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on

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Design Requirements for Seismic Safety of NPP

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- Safety objectives and functions
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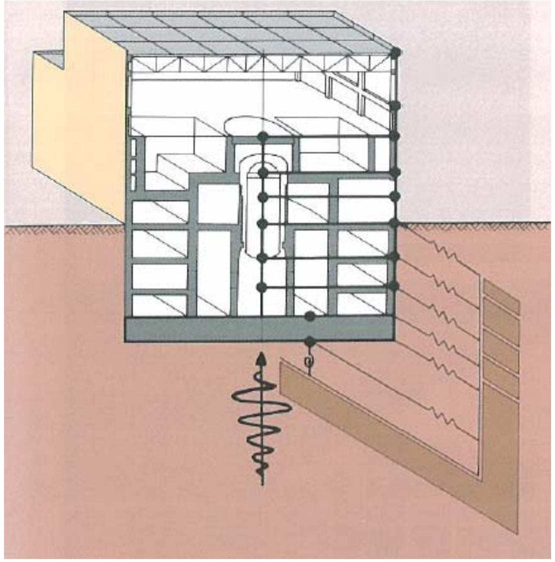


Images from: JNES presentations,
Bechtel Technology Journal, INGV

Basic approach
for ensuring Seismic Safety of NPP

- Establish the safety objective, criteria and requirements, …
- implement them in the design….. and
- demonstrate that the design satisfies the requirements

Safety Objectives & Safety Functions

The **safety objective** of the seismic design of NPP is to ensure the required **safety functions**:

- ☐ **shutdown the reactor & maintain a safe shutdown**
- ☐ **remove decay heat;**
- ☐ **maintain containment boundaries and function;**
- ☐ **control and monitor the plant**
- ☐ **maintain the functional & structural integrity of SSCs as required**

Seismic Design Input

***According to IAEA, (NS-G-3.3, IAEA,Vienna, 2002) <u>two levels</u> of ground motion hazard should be evaluated for each plant sited in a seismic area*:**

Seismic Level 1 and 2 : SL1 and SL2

SL2 is the Safety Shutdown Earthquake (SSE) for which the NPP has to be safely shutdown

SL1 is the Operating Basis Earthquake (OBE) for which the NPP has to be able to continue the operation

Seismic Levels

Selection of the SSE AND OBE

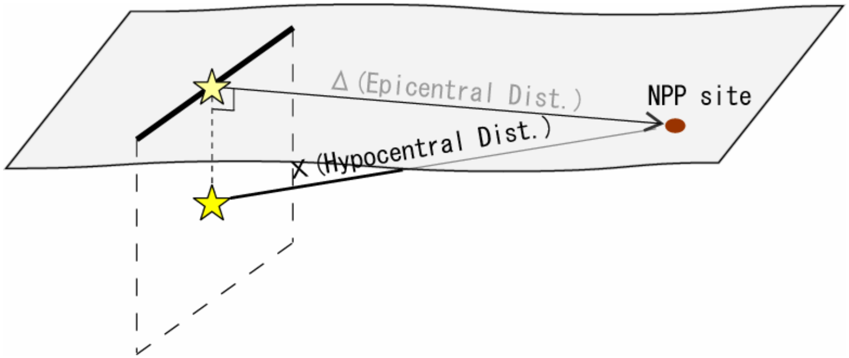
COMMON PRACTICE IN USA AND MANY WESTERN COUNTRIES

USE OF DETERMINISTIC EVALUATION OF GROUND MOTION
REFERENCE: NUREG-0800 - AUGUST 1989.

DETERMINISTIC SEISMIC HAZARD ANALYSIS (DHSA)

PROBABILISTIC SEISMIC HAZARD ANALYSIS (DHSA)

DSHA



- Identify all seismic sources posing a seismic hazard at the site
- Define their maximum credible earthquake magnitude and distance from the site for each source
- Using an appropriate ground motion attenuation relationship, determine the peak ground acceleration (PGA) at the site due to each seismic source.
- The design value for PGA at the site is the maximum of the PGA values due to the individual seismic sources.
- The response spectrum Is defined by a standard spectral shape (NRC RG 1.60) for a reference rock site.
- Site effects are accounted for by soil amplification analyses or SSI techniques (Soil Structure Interaction).

PSHA

- The Probabilistic Seismic Hazard Assessment in the well known format established by Cornell and further developed until RG 1.165 has emerged ad the preminent approach in western practice.
- It allows the definition of a Design Basis Event (SSE and OBE) in terms of engineering parameters as PGA or response spectra associated to a given exceedance probability.
- This technique takes into account the aleatory uncertainty inherent in the random nature of the ground motion and can be also used considering the epistemic uncertainty in the definition of the recurrence and attenuation laws.

SEISMIC HAZARD and SEISMIC RISK

- **Hazard and Risk are two fundamentally different concepts:**
- **Hazard is defined by a level of ground motion intensity (e.g. PGA, PGV,PGD, Spectral ordinates ......) versus its occurrence frequency, or exceedance probability.**
- **Risk is defined by the probability that a certain loss level can be exceeded, given a reference period, a fragility and exposure (loss=damage, contamination, cost, human casualties ....)**
- **Risk is a convolution between hazard, fragility of SSC’s and exposure (asset)**

SEISMIC RISK and PERFORMANCE BASED DESIGN

Seismic safety is a function of both the seismic hazard and the seismic fragility of the plant structures, systems, and components (SSC)

This consideration is the basis for the newest developments in the approach to ensure seismic safety

The Performance Based Approach aims at ensuring a final frequency objective (target) of a ‘’defined damage ‘’ (that is core damage)

Performance Based design is a risk consistent concept; seismic safety is evaluated including geological, structural and subsystems design aspects

PERFORMANCE BASED DESIGN IN NPP STANDARDS

- DOE Std 1020-02 introduced seismic risk as the basis for design of hazardous facilities, instead of seismic hazard
- The risk-based approach received a further boost after its incorporation in ASCE Standard 43-05.
- Both these standards specify a performance goal of 10^{-5} per year for Nuclear facilities (not specifically NPPs) (i.e., the probability of failure of any SSC due to a seismic event must be less than 10^{-5} per year).
- Using conservative fragility characteristics for typical nuclear SSCs, ASCE 43-05 provides a method for deriving the "performance-based" spectrum (PBS) for a risk of 10^{-5} per year.
- The application of the new approach to NPP is now possible in USA in accordance with RG 1.208

Rough comparison of seismic design levels and margins in design and construction

Ordinary Buildings vs NPP

Ordinary buildings	NPP
DBE return period 500-2000 yrs	DBE return period 10000-100000 yrs
Plastic deformation allowed Ductility in the range 1,5-6 (r.c.)	No plastic deformation – design almost in elastic range
Model uncertainty not necessarily considered	Model uncertainty taken into account
Quality Assurance and Quality control during design and construction – only for very important projects	Design and construction under strict Quality Assurance and Quality Control

Seismic Categorization for SSC’s

Based on the **safety functions** (previously mentioned) to be ensured in a NPP in case of seismic event

The safety relevant SSC’s are identified and classified

The **seismic classification** (categorizations) system can be slightly different as introduced by different standards or guides.

The most restrictive classification of SSCs is for those required to remain functional (functional integrity) during and after a SSE (SL2 in IAEA guideline)

Seismic Categories (NRC RG 1.29)

Seismic category I

Structures, systems, and components that are designed and built to withstand the maximum potential earthquake stresses for the particular region where a nuclear plant is sited.

Other structures are

NON-Seismic category I (or Seismic category II) unless those which failure could reduce the functioning of category I SSC’s

Seismic categories (IAEA NS-G-1.6)

Four categories are defined:

- **seismic category 1**: items to be designed to withstand the consequences of SSE. Seismic category 1 is usually the highest categories in terms of requirements
- **seismic category 2** : items not included in cat. 1, which 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 of items in seismic categories 1 and 3.
- **seismic category 3**: 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).
- **seismic category 4** include all items that are not in seismic category 1 or seismic category 2 or 3.

Seismic categories (Japan)

Example of Seismic categorization

BWR	PWR	Seismic category	Seismic Design force
Containment Vessel Control Rod Residual Heat Removal System Emergency Diesel Generator Reactor Pressure Vessel Emergency Core Cooling System	Containment Vessel Control Rod Residual Heat Removal System Emergency Diesel Generator Reactor Vessel Safety injecting System	S	Horizontal and vertical sesmic force (dynamic) due to the basic earthguake ground motion Ss Elastic design ground motion Sd or 3.0 * ordinary building forces if larger
Waste Disposal System Turbine equipment	Waste Disposal System	B	1.5 * ordinary building forces
Main Generator	Main Generator Turbine equipment	C	ordinary building forces

Seismic categories (ANSI/ANS-2.26, 2004)

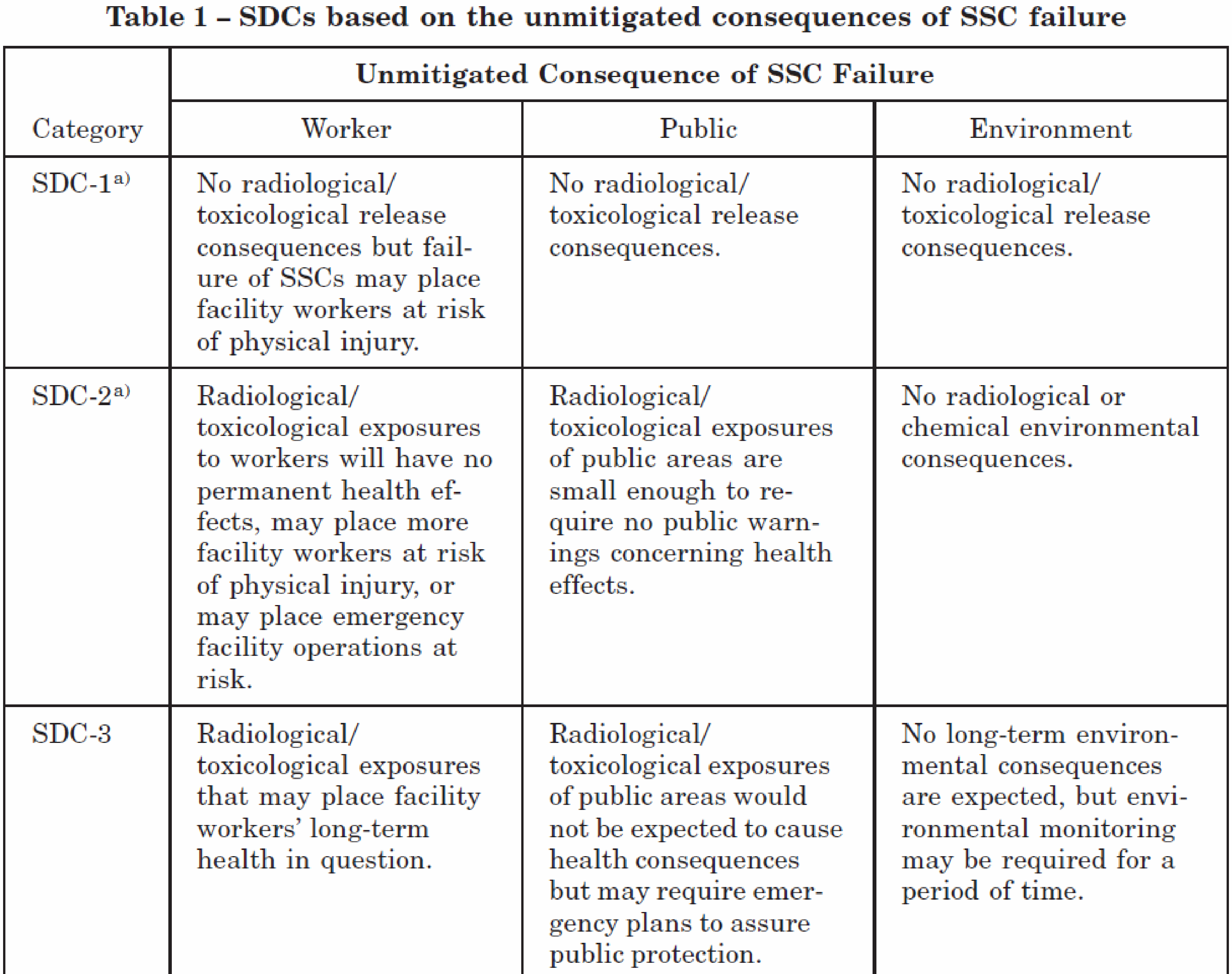
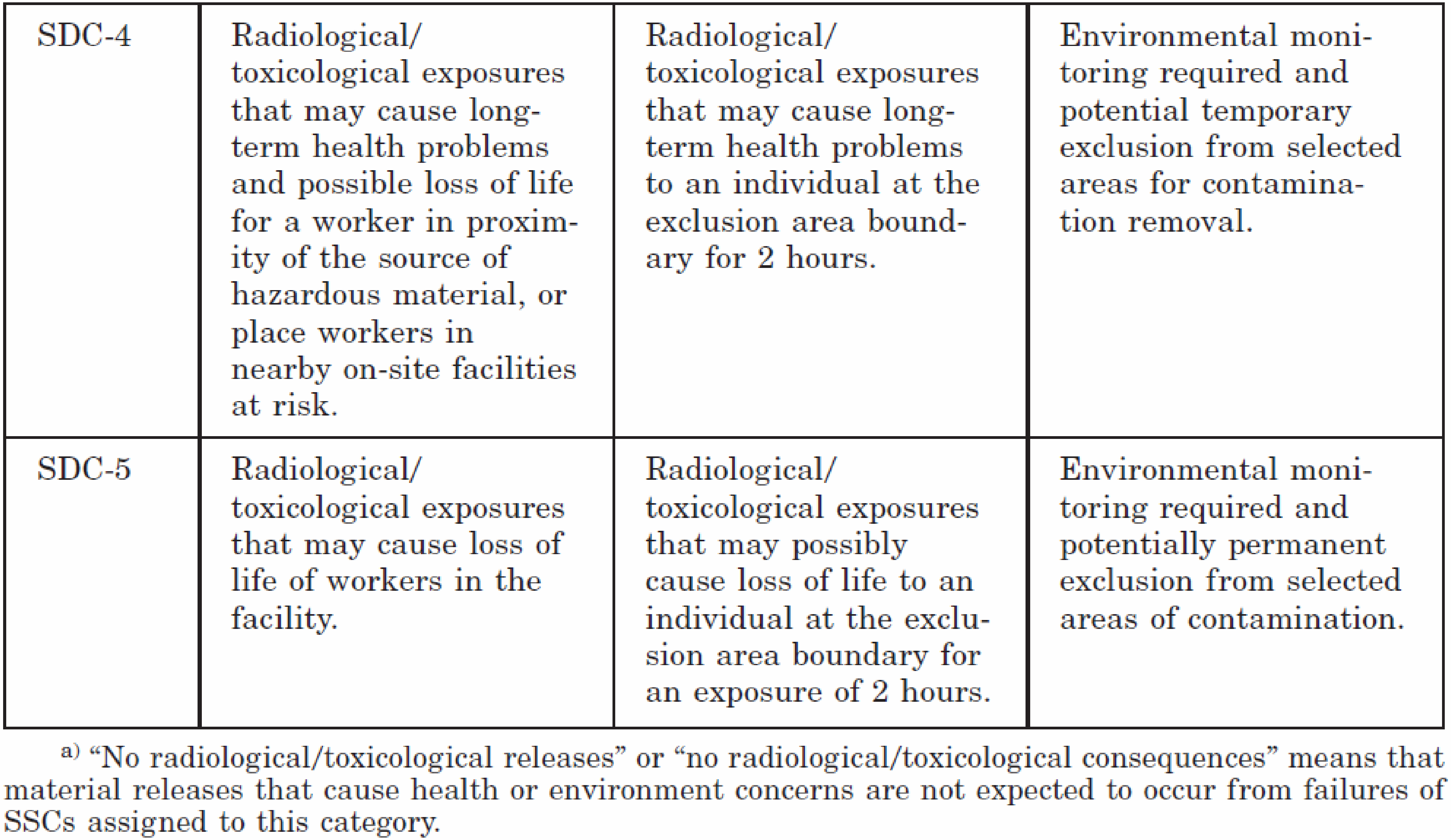


Table 1 – SDCs based on the unmitigated consequences of SSC failure

Category	Unmitigated Consequence of SSC Failure		
	Worker	Public	Environment
SDC-1[a)]	No radiological/ toxicological release consequences but failure of SSCs may place facility workers at risk of physical injury.	No radiological/ toxicological release consequences.	No radiological/ toxicological release consequences.
SDC-2[a)]	Radiological/ toxicological exposures to workers will have no permanent health effects, may place more facility workers at risk of physical injury, or may place emergency facility operations at risk.	Radiological/ toxicological exposures of public areas are small enough to require no public warnings concerning health effects.	No radiological or chemical environmental consequences.
SDC-3	Radiological/ toxicological exposures that may place facility workers' long-term health in question.	Radiological/ toxicological exposures of public areas would not be expected to cause health consequences but may require emergency plans to assure public protection.	No long-term environmental consequences are expected, but environmental monitoring may be required for a period of time.

Seismic categories (ANSI/ANS-2.26, 2004) (cont.)



SDC-4	Radiological/ toxicological exposures that may cause long-term health problems and possible loss of life for a worker in proximity of the source of hazardous material, or place workers in nearby on-site facilities at risk.	Radiological/ toxicological exposures that may cause long-term health problems to an individual at the exclusion area boundary for 2 hours.	Environmental monitoring required and potential temporary exclusion from selected areas for contamination removal.
SDC-5	Radiological/ toxicological exposures that may cause loss of life of workers in the facility.	Radiological/ toxicological exposures that may possibly cause loss of life to an individual at the exclusion area boundary for an exposure of 2 hours.	Environmental monitoring required and potentially permanent exclusion from selected areas of contamination.

[a] "No radiological/toxicological releases" or "no radiological/toxicological consequences" means that material releases that cause health or environment concerns are not expected to occur from failures of SSCs assigned to this category.

SEISMIC LOADS & LOADS COMBINATIONS

Seismic actions to be used for the design of SSC’s shall be combined with other actions in operating and accidental conditions.

The load combinations are based on a partial load factor approach, that takes into account the probability of simultaneous occurrence of the corresponding loads.

The load factors are defined in the appropriate design codes for civil and mechanical SSC’s.

Accidental loads, due to the lower probability of exceedance, are combined with lower simultaneous actions.
As a result, OBE condition can in some cases control the design.

SEISMIC DESIGN - ANALYSIS and MODELS

- **NPP structures under seismic actions can be analysed by mathematical models to evaluate the response to earthquake.**
- **Due to the complexity of the NPP, it is usually divided into several separate systems and one or more mathematical models are prepared**
- **The mathematical models used to generate the seismic excitation data for subsequent separate analyses of supported systems can be different from those used for the detailed localized analyses of the supporting structure.**

SEISMIC DESIGN - ANALYSIS PROCEDURE

1. Target Spectrum of DBE

2. Characterize Design Basis Earthquake by time histories, response spectra or power spectral density, according to the analysis type

3. Structural model of building and soil, (eventually of main equipment / systems)

4. Response Analysis of the Building

5. Development of Floor Response spectra or of floor time histories

6. Dynamic Analysis of Components under FRS or coherent time histories

7. Numerical check of Components

Uncertainties management in the design

Some key aspects in the design involve a considerable uncertainties, both aleatory and epistemic, e.g.

- Soil Structure Interaction
- Floor Response Spectra evaluation

- They are handled by:
  - Parametric analyses in SSI (multiple cases with different soil parameters)
  - FRS smoothing and broadening

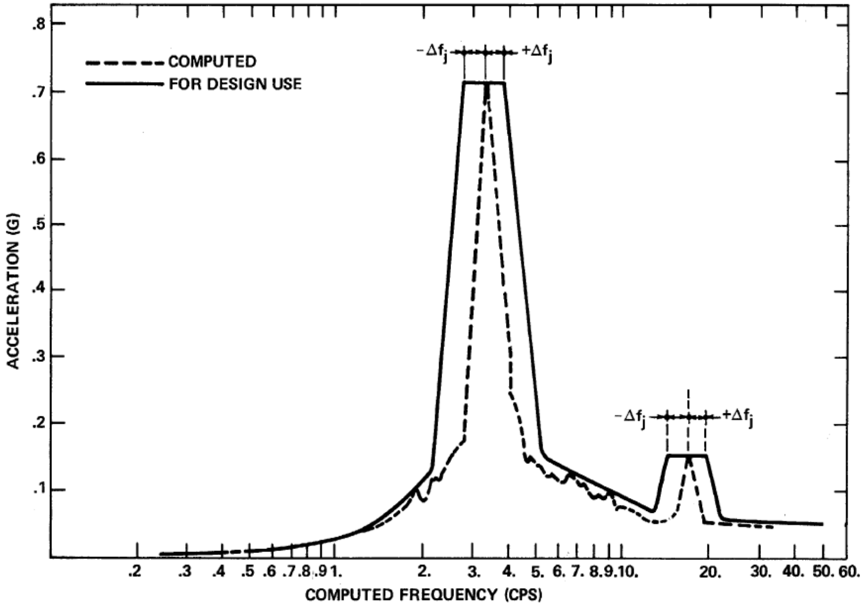


Figure 1 Response Spectrum Peak Broadening and Smoothing

Seismic Qualification of Equipment

- SSC relevant for safety shall be seismically qualified in accordance with requirements set up by IEEE, IEC, IAEA Standards, and other equivalent national standards
- Seismic Qualification means the demonstration that the equipment can perform the required safety functions during and after the seismic event when it is at the end of qualified life
- This demonstration shall be proved by:
  - Analysis
  - Operating experience
  - Test
  - Combination of above methods
- Key aspect of the EQ is the aging to be simulated before demonstrating the capability to perform the safety function at the end of qualified life.

  This aging depends on the environmental service conditions (normal and accident) and on the operational cycles

Qualification of components - Seismic Fragility Tests

A:Horizontal Shaft Pump

B:Electrical Panel

C:Control Rod Insertion of PWR

D:Control Rod Insertion of BWR

E:Large Vertical Shaft Pump

A, E: PERFORMANCE FOR ROTATION

B: ELECTRICAL FUNCTION

C, D: C.R. INSERTION

Evaluation of Margins

The complex set of design requirements and process described before implies adoption of margins, mainly due to the consideration of uncertainties in material properties and design procedures.

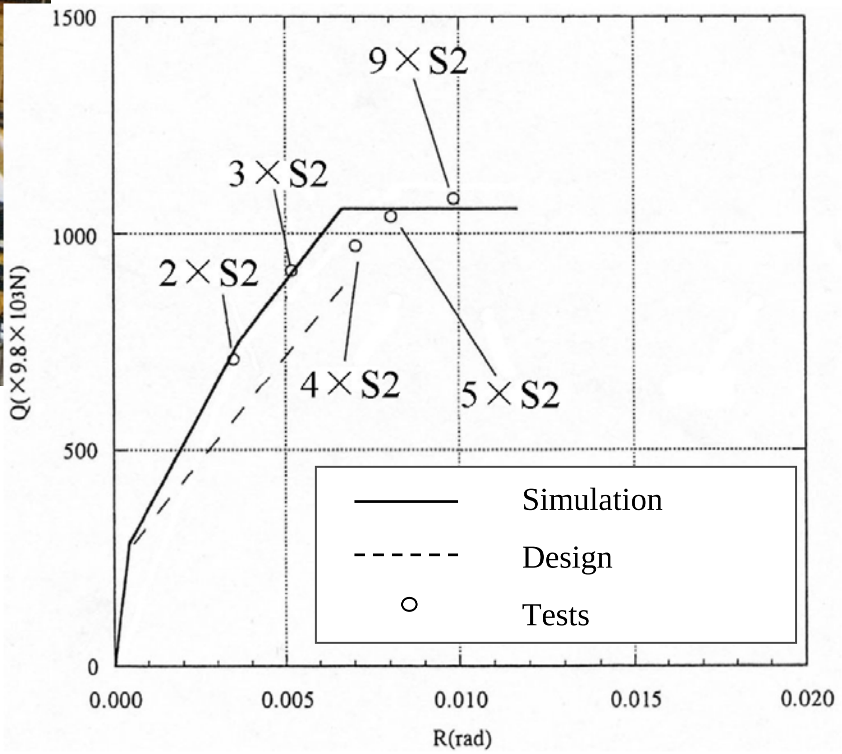
An in-depth evaluation of the safety margins embedded in design and construction practice is the basis for developing codes and standards.

How the margin will be effective in case of Beyond Design Basis events (BDBE) is the subject of analysis and investigation with experimental and numerical techniques.

Shaking table test of Concrete Containment Vessel

scale : 1/10

Results

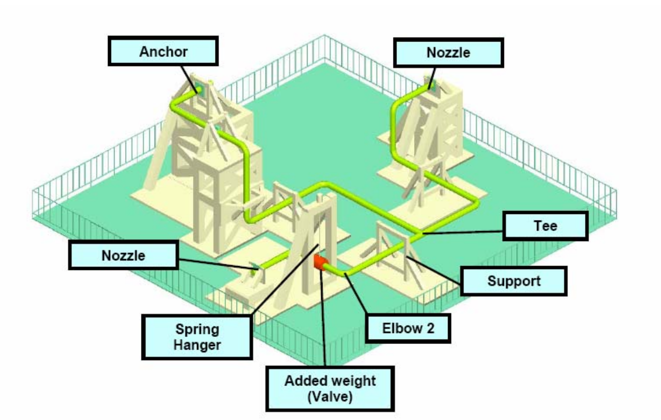


increasing input motion gradually (from 2×S_2)

○RCCV was safe up to 5×S_2.

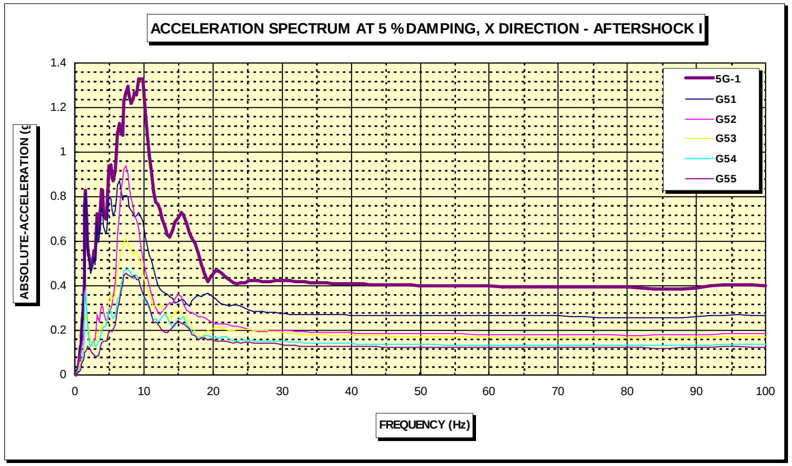
○RCCV collapsed (shear failure) at 9×S_2.

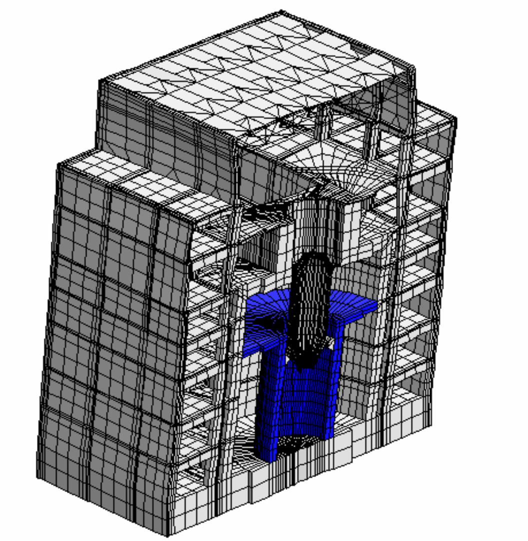
JNES-NUPEC Ultimate Strength Piping Test Program



Numerical analysis of case histories

Karisma Benchmark





CONCLUSIONS

- Seismic safety of a NPP is the result of a complex and important process starting from the establishment Safety Objectives to be achieved at level of NPP and proceeding trough the safety functions, safety & seismic classifications, seismic analysis,…. up to EQ and also maintenance of effectiveness of the seismic design.
- It is important that the regulatory authorities establish clear and understandable objectives and requirements for the seismic safety of NPP in order to provide the designers with clear inputs
- Performance-based approach in the design, recently introduced, is undergoing a feasibility and effectiveness assessment while applied to NPP seismic design.
- The development of new standards and design rules can benefit from a better understanding of seismic safety design margins of SSC’s in NPP.

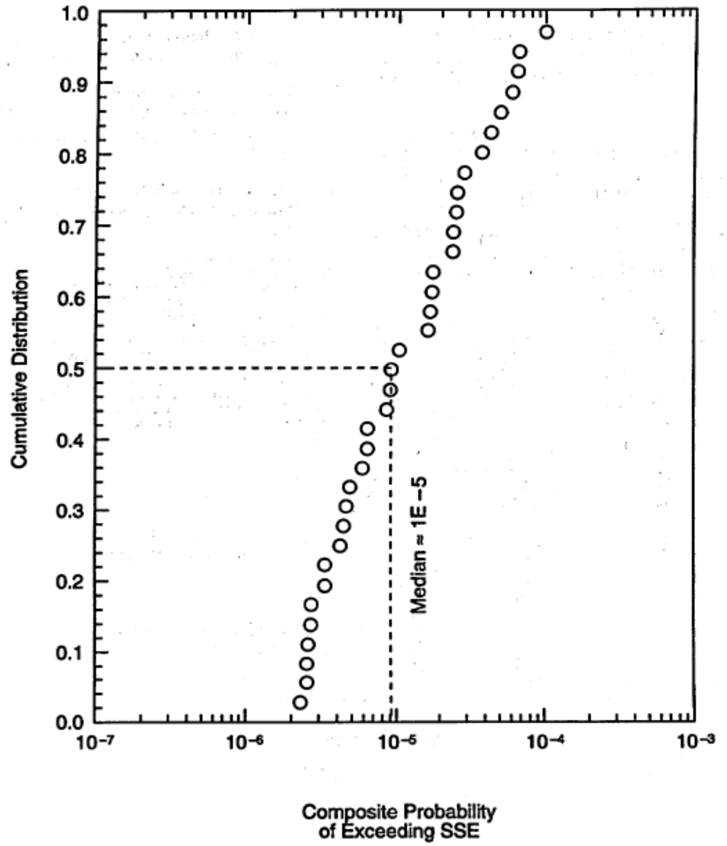
Origin of the risk-based approach

- Risk based approach stems from the individual plant examination for external events (IPEEE) program, launched by NRC in early 1990s.
- NRC asked all nuclear plant licensees to evaluate the plant risks associated with seismic events, high winds, internal fire etc.
- For reporting seismic assessment results, the licensees were given a choice to use either :
  - the “classic” seismic margins approach (i.e., maximum ground motion that could be resisted versus the PGA value that the plant was designed for)
  - or a more comprehensive annual seismic risk approach.
- Licensees of 25 (out of 70) existing plants conducted the seismic risk-based evaluations.
- The results proved to be a better indicator of each plant’s seismic safety because the studies addressed both the hazard and fragility aspects of the controlling SSCs.

SEISMIC HAZARD CRITERIA DEVELOPMENTS mid-1990s TO 2004

USE OF PROBABILISTIC SEISMIC HAZARD ANALYSIS
REFERENCE: 10CFR100 Subpart B; NRC RG 1.165 (1997)

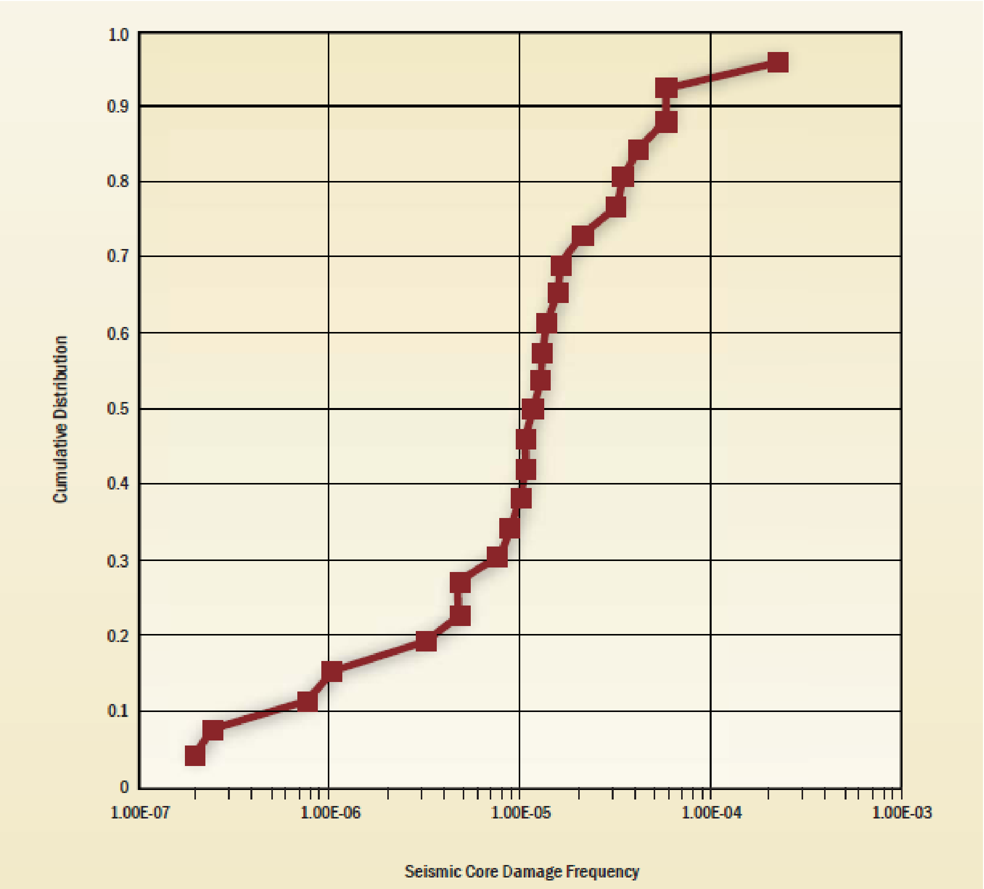
NRC RG 1.165 required the new generation of nuclear power plants to be designed for a seismic hazard of 10^{-5} per year (referred to as the reference probability in RG 1.165) using the PSHA method. This consideration is derived from an evaluation of the median level of the SSE exceedance probability from the existing US fleet of plants.



Seismic safety is a function of both the seismic hazard and the seismic fragility of the plant structures, systems, and components (SSC), not the seismic hazard alone.
This consideration is the basis for the newest developments of risk criteria

The NRC NUREG-1742 summary report enabled the nuclear industry to think in terms of a reference risk

This is determined as the median annual seismic risk for the existing NPP units— as an indicator of their seismic safety.



Annual Seismic Core Damage Frequency at Existing Nuclear Power Plants

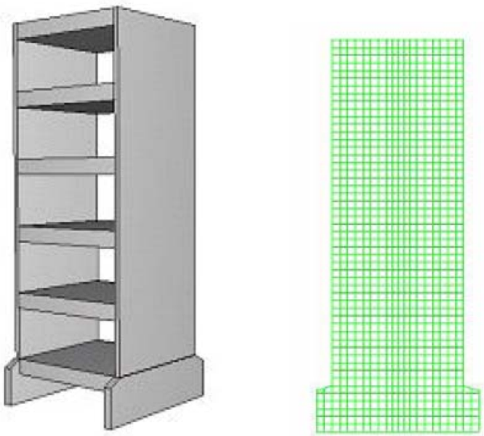
The reference risk value for seismically induced failure in existing US NPP was estimated about 1.2 x10-5.
With the growing information about seismicity data and ground motion models, the annual seismic risk estimate tends to be higher with increased hazard estimates.

Numerical evaluation of design margins

Numerical analysis versus testing

Hualien Large Scale Seismic Test

Lotung Large Scale Test Facility for SSI



Camus 1:3 scale R.C. wall used for IAEA CRP on Safety Significance of Near Field Earthquakes