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The IAEA Safety Guide on the Evaluation of Seismic Hazards for Nuclear Power Plants

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IAEA/ICTP Workshop on
Earthquake Engineering for Nuclear Facilities - Uncertainties in Seismic Hazard Assessment

"The IAEA Safety Guide on the Evaluation of Seismic Hazards for Nuclear Power Plants"

Unit 02 - Antonio R. Godoy, IAEA

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IAEA Safety Guide on
Evaluation of Seismic Hazards for NPPs

1 – INTRODUCTION:
IAEA SAFETY STANDARDS

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1. Introduction – IAEA Safety Standards

- **IAEA has a statutory function to establish standards of safety for the protection of health, life and property in the development and application of nuclear energy for peaceful purposes.**
- **IAEA Safety Standards are structured in 3 categories:**
  - **Safety Fundamentals:**
    , i.e. the objectives, *principles and concepts of protection*
  - **Safety Requirements:**
    , i.e. the requirements that must to be met to ensure the protection *(shall)*
  - **Safety Guides:**
    , i.e. the recommendations and guidance on how to comply with the requirements (*should*).

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1. Introduction – IAEA Safety Standards

- **IAEA Safety Standards are not legally binding on Member States.**
- **They are binding on the IAEA in relation to its own operations, and on Member States in relation to operations assisted by the IAEA.**
- **The IAEA Safety Standards are of 2 types:**
  - ***"Thematic"* standards,**
  - ***"Facility specific"* standards.**

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1. Introduction – IAEA Safety Standards

- **The *thematic* Safety Standards cover matters relevant to:**
  - *Legal and governmental infrastructure*
  - *Emergency preparedness and response*
  - *Management systems*
  - *Assessment and verification*
  - ***Site evaluation***
  - *Radiation protection*
  - *Radioactive waste management*
  - *Decommissioning*
  - *Rehabilitation of contaminated areas*
  - *Transport of radioactive material.*

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1. Introduction – IAEA Safety Standards

- **The *facility specific* Safety Standards cover the following type of facilities:**
  - ***Nuclear power plants: design***
  - ***Nuclear power plants: operation***
  - *Research reactors*
  - *Fuel cycle facilities*
  - *Radiation related facilities and activities*
  - *Waste treatment and disposal facilities*

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1. Introduction – IAEA Safety Standards

Specifically, in relation to earthquakes and Nuclear Power Plants:

•**Requirem ents:**

IAEA/NS-R-3 "Site Evaluation for Nuclear Installations"

•**Safet y Guides:**

on Site Evaluation: *IAEA-NS-G-3.3 "Evaluation of Seismic Hazards for Nuclear Power Plants", 2002*

on Facility Design: *IAEA-NS-G-1.6 "Seismic Design and Qualification for Nuclear Power Plants", 2003*

•**Safet y Report Series:** **for *evaluation of existing facilities***

IAEA/SRS N. 28 "Seismic Evaluation of Existing Nuclear Power Plants"

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1. Introduction – Site Evaluation Requirements

In general, the requirements for site evaluation of NPPs establishes that:

- **... the site characteristics that may affect the safety. . . shall be investigated and assessed. . .**
- **... the proposed sites . . . shall be examined with regard to the frequency and severity of external natural and human induced events and phenomena that could affect the safety . . .**

Particularly, in relation to earthquakes:

- **. . . , the hazards due to earthquake induced ground motion shall be assessed with account taken of the seismotectonic characteristics of the region and of specific site conditions. A thorough uncertainty analysis shall be performed as part of the evaluation of the seismic hazards. . . .**

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2 - IAEA SAFETY GUIDE: DEVELOPMENT OF CURRENT (2002) VERSION

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2. Development of current version

The "historical" development and evolution of the IAEA Safety Standard for the evaluation of the seismic hazards at NPPs, is as follows:

- 1979 : the initial version
  issue of the Safety Guide 50-SG-S1 on "*Earthquakes and Associated Hazards in Relation to NPP Siting*".
- 1991 : the 1st revision
  i.e. 50-SG-S1 (Rev. 1).
- 2002 : the 2nd revision
  issue of the Safety Guide NS-G-3.3 on "*Evaluation of Seismic Hazards for Nuclear Power Plants*".

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2. Basis for the new revision

- The feedback from IAEA review services provided to Member States in relation to the seismic input of nuclear facilities (1990-2001).
- New developments on:
  - regulatory approach to licensing,
  - new data from significant recent earthquakes,
  - external event PSA for new and existing plants,
  - new approaches in methods of analysis.

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2. Feedback from the IAEA Review Services

Summary of IAEA Review Services performed in the 12 years period (1990- 2001) in relation, exclusively, to the assessment of the seismic input of nuclear facilities:

Total number of reviews	*86*
Number of sites/facilities	*29*
Number of countries	*23*
Different types of facility	*3*
Number of external experts	*~100*
Number of reviews involving seismic PSA	*5*

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2. Sample of Reviewed Plants/Sites of Nuclear Installations (1990 – 2001)

- **Europe:** Gorki, Crimea, Leningrad, Smolensk, Temelin, Mochovce, Bohunice, Paks, Cernavoda, Pitesti, Kozloduy, Belene, Krsko, Armenian, Cekmece
- **Asia:** Bushehr, Alatau, Ulken, Ulugbek, Chashma, Kanupp, Rooppur, Muria, Madura, Bangkok, Ulchin, Sinpo, Tianwan
- **Africa:** Sidi Boulbra, Maamora, Rabat, Cairo, Koeberg
- **Australia**: Lucas Heights
- **South America:** Santiago, Huarangal, Angra.

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3 - IAEA SAFETY GUIDE: MAJOR CHANGES IN NEW VERSION

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3. Major Changes

1. Provide more guidance on new topics related to the data generation, such as paleoseismology.
2. Provide guidance on methods for probabilistic seismic hazard analysis (PSHA).
3. Provide further guidance on development of ground motion response spectra - decouple this from the 'design' issue.

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3. Major Changes

1. **More guidance on new topics, e.g. paleoseismology:**

- **The feedback from the IAEA review services confirmed the need for a 'solid' database before proceeding with analysis.**
- **Paleoseismology, i.e. the study of the geological record of past earthquakes, provides a crucial link between historical seismology and neotectonic studies. This will be even more important in cases where historical data is deficient.**

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Type and span of data

TYPE OF DATA	TIME FRAME (approx.)	LOWER MAGNITUDE THRESHOLD (approx.)	TIME RESOLUTION
Local networks	10- 20 years	1	second
Modern instruments	30-40 years	2	second
Early instruments	100 years	4	second/minute
Historical	from few centuries to few millennia (*)	3(**)	from minute to year
Archaeological data	from few centuries to a few millennia (*)	5	year
Paleoseismological data	10,000 years	6	century
Neotectonics data	100,000 years		millennium

(*) depending on history of the Country
(**) depending on time period, seismic activity of region and according to cultural and socio-economic historic context.

Table 1
Type of data for the reconstruction of long term seismic history

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3. Major Changes

2. Guidance on probabilistic seismic hazard analysis (PSHA) methods:

- **Probabilistic methods are specifically recommended for hazard studies associated with external natural and human induced events in the IAEA Safety Standard on Site Evaluation Requirements NS-R-3:**

  "...2.18. Appropriate methods shall be adopted for establishing the hazards that are associated with major external phenomena. ... **Special consideration should be given to applicable probabilistic methodologies.** It should be noted that probabilistic hazard curves are generally needed to conduct probabilistic safety assessments for external events."

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3. Major Changes

2. Guidance on probabilistic seismic hazard analysis (PSHA) methods:

- **Several examples from seismic input reviews had showed that there is a need for guidance on PSHA methods to be applied. This guidance is provided in the new version of the Safety Guide NS-G-3.3.**
- **PSHA is recommended more strongly also because of the current trend of conducting external events PSA in many Member States. This is also an IAEA requirement.**

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3. Major Changes

3. Response spectra:

- **New version provides guidance for developing response spectra tied with PSHA, that is, to generate uniform hazard response spectra:**

  (i.e, spectral amplitudes that have the same annual exceedance frequency for the range of structural periods of interest).

- **The response spectra are now treated separately in the *Seismic Hazard Evaluation Safety Guide* and in the *Seismic Design Safety Guide*, i.e. in the first as a "site related requirement" and in the latter as a "load case" for the facility.**

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4 - IAEA SAFETY GUIDE: STRUCTURE AND SAMPLE RECOMMENDATIONS

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4.1 - Structure of the Safety Guide NS-G-3.3

1. Introduction
2. General recommendations.
3. Necessary information and investigations (Database).
4. Construction of a regional seismotectonic model.
5. Evaluation of ground motion hazard.
6. Potential for surface faulting at the site.
7. Quality assurance.

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4.2 - Sample recommendations

2. General recommendations:

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

....

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4.2 - Sample recommendations

2. General recommendations:

2.8 . . . . . .Every aspect of the identification, analysis and characterization of seismic sources and estimation of ground motion may involve substantial subjective interpretation by experts. Particular care should be taken to avoid bias. Experts should not promote any one hypothesis or model but should evaluate all viable hypotheses and models using the available data and then develop an integrated evaluation which incorporates both knowledge and uncertainties.

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4.2 - Sample recommendations

3. Necessary information and investigations (database)

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

. . . .

3.3 Investigations should be conducted on four scales –regional, near regional, site vicinity and site area- thus leading to progressively more detailed investigation, data and information. . . . .

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4.2 - Sample recommendations

3. Necessary information and investigations

Type of data to be collected:

1. **Geological**
2. **Geophysical**
3. **Geotechnical**
4. **Seismological . . .and**
5. **Any other information relevant to evaluate the ground motion, faulting and geological hazards at the site.**

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4.2 - Sample recommendations

3. Necessary information and investigations

Recommended scales of study for all types of data:

- **Regional: a minimum radius of about 150 km and at a scale of 1 : 500 000**
- **Near regional: a minimum radius of about 25 km and at a scale of 1 : 50 000**
- **Site vicinity: a minimum radius of 5 km and a scale of 1 : 5 000**
- **Site area: fenced in area, at a scale of 1 : 500**

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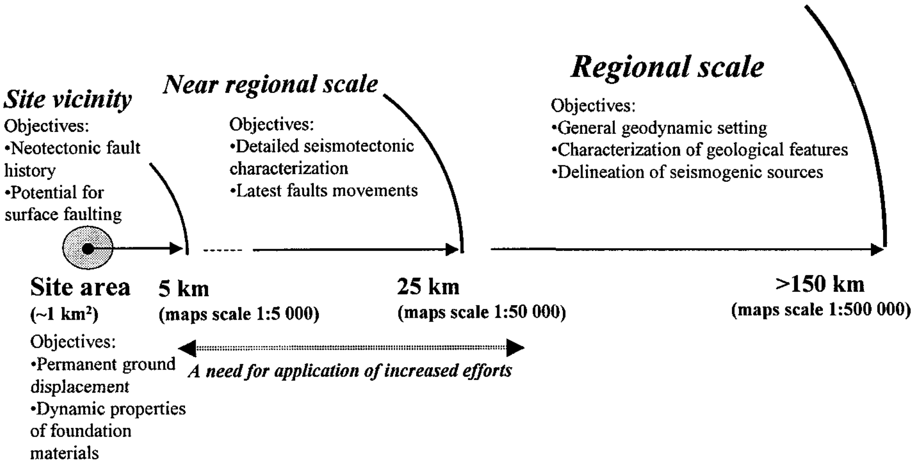
Seismic Hazard Evaluation – Scales of investigations

Geological, geophysical and geotechnical databases



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4.2 - Sample recommendations

3. Necessary information and investigations

Geological, geophysical, geotechnical database - Near regional areas

. . .

3.10 To supplement the published and unpublished information on near regional areas, specific investigations should typically include the definition of the stratigraphy, structural geology and tectonic history of the near region. Tectonic history should be very well defined for the current tectonic regime, for example: Upper Pleistocene-Holocene may be adequate for interplate regions and Pliocene-Quaternary for intraplate regions.

. . . .

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4.2 - Sample recommendations

3. Necessary information and investigations

Seismological database

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

i.e. :
- Historical earthquake data
- Instrumental earthquake data
- Site specific instrumental data

A site specific Earthquake Catalogue should be compiled. Its completeness and reliability should be assessed.

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4.2 – Sample recommendations

4. Construction of a regional seismotectonic model

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

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4.2 – Sample recommendations

4. Construction of a regional seismotectonic model

4.3. The seismogenic structures identified may not explain all the observed earthquake activity. . . .

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

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

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4.2 – Sample recommendations

4. Construction of a regional seismotectonic model

4.5 ...However, the second type, diffuse seismicity, is a particularly complex problem in seismic hazard assessment and generally will involve greater uncertainty because the sources of the earthquakes are not well understood. A complete definition of these elements involves expert interpretations that are uncertain. The uncertainty in the interpretations should be properly assessed in order to incorporate it into the ground motion hazard at the site.

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4.2 – Sample recommendations

4. Construction of a regional seismotectonic model

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

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

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4.2 - Sample recommendations

5. Evaluation of ground motion hazard

Levels of ground motion hazard

5.3. Typically, two levels of ground motion hazard (SL-1 and SL-2) are evaluated for each plant.

5.4. The SL-2 level corresponds directly to ultimate safety requirements. This level of ground motion shall have a very low probability of being exceeded during the lifetime of the plant and represents the maximum level of ground motion to be assumed for design purposes. . . .

5.5. ...minimum level is . . . a pga of 0.1g . . .

5.6. The SL-1 level corresponds to a less severe. More likely earthquake which has different safety implications from those of SL-2.

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4.2 - Sample recommendations

5. Evaluation of ground motion hazard

LEVELS OF GROUND MOTION HAZARD

Regardless of the method used to evaluate the ground motion hazard, both SL-1 and SL-2, should be defined by means of:

- Response spectra,
  - S ite specific spectra
  - S tandard spectra
- Time histories.

The motion should be defined for free field conditions at the:

- Surface of the ground,
- Level of foundation, or
- Bedrock.

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4.2 - Sample recommendations

5. Evaluation of ground motion hazard

It may be evaluated using:

- Deterministic methods, and/or
- Probabilistic methods

PROBABILISTIC METHODS

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

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4.2 – Sample recommendations

5. Evaluation of ground motion hazard

PROBABILISTIC METHODS

. . .

5.16 ...The method allows for uncertainties in the parameters of the seismotectonic model as well as alternative interpretations of models to be explicitly included in the hazard analysis and propagated through the hazard results. Alternative models may be proposed by different experts or expert groups and these may be formally included in the probabilistic hazard computation. When this method is used, the results of international practice in the application of such multiple evaluations for PSHA should be reviewed.

. . .

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4.2 – Sample recommendations

5. Evaluation of ground motion hazard

PROBABILISTIC METHODS

. . .

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

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4.2 - Sample recommendations

6. Potential for surface faulting at the site - Capable faults:

6.3 The main question with regard to surface faulting is whether a fault (buried or outcropping) at or near the site is capable. . .

Definition: **surface faulting** is the permanent offsetting or tearing of the ground surface by differential movement across a fault during an earthquake

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4.2 - Sample recommendations

6. Capable faults:

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

- **If it shows evidence of past movement or movements (such as significant deformation and/or dislocations) of a recurring nature within such a period that it is reasonable to infer that further movements at or near the surface may occur.**
- **In highly active areas, where both earthquake data and geological data consistently reveal short earthquake recurrence intervals, periods of the order of tens of thousands of years may be appropriate for the assessment of capable faults. In less active areas, it is likely that much longer periods are appropriate.**

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4.2 - Sample recommendations

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

- If a structural relationship with a known capable fault has been demonstrated such that movement of the one fault may cause movement of the other at or near the surface.
- If the maximum potential earthquake associated with a seismogenic structure, as determined in Section 4, is sufficiently large and at such a depth that, in the geodynamic setting of the plant, movement at or near the surface may occur.

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4.2 - Sample recommendations

6. Potential for surface faulting at the site - Capable faults:

   Examples of cases that requires extensive investigations to demonstrate that no surface faulting can occur at the site:

   - Nuclear: Armenian NPP
   - Non nuclear: Bridges

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4.2 - Sample recommendations

7. Quality Assurance:

- Establishment of a QA Programme.
- Use of technical procedures specific to the project.
- Conduct a peer review of the complete process.

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5 – SEISMIC HAZARD EVALUATION: NEW CHALLENGES

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5 – Seismic Hazard Evaluation - New Challenges

For the Project Manager:

- Avoid to formulate the *seismic input project* on the basis of biased/pre-assumed results to be obtained.
- Formulate, from the beginning, a work plan with emphasis in the collection of reliable and relevant data, grading the resources increasing the efforts towards the site, as an effective way to reduce the ignorance and uncertainties were really matter.

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5 – Seismic Hazard Evaluation - New Challenges

For the Hazard Analyst:

- Keep uncertainties as low as reasonably possible – involves substantial data collection.
- Calculate ground motion hazards corresponding to lower frequencies per year (~ 10^{-6}).

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5 – Seismic Hazard Evaluation - New Challenges

For the Ground Motion Specialist:

- Modelling of the ground motion from different types of sources separately – near / far field, frequencies content.
- Avoid duplication in modelling of the same phenomenon (in attenuation relationships and in site effects modelling).

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5 – Seismic Hazard Evaluation - New Challenges

For the External Event PSA Specialist:

- For innovative NPP designs (which depend mostly on passive systems) it is likely that external events (especially seismic) will become more and more dominant as a "Core Damage" initiator,
- Need for methods to evaluate probabilities of phenomenological failures (i.e. need to work closely with structural/mechanical engineers)

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5 – Seismic Hazard Evaluation - New Challenges

For the Structural Engineer:

- Need for effective analysis methods to distinguish between "first excursion" type failure (e.g. RS) and "cumulative" type (energy based) failure,
- Modelling of phenomenological failures of singletons (especially in innovative NPP designs)

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Conclusions

- The IAEA *Safety Guide on Evaluation of Seismic Hazards for NPPs* has been used and applied for the assessment of the seismic input at both new and existing nuclear facilities during a period of more than 20 years, by numerous Member States.
- Two revisions, in 1991 and 2002, allowed to keep it updated to the most recent developments, data and experience.
- Concepts and approaches proposed originally by this Guide are today well established and accepted by the internationally community.

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