

Guidance Document

Issue TU:

External Hazards

Guidance on

Seismic Events

Annex to the Guidance Head Document

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Table of Content

Guidance Document

Issue TU: External Hazards

Guidance on Seismic Events

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00	INTRODUCTION	4
01	OBJECTIVE	5
02	IDENTIFICATION OF EXTERNAL HAZARDS	6
03	SITE SPECIFIC EXTERNAL HAZARD SCREENING AND ASSESSMENT	9
04	DEFINITION OF DESIGN BASIS EVENTS FOR EXTERNAL HAZARDS	14
05	PROTECTION AGAINST DESIGN BASIS EVENTS	16
06	CONSIDERATIONS FOR EVENTS MORE SEVERE THAN THE DESIGN BASIS EVENTS	22
07	REVIEW OF THE SITE SPECIFIC HAZARDS AND THE DESIGN BASIS	25
	References	26

00

Introduction

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The purpose of this Guidance Document on Seismic Events is to provide additional explanations specific to seismotectonic hazards (RLs Issue TU) and the Guidance Head Document for the RLs of Issue TU. The document forms an Annexe to the Guidance Head Document on External Hazards and should be read in conjunction with this Head Document. It is further recommended that the chapters on design extension conditions are also read in combination with the RLs of Issue F and the Guidance Document on Issue F.

Hazards related to tsunami are addressed in the Guidance Document on External Flooding. Nevertheless, some aspects of the combination of seismotectonic and tsunami hazards are treated in this guide on Seismic Events.

This Guidance Document does not define any requirements in addition to those defined in the RLs of Issue TU, External Hazards.

01

Objective

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TU1.1 External hazards, comprising natural and external human induced hazards¹ shall be considered an integral part of the safety demonstration of the plant (including spent fuel storage). Threats from external hazards shall be removed or minimised as far as reasonably practicable for all operational plant states. The safety demonstration in relation to external hazards shall include assessments of the design basis and design extension conditions with the aim to identify needs and opportunities for improvement.

¹ Within these reference levels malicious acts are not considered.

No guidance is needed in addition to the guidance provided for Reference Level TU1.1 in the Guidance Head Document on External Hazards.

02

Identification of External Hazards

TU2.1 All external hazards that might affect the site shall be identified, including any related hazards (e.g. earthquake and tsunami, accidental aircraft crash with consequential aircraft fuel fire)². Justification shall be provided that the compiled list of external hazards is complete and relevant to the site.

² Human induced external hazards originate from any kind of human activity outside the site area. In accordance with IAEA Safety Glossary the “site area” is defined as the geographical area that contains an authorized NPP. It is enclosed by a physical barrier to prevent unauthorized access, by means of which the management of the authorized facility can exercise direct authority.

See guidance to Reference Level TU2.2.

TU2.2 The list of external hazards from which identification as stated in TU2.1 is conducted shall at least include:

- **Geological hazards;**
- **Seismotectonic hazards;**
- **Meteorological hazards;**
- **Hydrological hazards;**
- **Biological phenomena;**
- **External fire;**
- **Accidental aircraft crash;**
- **Accidents at facilities outside the site area;**
- **Transportation accidents;**
- **Electrical disturbances and electromagnetic interferences.**

Seismotectonic hazards include hazards which are either directly caused by vibratory ground motion, near fault effects, co-seismic fault slip, or triggered by such events (secondary seismotectonic effects). Hazard identification should further take into account possible sources of induced seismicity caused by human activity that alters the state of stress in the Earth’s crust. Correlations and dependencies with other natural hazards, human-induced external hazards, and internal hazards induced by seismic hazards should be included in the assessment.

The list of hazards generated should serve several purposes:

- link to other external hazards and/or initiating events
- revision of natural hazards as part of safety review processes, especially in the PSR (Periodic Safety Review)

The following hazard phenomena should, as a minimum be considered:

Ground motion hazards and the potential for fault displacement

- Vibratory ground motion (ground shaking waves due to earthquakes propagated from both far and near field fault rupture processes), including long period waves¹ and short period waves²
- Near fault effects on long period ground motion with very short duration (0.5-5 s) (forward directivity and fling-step ground motion observed from velocity pulses recorded in time histories)
- Site effects. Free field vibratory ground motion amplification/deamplification due to:
 - a) Variations in the site specific shear wave velocity profile from seismic bedrock (shear wave velocity up to ≈ 3 km/sec) to the surface [2]
 - b) Site topography
 - c) Basin geologic structure
- Surface faulting from the main or secondary fault ruptures (“fault capability”; ground displacement or surface rupture at or near the site surface due to co-seismic movements at a fault)

Hazard phenomena triggered by seismotectonic events

- Liquefaction (ground failure undermining the foundations and base courses of structures caused by water saturated sediments that are transformed into a substance that acts like a liquid during seismic shaking)
- Dynamic compaction (natural soil and human-made fillings: settlement induced by seismic shaking)
- Ground collapse (in areas of suberosion processes, e.g., by karstification)
- Earthquake-induced slope instability, debris or mud flow (mass movements of water-saturated sediments), and underwater landslides
- Flooding/drawdown by tsunami and seiche (a series of water waves caused by the displacement of a volume of a body of water, typically an ocean or large lake)
- Failure of dams or other water containment structures and flood protection systems
- External human-made hazards such as industrial and traffic accidents (e.g. chemical release, jet fire from a gas pipe line, external explosion)

¹ Vibratory ground movement with a frequency of 1 Hz or lower; such waves are important for long period structures, e.g. large-scale and high-rise buildings.

² Vibratory movement with a frequency higher than 15 Hz; such waves are important for sensitive components, e.g. relays.

- Loss of infrastructure, e.g. grid supplies
- Triggered internal events such as flooding, fire, or steam release

Induced and triggered seismicity (human-made ground shaking)

Seismic ground motion caused by human activity is treated together with natural seismicity due to the identical effects of both phenomena, and the difficulties which may arise to discriminate between human-induced and natural events. The hazard type includes induced seismicity, which is entirely controlled by human intervention, and triggered seismicity. In the latter case human intervention causes the initiation of the seismic rupture process of a fault while the subsequent rupture propagation is controlled by natural stress. A triggered earthquake is advanced by human intervention and natural stress aggravates the ground shaking.

Vibratory ground motion may be caused, for example by mine collapse, hydrocarbon extraction, deep ground water/thermal water extraction, build-up of water reservoirs, disposal of CO₂ or liquid waste in deep geological reservoirs, or hydrofracking.

03

Site Specific External Hazard Screening and Assessment

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TU3.1 External hazards identified as potentially affecting the site can be screened out on the basis of being incapable of posing a physical threat or being extremely unlikely with a high degree of confidence. Care shall be taken not to exclude hazards which in combination with other hazards³ have the potential to pose a threat to the facility. The screening process shall be based on conservative assumptions. The arguments in support of the screening process shall be justified.

³ This could include other natural hazards, internal hazards or human induced hazards. Consequential hazards and causally linked hazards shall be considered, as well as random combinations of relatively frequent hazards.

Screening

Screening of potential seismotectonic hazards typically starts by considering the regional seismotectonic setting and the site soil conditions.

Vibratory ground motion, near fault effects, and surface faulting hazards cannot be screened out for any site.

At specific sites, some phenomena triggered by seismotectonic events cannot physically occur and credit should be taken of this. Typical examples of screened out phenomena could be:

- The soil liquefaction hazard may be screened out for rock sites where all SSCs required by the protection concept are founded on rock or on stiff sediments.
- Flooding by tsunami or seiche may be screened out for a site located at a sufficiently large distance from the coast or large lakes [4].
- Slope instability hazards may be ruled out for sites in areas with flat topography.

Correlated hazards – including external human-induced hazards

Vibratory ground motion, near fault effects, and coseismic surface displacement may trigger a number of secondary hazards. Care should be taken to not exclude hazards which in combination with other hazards have the potential to pose a threat to the facility. Examples of such combined hazards include:

- Slope instability of water-saturated soil due to a combination of extreme precipitation and earthquake shaking at values less than the design basis event

- Slope instability affecting flood protection structures such as earth dams or dykes (see [4] for further guidance)
- Hazards by earthquake-triggered mass movements or dams failure occurring upstream of a river site that may lead to damming and ebbing of rivers, or floods [4]
- Flooding and drawdown of water due to tsunami or seiche
- Flooding and drawdown of water due to obstructed or changing river channels, water containment failure, or high ground water (in cases of coseismic subsidence).
- Severe earthquakes will also affect and potentially damage nearby infrastructure including industrial facilities, transport routes, and the external power grid. Seismic ground shaking may therefore cause events leading to, e.g., external explosion or chemical releases. Such possible effects should be considered in hazard screening.

TU3.2 For all external hazards that have not been screened out, hazard assessments shall be performed using deterministic and, as far as practicable, probabilistic methods taking into account the current state of science and technology. This shall take into account all relevant available data, and produce a relationship between the hazards severity (e.g. magnitude and duration) and exceedance frequency, where practicable. The maximum credible hazard severity shall be determined where this is practicable.

Seismic Hazard Analysis (SHA) provides the basic information for defining seismic design basis events. Furthermore, SHA results are also used for the assessment of DEC (Design Extension Conditions) analysis (TU6.1). Lessons learned from seismic events affecting nuclear power plant sites in Japan³, and in the U.S.A.⁴ emphasize the importance of considering not only ground motion hazards but also the complete range of potential seismic effects. References [1] and [2] provide further details on the assessment of vibratory ground motion and surface faulting as well as evaluation of geotechnical hazards triggered by seismotectonic events.

Reference [1] recommends evaluating the ground motion hazard using both Probabilistic Seismic Hazard Analysis (PSHA) and deterministic (DSHA) approaches. Similarly it recommends for existing plants evaluating ground ruptures by Probabilistic Displacement Seismic Hazard Analysis (PDSHA) if a capable fault is located in the vicinity of the site. The PSHA assessment provides hazard curves for a specified range of annual frequencies of exceedance required for defining the ground motion values for the DBE (Design Basis Event; not higher than 10^{-4} /year (TU4.2) and, when practicable, also ground motion values for lower frequencies of occurrence required for the assessment of DEC conditions (TU6.2).

³ Onagawa, 2005; Shika and Kashiwazaki-Kariwa, 2007; Fukushima Dai-Ichi, Tokay, Onagawa and Higashidori, 2011

⁴ North Anna, 2011

TU3.3 The following shall apply to hazard assessments:

- **The hazard assessment shall be based on all relevant site and regional data. Particular attention shall be given to extending the data available to include events beyond recorded and historical data.**
- **Special consideration shall be given to hazards whose severity changes during the expected lifetime of the plant.**
- **The methods and assumptions used shall be justified. Uncertainties affecting the results of the hazard assessments shall be evaluated.**

Vibratory ground motion and surface faulting

The assessment of vibratory ground motion, near fault effects, and coseismic surface displacement should be site specific and follow the DSHA and PSHA approaches outlined in [1] and [2] supplemented by the following guidelines:

- Seismic hazard assessment should be directed towards capturing and reducing uncertainties. An effective way to reduce uncertainties is to collect reliable geologic, paleoseismologic, seismologic and geotechnical data as complete as practicable. Expert judgment should not substitute the acquisition of new data.
- Estimates of maximum ground shaking or displacement should use deterministic methods that are based on the systematic assessment of seismogenic faults in an area extending to a sufficient distance from the site, and of capable faults in an area of not less than 25 km around the site (near regional scale [1]). For all seismogenic faults MCE (Maximum Credible Earthquake) magnitudes should be determined from fault dimensions and scaling laws. Experience from the 2011 Great Japan Earthquake (Tohoku) indicates that MCE assessments that consider fault segmentation need to be well justified and treated with care.
- The impact of the MCEs at the site can be modelled using appropriate ground motion prediction equations and specific site effects assessment. Alternative models and inputs should be developed to account for aleatory and epistemic variations.
- Gumbel statistics of extreme values and expert opinion should be used with care, even using new data or improved database, as they are not considered able to give reliable and reproducible MCE estimates.
- Particular effort should be made to extend the earthquake database by historical research⁵ and paleoseismologic surveys [1]. A recent review summarizing paleoseismological methods is provided by [10].

Most parts of Europe are intra-plate areas with slow fault displacement rates producing earthquakes at recurrence times of 10^3 to 10^5 years, which are significantly longer than both instrumental earthquake records (covering $< 10^2$ years) and historical catalogues (generally $< 10^3$ years). The hazard contribution of such seismogenic sources cannot be assessed from instrumental and historical earthquake data alone.

⁵ Historical earthquake data measured in intensity are therefore a necessary and valuable input for hazard analysis.

The resulting epistemic uncertainties should be reduced by systematic fault mapping and collecting paleoseismologic information to extend the time coverage of the seismological database. Such efforts should at least be made in the near-region of the site (not less than 25 km radius according to [1]). Geological, geophysical, geomorphologic, geodetic and paleoseismological data can be used to identify and characterize active and capable seismogenic faults (according to [1] and [10]), which might not have produced historical seismicity. The hazard caused by such faults can be assessed by:

- a) paleoseismologic trenching to produce data on the timing and magnitude of pre-historic earthquakes;
 - b) quantification of fault dimensions to constrain earthquake magnitudes;
 - c) quantifying fault slip rates from geologic or geodetic data, to constrain earthquake recurrence intervals;
 - d) identifying secondary earthquake effects to constrain macroseismic intensities of past earthquakes.
- Systematic field surveys for identifying and characterizing seismogenic faults significant for hazard results should extend to a sufficient distance from the site. This distance and the level of effort expended is related to the level of hazard expected at the site and the regional tectonic setting. Depending of these settings it may be necessary to apply near regional and site vicinity scales efforts as defined in [1] to characterize seismogenic sources to regions at larger distances than 25 km from the site.
 - The coverage of the seismic instrumentation on site should be evaluated so that the site's seismicity can be reliably recorded. In regions with low/moderate seismicity, regional seismic network coverage is usually not sufficient to record seismicity in the site vicinity and near-region with adequate accuracy. To acquire more detailed information on potential seismic sources, it is recommended to install a local network of broadband seismometer stations to continuously record the site's seismicity [1].
 - Characterisation of the site shear wave velocity profile from the seismic bedrock should be performed. Determination of compatible time histories should also be performed.
 - All assumptions, input parameters and data should be reviewed and not be based on single expert opinion or judgment. Assessment of uncertainty for the seismic hazard should suitably incorporate the scope of technically defensible interpretations from the relevant informed technical community.
 - All assumptions made and data used in the hazard assessment should be clearly identified, justified and documented. This particularly applies to:
 - the definition, characterization and modelling of seismogenic sources (i.e., capable faults and active faults as quoted in [1] and [10]),
 - the definition, characterization and modelling of zones of diffuse seismicity [1]) (including assumed completeness periods of instrumental, historical and prehistoric earthquake data),
 - ground motion prediction equations (also referred to as attenuation functions); it should particularly be justified that the ground motion prediction equations used are applicable to the site in terms of tectonic setting, magnitude/distance ranges, and site conditions,

- minimum and maximum magnitude,
- site effects (including topography and structure below the reactor basement, depths of bedrocks, and seismic velocity profile from seismic bedrock to the surface).
- Generally accepted solutions may not exist for several assumptions and input parameters. In accounting for aleatory and epistemic uncertainty, alternative models and inputs should be developed for the characterization of seismic sources, ground-motion prediction equations, and site effects.
- It is considered good practice to quantify the impact of those parameters on PSHA (Probabilistic Seismic Hazard Analysis) results by sensitivity studies.
- Uncertainties affecting the results of the hazard assessments should be quantified and transferred to results, and a clear distinction between aleatory and epistemic uncertainty should be made.
- The procedure performed to derive hazard values should be described in detail, including their justification and the related uncertainties.
- Seismic hazard code, data bases and input data should be kept safe in a suitable format, in order to be available for PSR purposes or whenever new evidences or concerns addresses update the SHA (Seismic Hazard Analysis) assessment.

In addition, a PSHA approach is supplemented by the following guidelines:

- Advanced probabilistic seismic hazard analysis techniques can model and quantify uncertainties, e.g., by confronting experts opinions and using logic tree and/or Monte-Carlo simulations.
- The hazard assessment should produce data which define a relationship between the hazard severity in terms of ground motion (and displacement if a capable fault requires consideration [1]), and exceedance frequency.
- It is common and widely accepted practice to characterize the seismic hazard in terms of site specific hazard curves, which relate the severity (amplitude) of a specific event with its annual frequency of exceedance. The ground motion hazard evaluation should include at least: mean and percentiles of confidence for peak ground acceleration and spectral accelerations for all plant-significant vibration frequencies, and strong motion duration. Peak ground velocity is also useful. These measures should be obtained for both horizontal and vertical free field motions.

Secondary seismotectonic hazards

The assessment of secondary seismotectonic hazards triggered by earthquakes should follow the procedures outlined in [1] and [2].

04

Definition of Design Basis Events for External Hazards

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TU4.1 Design basis events⁴ shall be defined based on the site specific hazard assessment.

⁴ These design basis events are individual external hazards or credible combinations of hazards (causally or non-causally linked). The design basis may either be the original design basis of the plant (when it was commissioned) or a reviewed design basis for example following a PSR.

Design basis events are individual seismotectonic hazards or combinations of ground motion hazards with seismic hazard features triggered by seismotectonic events.

TU4.2 The exceedance frequencies of design basis events shall be low enough to ensure a high degree of protection with respect to external hazards. An exceedance frequency, not higher than 10^{-4} per annum⁵, shall be used for the design basis event. Where it is not possible to calculate these frequencies with an acceptable degree of certainty, an event shall be chosen and justified to reach an equivalent level of safety.

For the specific case of seismic loading, as a minimum, a horizontal peak ground acceleration value of 0.1 g (where 'g' is the acceleration due to gravity) shall be applied, even if its exceedance frequency would be below 10^{-4} per annum.

For accidental airplane crashes and explosion blast waves a design basis event shall be defined to ensure a minimum protection of the plant.

⁵ According to the current practices, several WENRA countries require a value lower than 10^{-4} per annum for human induced and some also for natural hazards.

Exceedance Probabilities of the Design Basis Event

The seismic hazard assessment will produce a series of seismic hazard curves with differing levels of confidence associated with them. In selecting the values for use as design basis, consideration of the level of conservatism in the entire process needs to be undertaken. An appropriate confidence level should be chosen to ensure a conservative design basis.

Regardless of the exposure to seismic hazard, a seismic basis should be adopted for every nuclear power plant for the design of SSCs required by the protection concept. According to RL TU4.2 the minimum level shall correspond to a horizontal PGA (Peak Ground Acceleration) of 0.1 g (zero period of the design response spectrum), to be considered as a free field motion.

Spectra compatible with the basemat depth in the soil column with no modification for soil-structure interaction should be anchored to this PGA value (consistent with the IAEA definition of free field spectra [1]).

TU4.3 The design basis events for natural hazards shall be compared to relevant historical data to verify that historical extreme events are enveloped by the design basis with a sufficient margin.

The seismic design basis events should be compared to historical and paleoseismic data in order to verify that they cover those earlier extremes with a margin. This margin should be clearly substantiated. In cases where paleoseismic evidence identifies events that exceed the design basis ground motion it should be clearly demonstrated that such events have an annual frequency of exceedance of less than 10^{-4} /year.

TU4.4 Design basis parameters shall be defined for each design basis event taking due consideration of the results of the hazard assessments. The design basis parameter values shall be developed on a conservative basis.

The design basis for ground shaking events (Design Basis Event, DBE) is characterized by both, near and far field spectral ground motion accelerations, velocities and displacements. Good practice is to define the frequency content of both ground motions by specifying site specific acceleration design response spectra, related time histories and ground motion durations.

The ground shaking parameters derived for the DBE should be used for the assessment of the amplitude of seismic hazards triggered by earthquakes.

The design basis events should characterize the most penalizing combination of seismotectonic hazards. Examples for such combinations are ground shaking in combination with soil liquefaction or dynamic compaction; or ground shaking in combination with slope instability.

Seismically induced flooding/drawdown should be accounted for in the definition of the flood/drawdown water design basis.

05 Protection Against Design Basis Events

TU5.1 Protection shall be provided for design basis events.⁶ A protection concept⁷ shall be established to provide a basis for the design of suitable protection measures.

⁶ If the hazard levels of RL TU4.2 for seismic hazards were not used for the initial design basis of the plant and if it is not reasonably practicable to ensure a level of protection equivalent to a reviewed design basis, methods such as those mentioned in IAEA NS-G-2.13 may be used. This shall quantify the seismic capacity of the plant, according to its actual condition, and demonstrate the plant is protected against the seismic hazard established in RL TU4.2. A comparable approach may be used for demonstrating the minimum protection against aircraft crashes and explosion blast waves.

⁷ A protection concept, as meant here, describes the overall strategy followed to cope with external hazards. It shall encompass the protection against design basis events, events exceeding the design basis and the links to EOPs and SAMGs.

In order to establish a protection concept, the SSCs that have to be protected should be defined for design basis events (RL TU5) and events more severe than the design basis events (RL TU6). These SSCs are called 'SSCs required by the protection concept' in this guidance.⁶

Plants might not have included consideration of seismic hazards at levels which would be derived as the design basis using the current Reference Levels within their original design. Re-designing in a manner fully consistent with modern standards and processes against these revised demands may not be practicable, and a more pragmatic approach may be considered in that case. The approach taken to demonstrating the withstand of SSCs to seismotectonic hazards should provide an adequate high level of confidence that the associated impacts can be

⁶ Some but not all SSCs important to safety may be necessary to fulfil the fundamental safety functions depending on the hazards postulated. For a specific hazard:

- Some SSCs important to safety are needed to perform their safety function,
- Some SSCs important to safety may be needed to protect the aforementioned, and
- Some SSCs important to safety do not play a role in coping with the hazard.

For example, it is likely that emergency power generators will be needed to cope with some hazards affecting the plant. These generators will have to be protected against seismic hazards by being qualified for seismic ground motion. In addition, they will need to be located in a building resistant to seismotectonic hazards. Therefore both the emergency power generators and the building will be required by the protection concept.

Another example is the containment (reactor building) which is both necessary for the confinement function and protecting equipment located in the containment. Both of these functions are required by the protection concept.

controlled. Footnote 6 of RL TU5.1 offers two ways to verify the seismic capacity of a plant in cases of an update of the site specific seismic hazard.

The preferred approach is to “ensure a level of protection equivalent to a reviewed design basis”. To ensure a conservative approach consistent with design basis level requirements an approach more elaborate than those described in NS-G-2.13 [11] should be used. This should favour the use of design calculations and qualification tests over indirect methods to prove sufficient resistance of SSCs against seismic loads for the set of SSCs that have to be seismically qualified as defined in NS-G-1.6 [5].

In cases where it is shown that it is not reasonably practicable to ensure a level of protection applying a process as the one outlined above, methods as those mentioned in IAEA NS-G-2.13 may be used⁷. For the Seismic Margin Assessment (SMA) approach [11], the definition of success paths should be performed in consistence with RL TU5.3 c. For the SSCs required for the success paths the verification of the seismic safety should:

- Determine HCLPF (High Confidence of Low Probability of Failure) of the SSCs
- Include spot tests for a sample of typical components to validate HCLPF estimates (e.g., tests or computations for characteristic pipes, tanks, etc.)
- Determine those SSCs which have lowest robustness and therefore limit seismic safety
- Determine the withstand for the SSCs with the lowest robustness with advanced methods (e.g., type tests, computational methods)

As an outcome of this reassessment extensive requalification and improvement of SSCs might be necessary.

The Seismic Probabilistic Safety Assessment (SPSA), proposed by NS-G-2.13 may also be considered.

TU5.2 The protection concept shall be of sufficient reliability that the fundamental safety functions are conservatively ensured for any direct and credible indirect effects of the design basis event.

See guidance to Reference Level TU5.3.

TU5.3 The protection concept for external hazards shall:

- a) apply conservatism providing safety margins in the design;**
- b) rely primarily on passive measures as far as reasonably practicable;**
- c) ensure that sufficient measures to cope with a design basis accident remain effective during and following a design basis event as defined in TU4.2;**

⁷ It should be noted that [11] “focuses mainly on the methodologies for seismic safety evaluation that do not involve a change in the design basis earthquake, but that involve evaluation of the seismic safety for seismic hazards more severe than those originally established for the design basis and a realistic determination of the available safety margin”.

- d) take into account the predictability and development of the event over time;**
- e) ensure that procedures and means are available to verify the plant condition during and following design basis events;**
- f) consider that events could simultaneously challenge several redundant or diverse trains of a safety system, multiple SSCs or several units at multi-unit sites, site and regional infrastructure, external supplies and other countermeasures;**
- g) ensure that sufficient resources remain available at multi-unit sites considering the use of common equipment or services;**
- h) not inadmissibly affect the protection against other design basis events (not originating from external hazards).**

Protection Concept

A protection concept should be developed to ensure the safety of the plant in response to a DBE (Design Basis Event). The protection concept shall ensure that the fundamental safety functions as identified in Reference Level E3.1 [6] are fulfilled for the DBE. The seismic protection should also account for all secondary effects that may adversely affect the plant including due to hazardous installations close to the site. Possible effects include flooding, fire, steam release, and loss of infrastructure (e.g., grid supply).

As part of the protection concept, for the design basis earthquake the effects on the plant including consequential hazards should be determined in a conservative manner. In addition, the potential for design basis events to simultaneously challenge multiple structures, systems and components (SSCs), site and regional infrastructure, external supplies, and deployment of other countermeasures should be considered.

The protection concept should take into account the development of a seismic event over time, i.e., pre-, main- and aftershocks, and all potential consequential effects.

As a standard approach protection against seismic events is provided by seismic design and qualification of the SSCs required by the protection concept. Detailed guidance is provided in [5]. Advantages and drawbacks of additional specific seismic protection measures should be evaluated, such as seismic base isolation of structures and/or components.

The protection concept should include administrative besides permanent measures most notably when the protection of the plant benefits from pre-planned human interventions (see also TU5.5). Such measures could include:

- A seismic monitoring system providing immediate information on the experienced vibration at selected locations, including free field, and their relation to the plant design basis [1]
- Pre-planned procedures and administrative measures during and after a seismic event such as inspections and maintenance linked with technical specifications and emergency plans of the plant, and take into account measurements from the seismic monitoring system

The protection concept should also address accident management needs and provisions. A seismic event could, for instance:

- Hinder or impede access the site
- Limit the availability of external resources as strong damaging earthquakes will challenge the availability and capacity of off-site emergency crews
- Cause replacement personnel to arrive late or not at all
- Lead to failure of telecommunications

Seismic events are not long-lasting but may have long-lasting consequences. For example, they may hinder the replacement of personnel and supplies for significant times by damaging or blocking critical infrastructure around (e.g., by damaging bridges, elevated roads, flyovers).

Counter measures for such effects could for example be:

- Multiple access roads, helipads and/or transport by boats
- On and off-site storage of sufficiently large stocks of critical resources and equipment
- Dedicated facilities, resources and procedures allowing personnel to remain at their post for longer than usual time spans

TU5.4 For design basis events, SSCs identified as part of the protection concept with respect to external hazards shall be considered as important to safety.

No guidance is needed in addition to the guidance provided for Reference Level TU5.4 in the Guidance Head Document on External Hazards.

TU5.5 Where appropriate, monitoring and alert processes shall be part of the protection concept to cope with external hazards and thresholds (intervention values) shall be defined to facilitate the timely initiation of protection measures. In addition, thresholds shall be identified to initiate the execution of pre-planned post-event actions (e.g. inspections).

Event Monitoring and Post-Event Action

- A monitoring system to record the progression of a seismic event should be available. The systems should be qualified against hazards as necessary when the protection concept makes claims on the ability to measure key parameters associated with the event, e.g., for shutdown or for post event inspections.

The data gathered by this instrumentation should allow the estimation of seismic demands placed upon SSCs required by the protection concept. To achieve this, seismic accelerometers should be installed in the free field and in structures, which house these SSCs and which have separate basemats to the degree necessary. Specific guidance is given in [1] and [5] supplemented by the following guidelines as lessons learned after the seismic events that occurred on Fukushima Dai-ichi and Kashiwazaki-Kariwa NPPs sites:

- Universal time with sufficient accuracy able to share data with regional networks
 - Power supply and recording capacity enough to preserve the main and fore/after-shocks
 - For multi-unit sites a single free-field accelerometer may not be sufficient to capture the necessary data due to site variability
- Spectra threshold values of ground motion and/or cumulative absolute velocity (CAV) (intervention values) should be defined the exceedance of which will launch pre-planned actions linked to technical specifications and emergency plans, such as reactor scram triggered by the plant seismic monitoring system or manual shutdown (in accordance with operating procedures), and SSCs inspection walkdowns. The levels of ground motion triggering such action should correspond to an earthquake that is less severe and more probable than the DBE⁸.

The associated inspections should confirm that plant safety systems did not experience high loads, which might cause some significant but not obvious damage (e.g. expansions of cracks, crack-initiations on the sub-millimeter scale, weakening of parts or suspensions). Such damage may weaken parts of safety systems causing failure during later accident scenarios.

Significant loads might appear if soil resonances due to inhomogeneous subsoil appear near surface at the local site. Such effects are known as “site effect” and the layout of the seismic monitoring system should account for these effects.

⁸ A corresponding earthquake is sometimes referred to as Operation Base Earthquake (OBE) or Seismic Safety Level 1 (SL-1) earthquake [1]

- The design of the seismic monitoring system should take account of the building's dynamic behaviour under the postulated design basis event, as well as the location of systems and components used for ensuring the fundamental safety functions.

06

Considerations for Events more severe than the Design Basis Events

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TU6.1 Events that are more severe than the design basis events shall be identified as part of DEC analysis. Their selection shall be justified.⁸ Further detailed analysis of an event will not be necessary, if it is shown that its occurrence can be considered with a high degree of confidence to be extremely unlikely.

⁸ See issue F section 2.

See guidance to TU6.2.

TU6.2 To support identification of events and assessment of their effects, the hazards severity as a function of exceedance frequency or other parameters related to the event shall be developed, when practicable.

Hazard Progression and Assessment of Maximum Credible Earthquake Magnitude

Design extension condition (DEC) analysis should cover all seismotectonic events, and combinations with hazards triggered by seismotectonic events, leading to accident conditions which are neither included in the design basis accidents nor have been screened out because they can be considered with a high degree of confidence to be extremely unlikely to occur [7].

DEC analysis therefore requires the consideration of earthquakes more severe than the DBE, thus having annual frequencies of exceedance below the design basis event ($< 10^{-4}$). Site specific probabilistic seismic hazard assessment should consequently characterize the severity of events down to annual frequencies of exceedance below 10^{-4} with a suitable margin taking uncertainties into account.

For seismotectonic hazards demonstration of extreme unlikeliness with a high degree of confidence is often not possible due to the levels of uncertainty at such low occurrence frequencies. Therefore, demonstration of physical impossibility is the preferred method. This is usually done by the determination of the hazard parameters associated with the Maximum Credible Earthquake (MCE).

Estimates of maximum ground shaking at the site corresponding to the MCE should use deterministic methods that are based on the systematic assessment of all identified seismogenic

faults (fault sources). A similar approach may be applied to zones of diffused seismicity where MCE estimates can be obtained from the dimension of faults with suitable orientation which may be assumed to move under the current stress conditions. The procedure to assess the MCE and the impact of the MCEs at the site should follow the approach outlined in guidance to RL TU3.3.

TU6.3 When assessing the effects of external hazards included in the DEC analysis, and identifying reasonably practicable improvements related to such events, analysis shall, as far as practicable, include:

- a) demonstration of sufficient margins to avoid “cliff-edge effects” that would result in unacceptable consequences;
- b) identification and assessment of the most resilient means for ensuring the fundamental safety functions;
- c) consideration that events could simultaneously challenge several redundant or diverse trains of a safety system, multiple SSCs or several units at multi-unit sites, site and regional infrastructure, external supplies and other counter-measures;
- d) demonstration that sufficient resources remain available at multi-unit sites considering the use of common equipment or services;
- e) on-site verification (typically by walk-down methods).

Margin Assessment

Evaluation of the seismic capacity of a plant beyond the design basis should consider all possible success paths for ensuring the fundamental safety functions (see F4.1), thus ensuring safe shutdown where appropriate. The weakest system, structure or component (SSCs) in each success path constrains the seismic margin of that path. The seismic margin of the plant is determined as the difference (or ratio) between the ground motion value that leads to failure of the weakest component (in the most robust success path) and the DBE [8].

The seismic capacity may be expressed in terms of a ground motion value and its associated frequency of exceedance determined by the HCLPF (High Confidence of Low Probability of Failure) value (typically: a Peak Ground Acceleration value) or as a Conservative Deterministic Failure Margin (CDFM) for a given ground motion. HCLPF is established as 95% confidence that there is less than 5% probability of failure for a given ground motion.

The assessment of seismic margin beyond design basis may be performed by applying one of the following approaches: Seismic Probabilistic Safety Analysis (SPSA) [11], Seismic Probabilistic Risk Analysis (SPRA) [9], or Deterministic Seismic Margin Assessment (DSMA) [8] [11]. The DSMA methodology is based on defining a set of SSCs that, when shown to have acceptable seismic capacity, provide high confidence that the plant will successfully reach a safe state after an earthquake occurs. The identified sets of SSCs constitute the success paths.

To determine the HCLPF capacity of success paths, the CDFM (Conservative Deterministic Failure Margin) method may be used. In this method the seismic margin is calculated by using a

set of deterministic rules that are more realistic than design procedures [9]. Otherwise, the SPSA methodology uses fault-tree and event-tree in drawing accident sequences and develops fragility curves from which the HCLPF is extracted. In some conditions, it is possible to apply CDFM method to derive SPRA fragilities.

Systematic plant walkdowns are essential elements of SPSA and DSMA methodologies and should be performed as an integral part of the seismic margin for DEC assessment [9].

In the seismic safety evaluation of a nuclear installation, the objective is to understand the true state of the SSCs in terms of their required safety function and their seismic capacity, and, as a result, to assess the plant seismic safety margin. It is therefore important to use realistic and best estimate values for the as-is condition of the SSCs and not to introduce safety factors that may unnecessarily bias the results. In the same way, aging of the components or detected defaults or degradation should be taken into account in order to define the capacity of the SSCs.

Isolation of the plant

According to TU6.3c, an assessment of the length of the period over which the fundamental safety functions can be maintained without external support should be performed. For such an assessment, only SSCs (Systems, Structures and Components) and equipment available under the conditions of design basis for natural events can be credited.

Output of Seismic Design Extension Analysis

The outputs of the margins assessment should identify potential enhancements of the protection concept to improve plant robustness, ensure cliff edges are sufficiently remote from the design basis and provide a balance of risk across the facility. This may include retrofitting, enhancements to accident management strategies, emergency arrangements and associated provisions.

07

Review of the Site Specific Hazards

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The principle of continuous improvement of nuclear safety applies to the issue of external hazards [see RL A2.3]. The site specific hazards and the protection concepts against external hazards should be reviewed at least as part of the PSR [see RL P2.1 and P2.2] according to the advances of science and technology, and new information. This guidance provides further, specific guidance for the treatment of seismotectonic hazards in such reviews.

The seismic hazard assessment should be reviewed thoroughly and periodically. The reviewers should consider conducting independent hazard assessments involving different groups of experts and considering all relevant interpretations in order to improve and strengthen the bases for regulatory decisions.

The hazard definition and protection should also be reviewed following significant events or novel scientific findings which identify shortfalls in current knowledge and understanding. New evidence or concerns may arise, e.g. related to seismic sources, newly discovered active or capable faults, new data on ground motion attenuation, or local site effects.

Methods and models for seismic hazard assessments are developing rapidly. The review of the site specific seismic hazard should therefore include:

- The evaluation of new knowledge on seismic hazard, due to new data or new assessment methods and approaches
- The evaluation of recent experience from seismic events, particularly those with impact to nuclear power plants worldwide and those close to the site
- The condition assessment of the SSCs with particular focus on their compatibility with the design requirements

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