

References

[1] Autoriteit Nucleaire Veiligheid en Stralingsbescherming, ANVS Guidelines on the Safe Design and Operation of Nuclear Reactors, ANVS, The Hague (2015).

[2] Autoriteit Nucleaire Veiligheid en Stralingsbescherming, ANVS Guidelines on Seismic Hazards in Site Evaluation for Nuclear Installations (revised version of IAEA standard SSG-9, 2010) May 2017

[3] Ministerie van Economische Zaken, Landbouw en Innovatie, Veiligheidsrichtlijn NVR.NS-G-3.6 "Geotechnische aspecten bij de beoordeling van de vestigingsplaats en funderingen voor kernenergiecentrales", The Hague (2011).

[4] Ministerie van Economische Zaken, Landbouw en Innovatie, Veiligheidsrichtlijn NVR.NS-G-1.5 "Externe gebeurtenissen met uitzondering van aardbevingen in het ontwerp van kernenergiecentrales", The Hague (2011).

[5] Ministerie van Economische Zaken, Landbouw en Innovatie, Veiligheidsrichtlijn NVR.NS-G-1.9 "Ontwerp van het reactor koel- en aanverwante systemen in kernenergiecentrales", The Hague (2011).

[6] Ministerie van Economische Zaken, Landbouw en Innovatie, Veiligheidsrichtlijn NVR.NS-G-1.10 "Ontwerp van reactor insluiting systemen voor kernenergiecentrales", The Hague (2011).

[7] Ministerie van Economische Zaken, Landbouw en Innovatie, Veiligheidsrichtlijn NVR.NS-G-1.8 "Ontwerp van noodstroom systemen voor kernenergiecentrales", The Hague (2011).

[8] Ministerie van Economische Zaken, Landbouw en Innovatie, Veiligheidsrichtlijn NVR.NS-G-1.3 "Veiligheidsrelevante meet- en regelsystemen voor kernenergiecentrales", The Hague (2011).

[9] Ministerie van Economische Zaken, Landbouw en Innovatie, Veiligheidsrichtlijn NVR.NS-G-1.2 "Veiligheidsbeoordeling en –verificatie voor kernenergiecentrales", The Hague (2011).

[10] International Atomic Energy Agency, Evaluation of the Safety of Operating Nuclear Power Plants Built to Earlier Standards: A Common Basis for Judgement, Safety Reports Series No. 12, IAEA, Vienna (1998).

[11] International Atomic Energy Agency, Quality Assurance for Software Important to Safety, Technical Reports Series No. 397, IAEA, Vienna (2000).

[12] Ministerie van Economische Zaken, Landbouw en Innovatie, Veiligheidsrichtlijn NVR.NS-G-2.2 "Bedrijfslimieten en –voorwaarden en bedrijfsvoeringsprocedures voor kernenergiecentrales", The Hague (2011).

[13] Autoriteit Nucleaire Veiligheid en Stralingsbescherming, Technical Review Plan (TRP) - Guidance on the Technical Review of the Safety Analysis Report as Part of Nuclear Reactor Licensing in the Netherlands, ANVS, The Hague (2016).

This report is published by:

Authority for Nuclear Safety and Radiation protection ANVS

Bezuidenhoutseweg 67 | 2594 AC The Hague
PO Box 16001 | 2500 AB The Hague

www.anvs.nl

June 2017 | 103103