The Abdus Salam
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United Nations
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"2nd Workshop on Earthquake Engineering for Nuclear Facilities: Uncertainties in Seismic Hazard"

14 - 25 February 2005

IAEA TECDOC 724 - Probabilistic Safety Assessment for Seismic Events (Seismic PSA)

Antonio R. Godoy

IAEA, Vienna

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

"IAEA TECDOC 724 – Probabilistic safety assessment for seismic events (Seismic PSA)"

Unit 03 - Antonio R. Godoy, IAEA

Trieste, Italy, 14 – 25 February 2005

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6. Plant Response Analysis and Fragility
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8. Results of a Seismic PSA

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1 – INTRODUCTION

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1. Introduction – Background

- According to the experience of Member States that conducted PSA studies of operating NPPs, earthquakes are one of the most important external events affecting NPP safety.
- In some cases, the risk caused by earthquakes has been found to be comparable with the risk caused by internally initiated events.

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1. Introduction – Reasons for a Seismic PSA

- Response to a regulatory requirement for licensing a new plant;
- Resolution of existing seismic issues;
- Resolution of new seismic issues;
- Development of a risk management program;
- Performance of cost/benefit studies for decision on plant upgrading;
- Assessment of an existing plant safety for a newly defined seismic input exceeding the original design basis
- Plant life extension.

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1. Introduction – Applicability

- The general methodology is applicable to all of the potential applications.
- The depth of the study may depend upon the objective of the project and the level of seismicity of the site.
- All types of reactors:
  - commercial PWRs, BWRs, LMFBRs,
  - research reactors, and
  - military reactors.

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1. Introduction – Objectives of a Seismic PSA

- To develop an appreciation of accident behaviour;
- To understand the most likely accident sequences;
- To gain an understanding of the overall likelihood of core damage;
- To identify the dominant seismic risk contributors;
- To identify the range of peak ground acceleration that contributes significantly to plant risk;
- To compare seismic risk to risk from other events.

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1. Introduction –Seismic PSA Results

- For Level 1 PSA. Potential releases and off-site consequences are not included.
- The main result is to provide an order of magnitude of the frequency of core damage associated with earthquakes, which might contribute to the total frequency of core damage.
- A number of beneficial side effects:
  - Consideration of different spectral shapes;
  - Alternative hypotheses regarding soil properties, structural models, material characteristics, etc.
  - All leading to a weighted sensitivity analysis, as a way to detect the weaker links in the chains going to undesired events.

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2 – PURPOSE AND SCOPE OF THE DOCUMENT

IAEA-TECDOC-724
Published in October 1993.

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2. Purpose and scope of the TECDOC

- **To provide information and guidance to those starting a seismic PSA, giving a overall picture of the usually applied procedure.**
- **It covers mainly:**
  - **Frequency of occurrence of ground motions, i.e. the seismic hazard evaluation;**
  - **Seismic accident sequence initiators;**
  - **Fragility analysis of safety related plant items;**
  - **Capability of systems to mitigate accidents from seismic events;**
  - **Integration of all above aspects which can lead to core damage.**

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2. Purpose and scope of the TECDOC

- It does not cover the effects of earthquakes after the event of core damage.
- Aspects that may have significant contribution to the overall risk and have not been considered in the document are:
  - Increased probability of human errors, subsequent to the occurrence of a destructive earthquake;
  - Significant probability of damages to lifelines and other infrastructures which may have been planned for use in the context of emergency planning and evacuation.
  - Increased probability of delayed response to the nuclear accident due to the interference of another catastrophic event.

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2. Purpose and scope of the TECDOC

- An "internal" initiator
  - is an event in the plant itself which may affect or have consequences on the "exterior"
- An "external" initiator as an earthquake, or other natural events of regional scale,
  - is an event that affects also and simultaneously the "exterior" of the plant, i.e. the region and the public, who may receive on the top of that the consequences of a nuclear accident;
  - affects passive safety systems;
  - may lead to common cause failures, affecting redundancy;
  - is a cause of interactions between items.

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3 – OVERVIEW OF SEISMIC PSA PROCEDURE

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3. Overview of a seismic PSA procedure

- **The major steps for accomplishing a Seismic PSA are:**
  1. **Development of a seismic hazard curve;**
  2. **Structure and component seismic response determination;**
  3. **Assessment of structure and component fragility;**
  4. **Random failure data development;**
  5. **Event/fault tree construction and solution;**
  6. **Risk quantification incorporating results of steps 1) to 5)**

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Overview of a seismic PSA

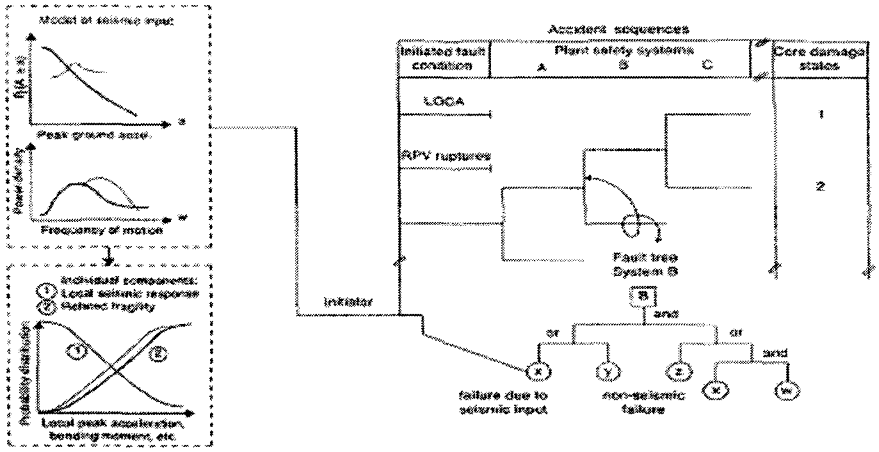

FIG. 1. Schematic overview of a seismic PSA.

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3. Overview of Seismic PSA Procedure

- ***Seismic hazard*** **(i.e. the seismic input), and the**
- ***Seismic fragilities and response*** **of individual plant items (i.e. components, systems and structures) . . .**

  . . . . . .   are combined to provide an estimate of the probability of various plant damage states
- **The seismic hazard is the initiator of the accident sequences.**
- **The accident sequences are developed from an initiated fault condition (e.g. ATWS, LOCA) produced directly by the earthquake ground motion.**

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3. Overview of Seismic PSA Procedure

- Attention is called to the possibility that the "initiated fault conditions" may arise from failures which are of negligible probability on case of an internal initiator PSA.
- Multiple failures with simultaneous occurrence must be considered in the case of a seismic initiator because of its potential to generate common cause failures.
- References in which the detailed procedure is described:
  - US-NUREG/CR-2300
  - US-NUREG/CR-2815
  - US-NUREG/CR-2015
  - US-NUREG/CR-1150 . . . .

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4 – SEISMIC HAZARD

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4. Seismic hazard

- The 1st step of a seismic PSA is the quantification of the seismic hazard.
- The final output of the seismic hazard study is:
  - Hazard curve, i.e. frequency of the vibratory ground motion parameter (usually, acceleration)
  - Response spectrum in the free field.
- This seismic input is derived using a probabilistic methodology, dealing with randomness and uncertainties, (i.e. the PSHA).
- The procedure is described in IAEA Safety Guide NS-G-3.3 and a short overview is shown in the following graph.

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Flow chart of a PSHA

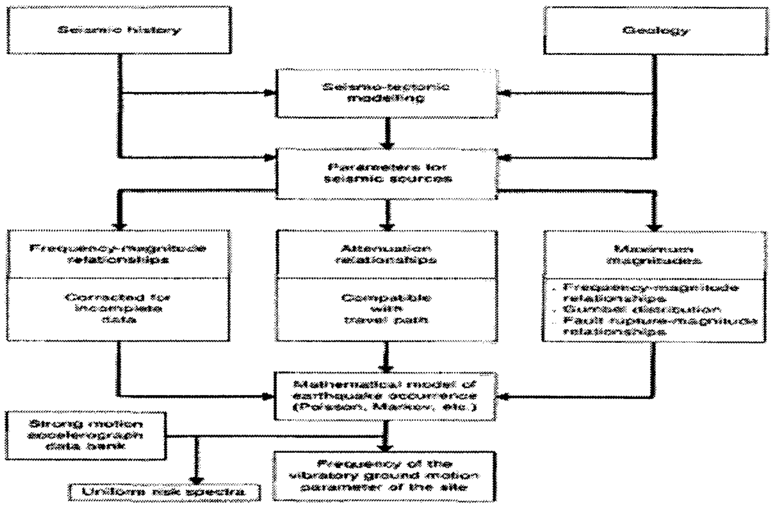

FIG. 3. Flow chart of PSHA.

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Analytical task flow of a PSHA

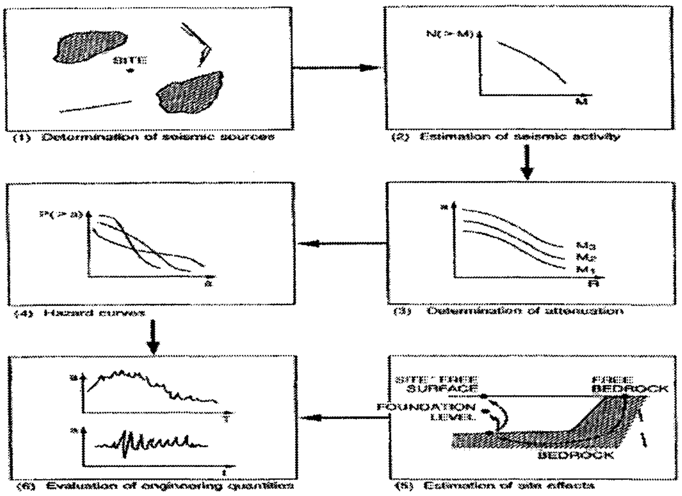

FIG. 4. Analytical task flow of PSHA.

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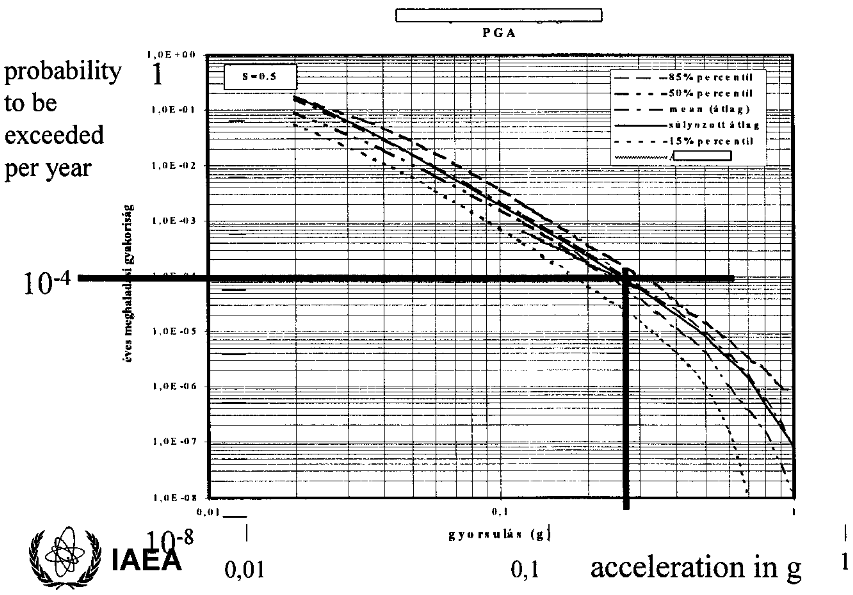
Example of a seismic hazard curve



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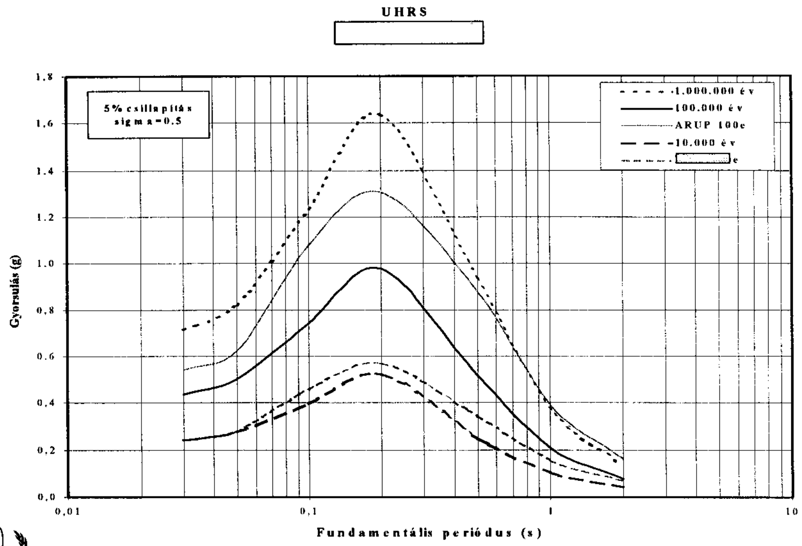
Example of a Uniform Hazard Response Spectra



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4. Uncertainties in the PSHA

The main contributors to the uncertainties of the hazard curve are:

- Boundaries of the seismogenic structures and provinces;
- Geometrical parameters of seismic sources;
- Specification of the seismic activity of the sources;
- Choice of attenuation relationships;
- Choice of stochastic model;
- Other: calculation of magnitude from intensity and transformation into acceleration.

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4. PSHA and Engineering Quantities

- Any hazard curve must ultimately be translated into engineering quantities.
- The main problem is that hazard curves are defined in terms of a single parameter, i.e. pga or intensity.
- Structural Engineers require a response spectra or a set of time histories.
- Influence of duration and/or frequency content of the ground motion have to be added.
- Hazard curves give the probability of exceedance of pga in the free field or in a hypothetical outcrop. Influence of local geological conditions –site effect- are not usually included.

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4. Seismic hazard – range of frequencies

- The seismic hazard should be discretized into a number of intervals, to quantify the probability of each accident sequence at the upper bound of these intervals, e.g.:
  - 0.10 – 0.25g
  - 0.26 – 0.50g
  - 0.51 – 0.75g
  - 0.76 – 1.00g
- The upper limit is chosen so as to be certain that no significant contribution to the assessed probability of core damage is omitted.
- The probability of each accident sequence would be quantified at the upper bound of each of these intervals
- A sufficient range of of earthquakes has been examined if the assessed probabilities reached a maximum within the range of levels considered and decrease as one moves to either extreme.

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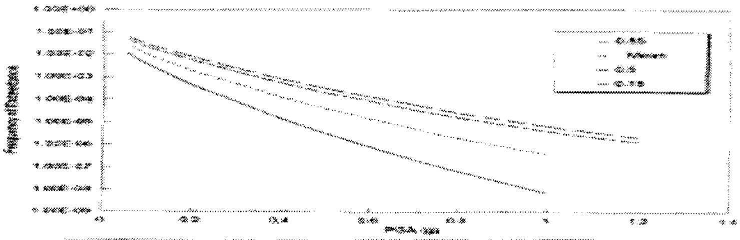
Seismic PSA results



PGA (g's)	ANNUAL EXCEEDANCE PROBABILITIES FOR MEAN, 15th, 50th, AND 85th PERCENTILES			
	0.15	0.5	Mean	0.85
0.05	3.13E-02	1.54E-02	1.64E-02	2.12E-02
0.1	3.36E-03	3.81E-03	6.90E-03	1.03E-02
0.2	4.10E-04	1.36E-03	1.97E-03	3.60E-03
0.3	7.80E-05	3.89E-04	6.73E-04	1.25E-03
0.4	1.40E-05	1.20E-04	3.55E-04	4.50E-04
0.5	2.20E-06	2.59E-05	1.07E-04	1.60E-04
0.6	7.40E-07	1.30E-05	4.70E-05	7.10E-05
0.7	2.16E-07	5.00E-06	2.54E-05	3.04E-05
0.8	6.40E-08	1.90E-06	1.00E-05	1.46E-05
1.0	7.14E-09	3.70E-07	2.59E-06	3.70E-06
1.2			8.20E-07	1.30E-06

FIGURE 1.A.2-2 : Seismic Hazard Analysis Curves

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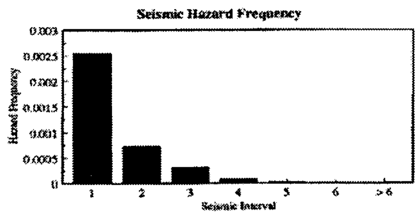
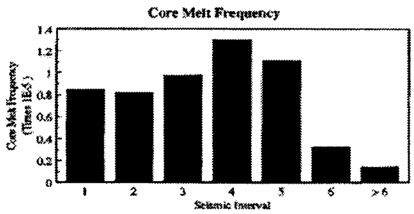
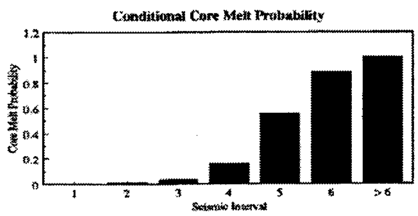
Seismic PSA results

FIGURE 1.A.2-14 : Quantification Results Summary







	Haz Freq.	Cond Core Melt	Core Melt Freq.
Int 1	2.54E-3	3.311E-3	8.433E-6
Int 2	7.32E-4	1.100E-2	8.111E-6
Int 3	3.11E-4	3.133E-2	9.766E-6
Int 4	8.20E-5	1.588E-1	1.300E-5
Int 5	2.00E-5	5.533E-1	1.100E-5
Int 6	3.60E-6	8.855E-1	3.188E-6
> 6	1.40E-6	1.000E+0	1.400E-6
Total			5.500E-5

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5 – SECONDARY SEISMIC EFFECTS

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5. Secondary Seismic Effects

- **PSAs include seismic loads directly generated by the vibratory ground motion of the earthquake.**
- **However, there a number of other secondary effects which may appear as consequence of earthquakes and lead to accident conditions:**
  - ***Systems* interactions;**
    - ***Spatial* interactions: falling, hammering, spray, internal flooding.**
    - ***Systematic* interactions: function failure of a non-safety component that may affect a safety system (earlier NPPs)**
  - ***Fire* interactions;**
  - ***Flooding.***

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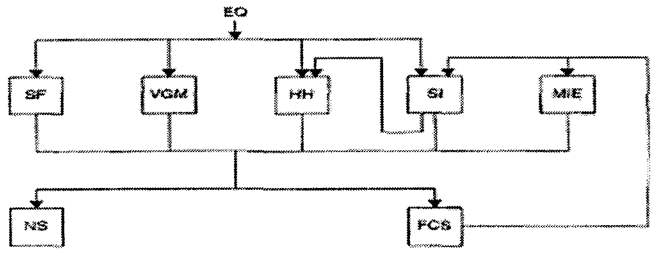
5. Secondary Seismic Effects - Other Pathways



EQ: Earthquake
VGM: Vibratory ground motion
SF: Surface faulting
HH: Hydrological hazards: Tsunami, Seiche
SI: Soil instabilities: Liquefaction, slope instability, subsidence, collapse
MIE: Man-induced events: Flood, fire, drifting cloud, explosion
FCS: Failure of conventional structures (dams, pipelines, storage facilities for explosive material)
NS: Nuclear structures (containment, reactor building, buildings neighbouring reactor, power lines, switchyard, water intake structures, ultimate heat sink, diesel generator building, fuel storage facility).

Hazards considered for NS: Fire, explosion, flood, settlement, uplift, loss of bearing capacity, overturning, tilting, sliding, foundation rupture, impact due to collapse of other structures, drawdown.

FIG. 3. Block diagram for pathways.

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5. Secondary Seismic Effects - Examples of scenarios

TABLE I. EXAMPLES OF SCENARIOS FOR OTHER SEISMIC SECONDARY EFFECTS

SECONDARY SEISMIC EFFECT	CONSEQUENTIAL EFFECTS
1A. Soil liquefaction under NPP structures	Severe structural damage leading to core damage
1B. Soil liquefaction not under NPP structures	Loss of off-site power Loss of cooling water Worsened access
2. Slope instability, subsidence or ground collapse	Direct damage to NPP structures Blockage of river causing flood Damage to water retaining structures
3. Surface faulting	Direct damage to NPP structures Loss of ultimate heat sink
4. Structural damage to power lines, switchyards, etc.	Loss of off-site power
5. Tsunami, seiche or dam failure	Flooding of safety related items Damage to power lines, etc. — loss of off-site power Damage to NPP structures
6. Damage to pipelines or hazardous storage	Fire Explosion Toxic effects Missiles

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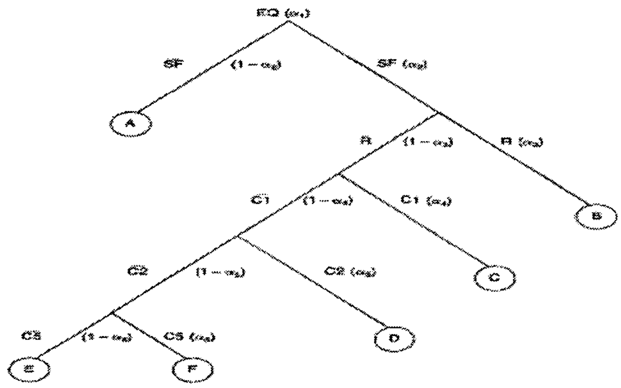
5. Secondary Seismic Effects - Event tree for surface faulting



α_1: annual probability of an earthquake of $M \geq M^*$ in the site vicinity
α_2: probability of surface faulting SF
α_3: probability of SF intersecting the reactor building R
α_4: probability of SF intersecting other category 1 structures C1
α_5: probability of SF intersecting category 2 structures C2
α_6: probability of SF intersecting conventional structures C5

FIG. 6. Event tree for surface faulting.

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6 – PLANT RESPONSE ANALYSIS AND FRAGILITIES

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6. Plant Response Analysis

- It is the analysis of the full spectrum of possible undesirable plant responses in case of occurrence of an earthquake.
- The first task is to determine the response of structures, systems and components to the seismic input.
- For that purposes, plant specific information should be obtained, either (a) scaling existing design information or (b) conducting selective new response analysis.
- The definition of the earthquake induced failure mode for each item should be included.

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6. Plant Response Analysis

- As a simplifying measure it is important to focus attention, initially only on the apparently most vulnerable plant items e.g.:
  - Off-site power insulators
  - 100 kv feeder
  - Condenser
  - 600/208 V transformer
  - Auxiliary building: masonry walls
  - Station and auxiliary transformers
  - Reactor vessel internals
  - . . . .etc.

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6. Plant Response Analysis

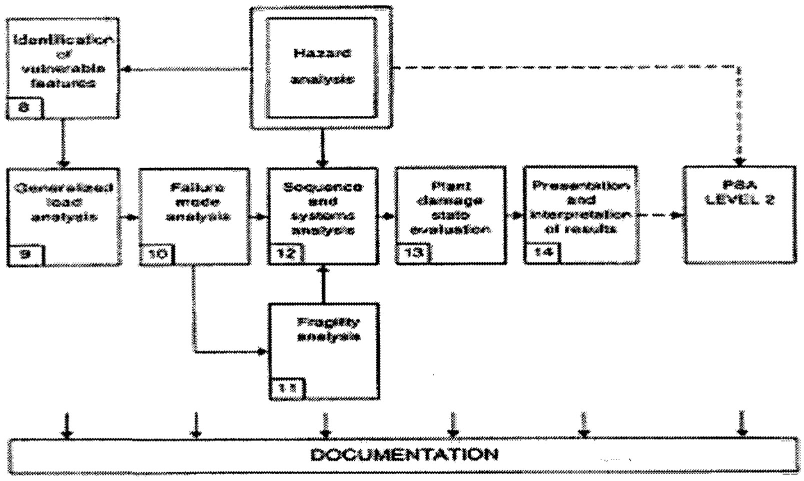

FIG. 4. Plant response analysis.

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Response and fragility curves

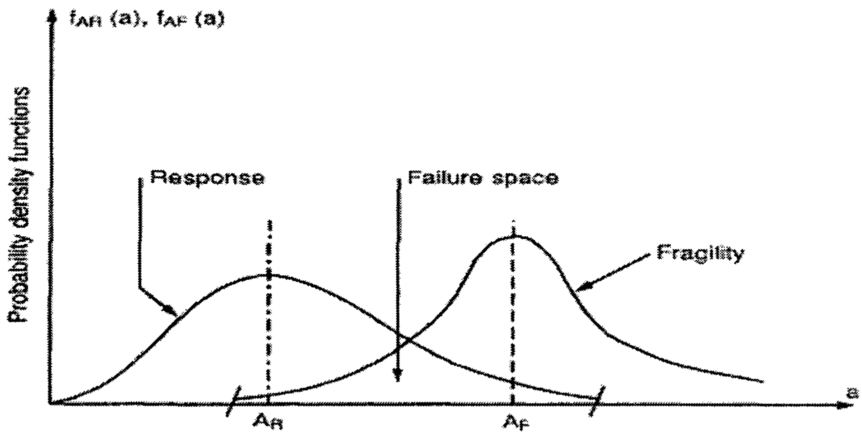

FIG. 2. Combinations of response and fragility values leading to failure.

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6. Fragility

- The **seismic fragility** of a component or system is defined by a curve that gives:
  - the **conditional probability of failure,**
  - for a given number of a **seismic input motion parameter**, e.g. the pga.
- The **input motion** can be defined at :
  - the structure/component interface (support location), or at
  - the base of the supporting structure (ground level).

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6. Fragility

- There are many sources of variability (randomness and uncertainties) in developing a component fragility, in both, *response* and *capacity* evaluation, e.g.:
  - Peak to peak variation in input motion,
  - Phasing of earthquakes components,
  - Phasing of modal responses,
  - Vertical/horizontal acceleration ratios,
  - Soil stiffness,
  - Soil damping,
  - Structural stiffness,
  - Soil-structure interaction
  - Material strength....... etc.
- An entire fragility family to a particular failure mode should be developed and it can be expressed as the best estimate of the median input motion parameter and 2 random variables:
  - $A = Am \cdot \varepsilon_R \cdot \varepsilon_U$

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Fragility curve representations

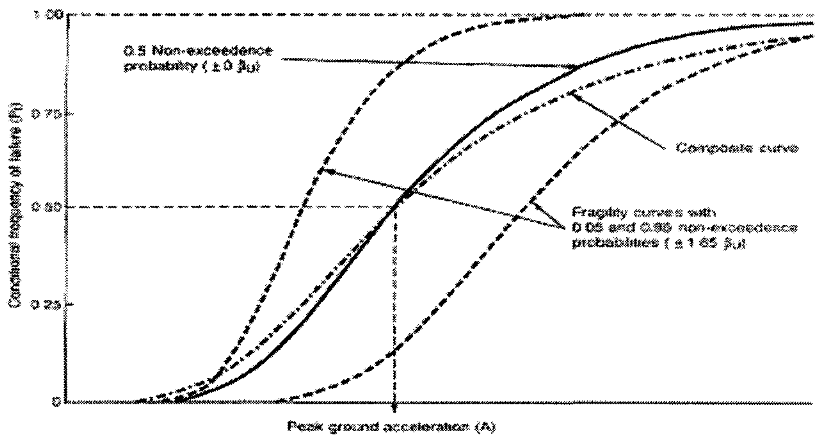

FIG. 8. Fragility curve representations.

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Flow chart for seismic fragility development

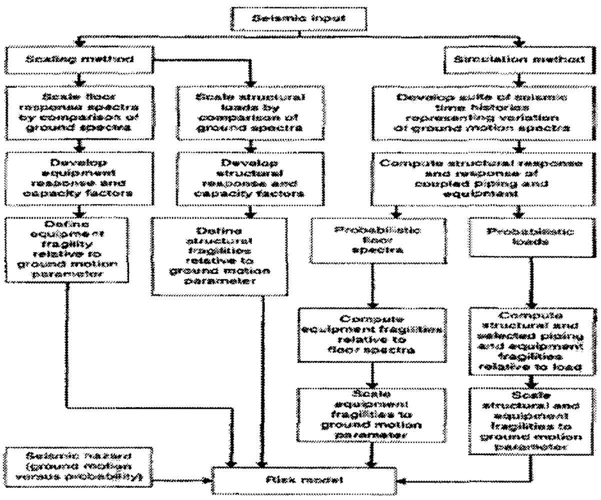

FIG. 7. Flow chart for seismic fragility development.

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7 – SYSTEMS ANALYSIS AND SAFETY EVALUATION

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7. Systems analysis and safety evaluation

The major steps for accomplishing a Seismic PSA are:

1. Development of a seismic hazard curve;
2. Structure and component seismic response determination;
3. Assessment of structure and component fragility;
4. Random failure data development;
5. Event/fault tree construction and solution;
6. Risk quantification incorporating results of steps 1) to 5)

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7. Systems analysis and safety evaluation

1. **Accident sequence definition/event trees:**
   - Initiated plant states
   - Facility functional response
2. **Systems analysis and fault tree development:**
   - Safety system failure criteria
   - Fault tree development

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8 – RESULTS OF SEISMIC PSA

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8. Interpretation of Seismic PSA results

- The results of a Level 1 seismic PSA consists of the "*frequency of occurrence of core damage in case of earthquakes*".
- The information is synthesized into a central value (median or mean) and two fractile values (lower and upper) defining a range of frequencies within 90% of the frequency contained.
- The central value can be roughly thought to reflect the contribution to the risk due to *intrinsic randomness*, while the confidence interval gives the *measure of the uncertainty* involved in the process.

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Example of Seismic PSA results

	Probability of core melt			
	5th	Median	95th	Mean
Case NPP A				
(*) LLNL	3.92E-7	1.48E-5	4.38E-4	1.16E-4
(*) EPRI	3.00E-7	6.12E-6	1.03E-4	2.50E-5
Fire	2.20E-6	8.32E-6	3.08E-5	1.13E-5
Internal	6.80E-6	2.30E-5	1.30E-4	4.10E-5
Case NPP B				
(*) LLNL	5.33E-8	4.41E-6	2.72E-4	7.66E-5
(*) EPRI	2.30E-8	7.07E-7	1.27E-5	3.09E-6
Fire	1.09E-6	1.16E-5	6.37E-5	1.96E-5
Internal	3.50E-7	1.90E-6	1.30E-5	4.50E-6

(*) Seismic PSA.

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8. Interpretation of Seismic PSA results

- Results of a seismic PSA are typically compared to results from internal events and other external events (e.g. fire).
- It is an IAEA requirement that the *radiological risk associated with external events* should not exceed the range of *radiological risk associated with the accidents of internal origin*.
- When this comparison is made by a PSA requires a Level 3 analysis.
- When comparing Level 1 results, the comparisons may be misleading due to the fact that the uncertainty in the seismic induced core damage frequency may be much greater than for internal events or other external events.
- The analyst must be objective in his evaluation of the results and actions that he may recommend for improving plant safety.

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Interpretation of Seismic PSA results

TABLE II. CONTRIBUTION OF INITIATING EVENTS TO MEAN ANNUAL CORE MELT FREQUENCY FOR PUBLISHED PSAS WITH COMPLETE SEISMIC ANALYSIS

Plant	Date	Contribution (%)					
		Seismic	Internal	Fire	Wind	External	Mean annual core melt frequency
Zion	1981	8	85	7	-	-	6.7×10^{-5}
IP2	1983	6	58	10	26	-	1.4×10^{-4}
IP3	1983	2	88	9	1	-	1.4×10^{-4}
Seabrook	1983	13	75	11	-	1	2.3×10^{-4}
Limerick	1983	13	34	53	-	-	4.4×10^{-5}
Millstone 3	1984	15	77	8		-	5.9×10^{-5}
Oconee 3	1984	25	56	4	5	10	2.5×10^{-5}

Notes:
- Contribution to core melt is not necessarily indicative of public health risk contribution.
- Seismic events that initiate core melt accident sequences are generally more likely to also cause damage to containment than other initiating event.
- Comparison of median (rather than mean) seismic risk to median core melt frequency would indicate in most (but not all) cases lower seismic contribution.

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Interpretation of Seismic PSA results

- A warning! :

  In case of the seismic re-evaluation, and consequently possible upgrading, of an operating existing NPP, for a newly defined seismic input exceeding the original design basis . . .

  . . . special care should be taken on the decision about the opportunity to conduct a Seismic PSA and the real physical actions for improving plant safety . Easy to perform fixes can be more cost-efficient and safety-effective, as well they will also have influence on the fragilities of the plant systems and items, on the basis of which the results of the seismic PSA are obtained.

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Interpretation of Seismic PSA results

Another warning! :

- The output of a PSHA can never be better than its input, or
- *"the output of a PSHA is only as good as its input. To improve the value and credibility of PSHA, one must improve the quality and increase the quantity of earth science information related to seismic hazards..."* (*)

(*) Panel on Seismic Hazard Analysis – PSH Analysis – US National Research Council, 1988.

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THANK YOU VERY MUCH

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

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1 – INTRODUCTION

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1. Introduction – Background

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- In some cases, the risk caused by earthquakes has been found to be comparable with the risk caused by internally initiated events.

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- Resolution of existing seismic issues;
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- Development of a risk management program;
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- Assessment of an existing plant safety for a newly defined seismic input exceeding the original design basis
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- The general methodology is applicable to all of the potential applications.
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1. Introduction –Seismic PSA Results

- For Level 1 PSA. Potential releases and off-site consequences are not included.
- The main result is to provide an order of magnitude of the frequency of core damage associated with earthquakes, which might contribute to the total frequency of core damage.
- A number of beneficial side effects:
  - Consideration of different spectral shapes;
  - Alternative hypotheses regarding soil properties, structural models, material characteristics, etc.
  - All leading to a weighted sensitivity analysis, as a way to detect the weaker links in the chains going to undesired events.

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Probabilistic Safety Assessment for Seismic Events

2 – PURPOSE AND SCOPE OF THE DOCUMENT

IAEA-TECDOC-724

Published in October 1993.

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2. Purpose and scope of the TECDOC

- **To provide information and guidance to those starting a seismic PSA, giving a overall picture of the usually applied procedure.**
- **It covers mainly:**
  - **Frequency of occurrence of ground motions, i.e. the seismic hazard evaluation;**
  - **Seismic accident sequence initiators;**
  - **Fragility analysis of safety related plant items;**
  - **Capability of systems to mitigate accidents from seismic events;**
  - **Integration of all above aspects which can lead to core damage.**

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2. Purpose and scope of the TECDOC

- It does not cover the effects of earthquakes after the event of core damage.
- Aspects that may have significant contribution to the overall risk and have not been considered in the document are:
  - Increased probability of human errors, subsequent to the occurrence of a destructive earthquake;
  - Significant probability of damages to lifelines and other infrastructures which may have been planned for use in the context of emergency planning and evacuation.
  - Increased probability of delayed response to the nuclear accident due to the interference of another catastrophic event.

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2. Purpose and scope of the TECDOC

- An "internal" initiator
  - is an event in the plant itself which may affect or have consequences on the "exterior"
- An "external" initiator as an earthquake, or other natural events of regional scale,
  - is an event that affects also and simultaneously the "exterior" of the plant, i.e. the region and the public, who may receive on the top of that the consequences of a nuclear accident;
  - affects passive safety systems;
  - may lead to common cause failures, affecting redundancy;
  - is a cause of interactions between items.

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3 – OVERVIEW OF SEISMIC PSA PROCEDURE

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3. Overview of a seismic PSA procedure

- The major steps for accomplishing a Seismic PSA are:
  1. Development of a seismic hazard curve;
  2. Structure and component seismic response determination;
  3. Assessment of structure and component fragility;
  4. Random failure data development;
  5. Event/fault tree construction and solution;
  6. Risk quantification incorporating results of steps 1) to 5)

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Overview of a seismic PSA

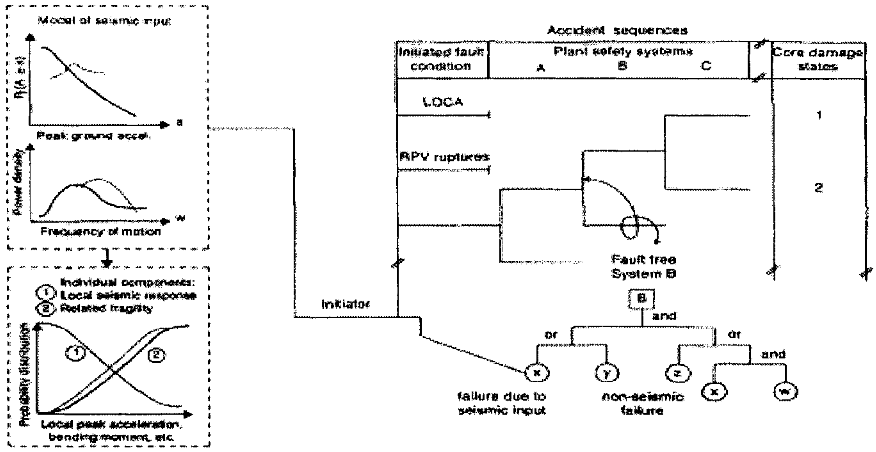

FIG. 1. Schematic overview of a seismic PSA.

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3. Overview of Seismic PSA Procedure

- *Seismic hazard* (i.e. the seismic input), and the
- *Seismic fragilities and response* of individual plant items (i.e. components, systems and structures) . . .

  . . . . . . are combined to provide an estimate of the probability of various plant damage states
- The seismic hazard is the initiator of the accident sequences.
- The accident sequences are developed from an initiated fault condition (e.g. ATWS, LOCA) produced directly by the earthquake ground motion.

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3. Overview of Seismic PSA Procedure

- Attention is called to the possibility that the "initiated fault conditions" may arise from failures which are of negligible probability on case of an internal initiator PSA.
- Multiple failures with simultaneous occurrence must be considered in the case of a seismic initiator because of its potential to generate common cause failures.
- References in which the detailed procedure is described:
  - US-NUREG/CR-2300
  - US-NUREG/CR-2815
  - US-NUREG/CR-2015
  - US-NUREG/CR-1150 . . . .

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4 – SEISMIC HAZARD

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4. Seismic hazard

- The 1st step of a seismic PSA is the quantification of the seismic hazard.
- The final output of the seismic hazard study is:
  - Hazard curve, i.e. frequency of the vibratory ground motion parameter (usually, acceleration)
  - Response spectrum in the free field.
- This seismic input is derived using a probabilistic methodology, dealing with randomness and uncertainties, (i.e. the PSHA).
- The procedure is described in IAEA Safety Guide NS-G-3.3 and a short overview is shown in the following graph.

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Flow chart of a PSHA

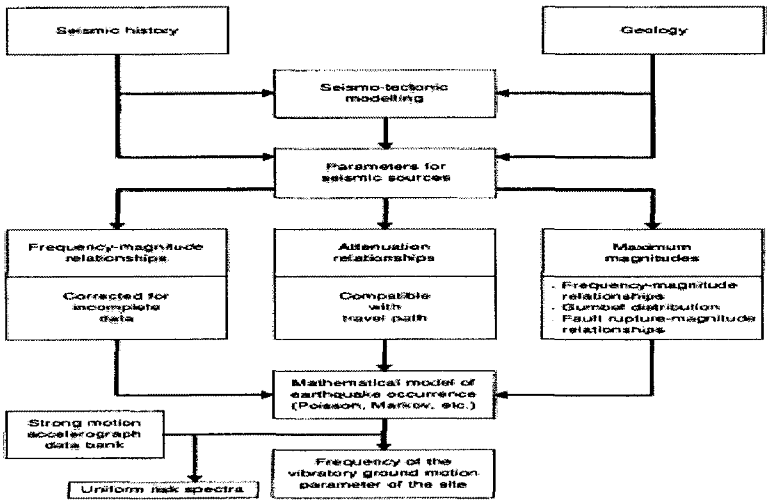

FIG. 3. Flow chart of PSHA.

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Analytical task flow of a PSHA

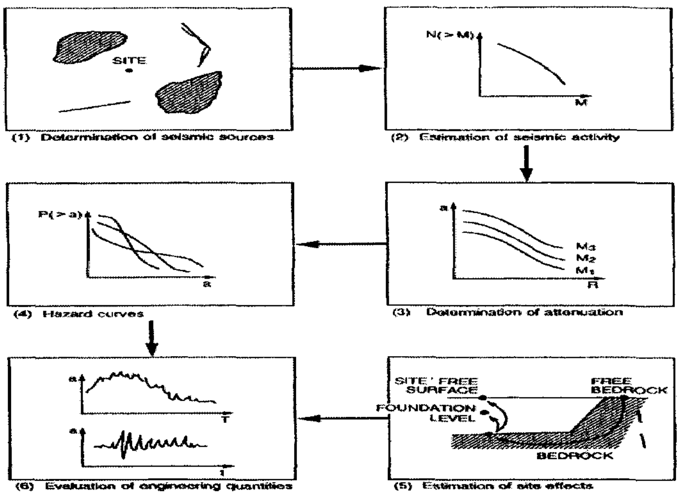

FIG. 4. Analytical task flow of PSHA.

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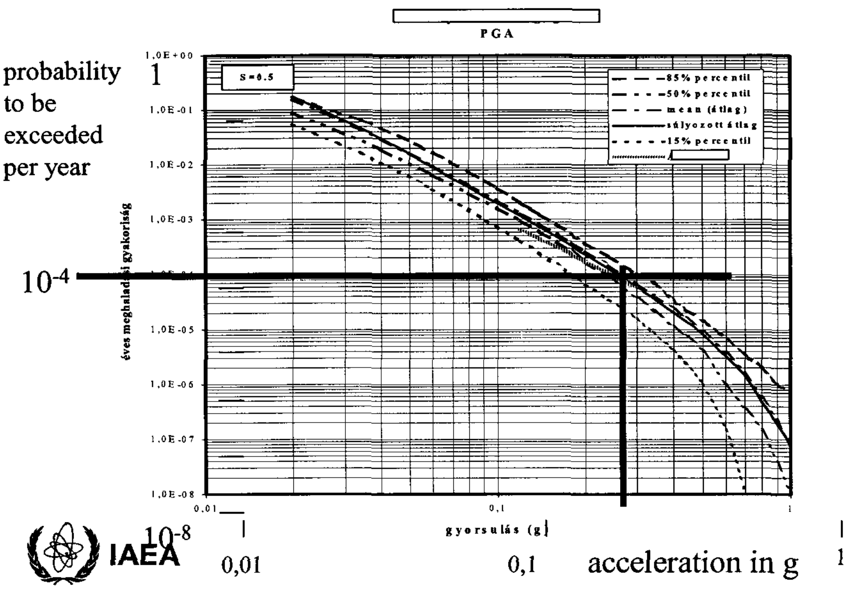
Example of a seismic hazard curve



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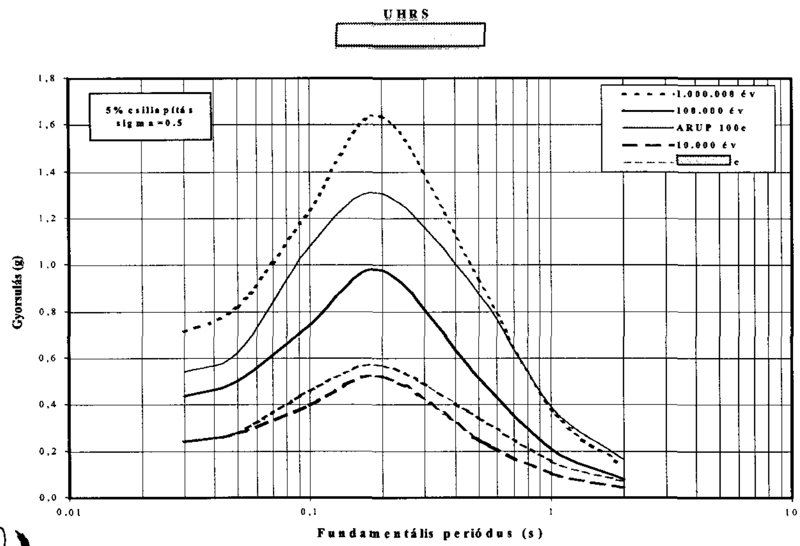
Example of a Uniform Hazard Response Spectra



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4. Uncertainties in the PSHA

The main contributors to the uncertainties of the hazard curve are:

- Boundaries of the seismogenic structures and provinces;
- Geometrical parameters of seismic sources;
- Specification of the seismic activity of the sources;
- Choice of attenuation relationships;
- Choice of stochastic model;
- Other: calculation of magnitude from intensity and transformation into acceleration.

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4. PSHA and Engineering Quantities

- Any hazard curve must ultimately be translated into engineering quantities.
- The main problem is that hazard curves are defined in terms of a single parameter, i.e. pga or intensity.
- Structural Engineers require a response spectra or a set of time histories.
- Influence of duration and/or frequency content of the ground motion have to be added.
- Hazard curves give the probability of exceedance of pga in the free field or in a hypothetical outcrop. Influence of local geological conditions –site effect- are not usually included.

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4. Seismic hazard – range of frequencies

- The seismic hazard should be discretized into a number of intervals, to quantify the probability of each accident sequence at the upper bound of these intervals, e.g.:
  - 0.10 – 0.25g
  - 0.26 – 0.50g
  - 0.51 – 0.75g
  - 0.76 – 1.00g
- The upper limit is chosen so as to be certain that no significant contribution to the assessed probability of core damage is omitted.
- The probability of each accident sequence would be quantified at the upper bound of each of these intervals
- A sufficient range of of earthquakes has been examined if the assessed probabilities reached a maximum within the range of levels considered and decrease as one moves to either extreme.

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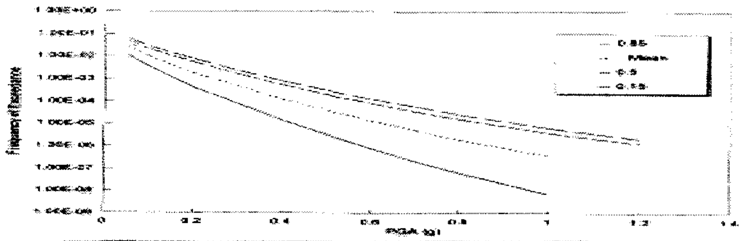
Seismic PSA results



PGA (g's)	ANNUAL EXCEEDANCE PROBABILITIES FOR MEAN, 15TH, 50TH, AND 85TH PERCENTILES			
	0.15	0.5	Mean	0.85
0.05	1.13E-02	1.54E-02	1.66E-02	2.12E-02
0.1	3.36E-03	5.81E-03	6.97E-03	1.03E-02
0.2	4.10E-04	1.34E-03	1.97E-03	3.60E-03
0.3	7.80E-05	3.80E-04	6.73E-04	1.15E-03
0.4	1.60E-05	1.10E-04	2.59E-04	4.00E-04
0.5	1.20E-05	3.50E-05	1.07E-04	1.60E-04
0.6	3.90E-07	1.30E-05	4.70E-05	7.10E-05
0.7	2.10E-07	5.00E-06	2.50E-05	3.00E-05
0.8	6.40E-08	1.30E-06	1.00E-05	1.40E-05
1.0	7.12E-09	3.70E-07	2.50E-06	3.70E-06
1.2			6.30E-07	1.30E-06

FIGURE 1.A.2-2 : Seismic Hazard Analysis Curves

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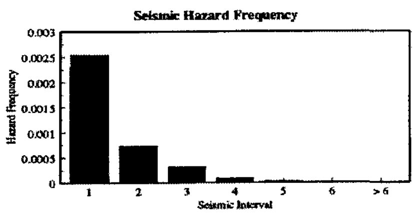
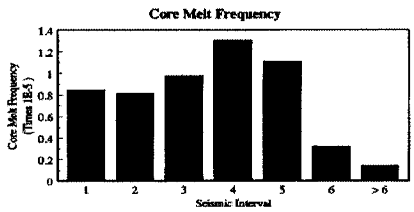
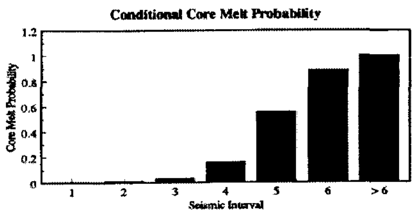
Seismic PSA results

FIGURE 1.A.2-14 : Quantification Results Summary







	Haz Freq.	Cond Core Melt	Core Melt Freq.
Int 1	2.54E-3	3.311E-3	8.433E-6
Int 2	7.32E-4	1.100E-2	8.111E-6
Int 3	3.11E-4	3.133E-2	9.766E-6
Int 4	8.20E-5	1.588E-1	1.300E-5
Int 5	2.00E-5	5.533E-1	1.100E-5
Int 6	3.60E-6	8.855E-1	3.188E-6
> 6	1.40E-6	1.000E+0	1.400E-6
Total			5.500E-5

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5 – SECONDARY SEISMIC EFFECTS

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5. Secondary Seismic Effects

- **PSAs include seismic loads directly generated by the vibratory ground motion of the earthquake.**
- **However, there a number of other secondary effects which may appear as consequence of earthquakes and lead to accident conditions:**
  - ***Systems* interactions;**
    - ***Spatial* interactions: falling, hammering, spray, internal flooding.**
    - ***Systematic* interactions: function failure of a non-safety component that may affect a safety system (earlier NPPs)**
  - ***Fire* interactions;**
  - ***Flooding.***

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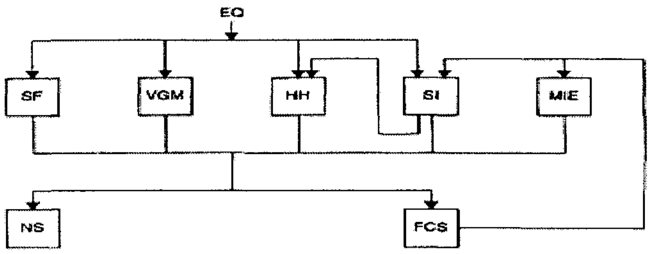
5. Secondary Seismic Effects - Other Pathways



EQ: Earthquake
VGM: Vibratory ground motion
SF: Surface faulting
HH: Hydrological hazards: Taunami, Seiche
SI: Soil instabilities: Liquefaction, slope instability, subsidence, collapse
MIE: Man-induced events: Flood, fire, drifting cloud, explosion
FCS: Failure of conventional structures (dams, pipelines, storage facilities for explosive material)
NS: Nuclear structures (containment, reactor building, buildings neighbouring reactor, power lines, switchyard, water intake structures, ultimate heat sink, diesel generator building, fuel storage facility).

Hazards considered for NS: Fire, explosion, flood, settlement, uplift, loss of bearing capacity, overturning, tilting, sliding, foundation rupture, impact due to collapse of other structures, drawdown.

FIG. 5. Block diagram for pathways.

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5. Secondary Seismic Effects - Examples of scenarios

TABLE I. EXAMPLES OF SCENARIOS FOR OTHER SEISMIC SECONDARY EFFECTS

SECONDARY SEISMIC EFFECT	CONSEQUENTIAL EFFECTS
1A. Soil liquefaction under NPP structures	Severe structural damage leading to core damage
1B. Soil liquefaction not under NPP structures	Loss of off-site power Loss of cooling water Worsened access
2. Slope instability, subsidence or ground collapse	Direct damage to NPP structures Blockage of river causing flood Damage to water retaining structures
3. Surface faulting	Direct damage to NPP structures Loss of ultimate heat sink
4. Structural damage to power lines, switchyards, etc.	Loss of off-site power
5. Tsunami, seiche or dam failure	Flooding of safety related items Damage to power lines, etc. — loss of off-site power Damage to NPP structures
6. Damage to pipelines or hazardous storage	Fire Explosion Toxic effects Missiles

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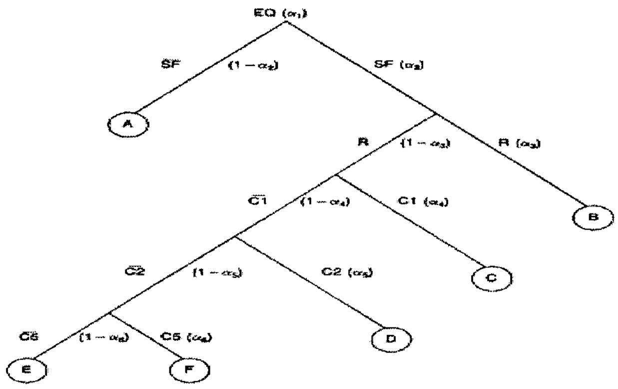
5. Secondary Seismic Effects - Event tree for surface faulting



α_1: annual probability of an earthquake of $M \geq M^*$ in the site vicinity
α_2: probability of surface faulting SF
α_3: probability of SF intersecting the reactor building R
α_4: probability of SF intersecting other category 1 structures C1
α_5: probability of SF intersecting category 2 structures C2
α_6: probability of SF intersecting conventional structures C5

FIG. 6. Event tree for surface faulting.

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6 – PLANT RESPONSE ANALYSIS AND FRAGILITIES

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6. Plant Response Analysis

- It is the analysis of the full spectrum of possible undesirable plant responses in case of occurrence of an earthquake.
- The first task is to determine the response of structures, systems and components to the seismic input.
- For that purposes, plant specific information should be obtained, either (a) scaling existing design information or (b) conducting selective new response analysis.
- The definition of the earthquake induced failure mode for each item should be included.

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6. Plant Response Analysis

- As a simplifying measure it is important to focus attention, initially only on the apparently most vulnerable plant items e.g.:
  - Off-site power insulators
  - 100 kv feeder
  - Condenser
  - 600/208 V transformer
  - Auxiliary building: masonry walls
  - Station and auxiliary transformers
  - Reactor vessel internals
  - . . . .etc.

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6. Plant Response Analysis

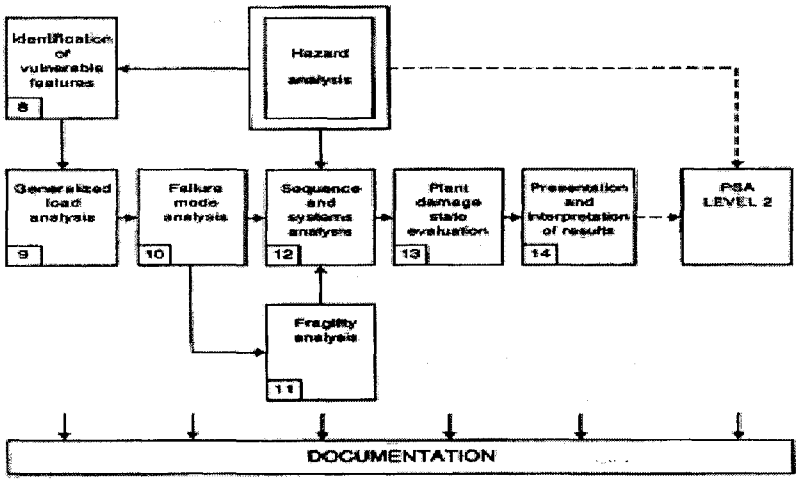

FIG. 4. Plant response analysis.

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Response and fragility curves

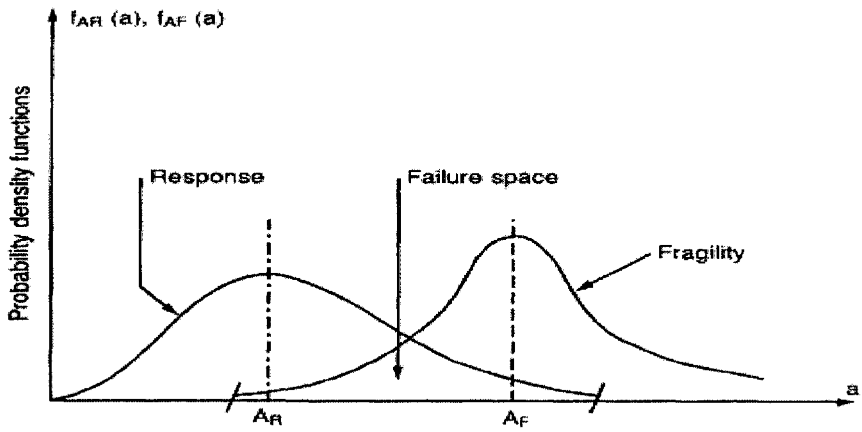

FIG. 2. Combinations of response and fragility values leading to failure.

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6. Fragility

- The **seismic fragility** of a component or system is defined by a curve that gives:
  - the **conditional probability of failure,**
  - for a given number of a **seismic input motion parameter**, e.g. the pga.
- The **input motion** can be defined at :
  - the structure/component interface (support location), or at
  - the base of the supporting structure (ground level).

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6. Fragility

- There are many sources of variability (randomness and uncertainties) in developing a component fragility, in both, *response* and *capacity* evaluation, e.g.:
  - Peak to peak variation in input motion,
  - Phasing of earthquakes components,
  - Phasing of modal responses,
  - Vertical/horizontal acceleration ratios,
  - Soil stiffness,
  - Soil damping,
  - Structural stiffness,
  - Soil-structure interaction
  - Material strength....... etc.
- An entire fragility family to a particular failure mode should be developed and it can be expressed as the best estimate of the median input motion parameter and 2 random variables:
  - $A = Am \, . \, e_R \, . \, e_U$

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Fragility curve representations

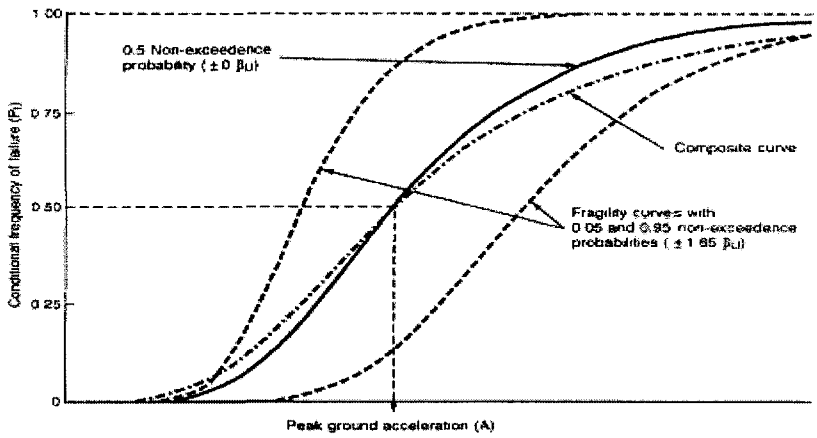

FIG. 8 Fragility curve representations.

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Flow chart for seismic fragility development

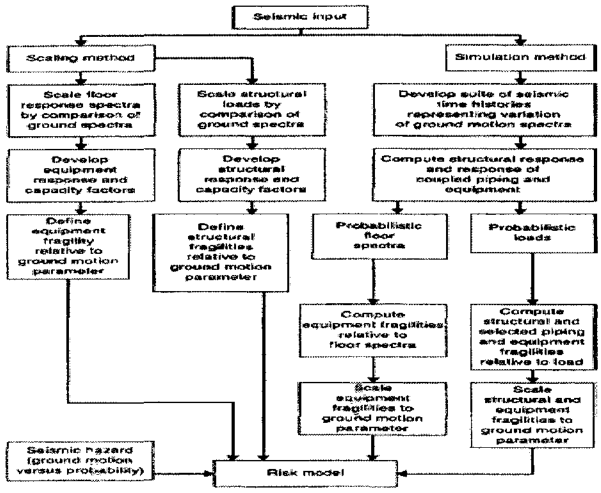

FIG. 7. Flow chart for seismic fragility development.

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7 – SYSTEMS ANALYSIS AND SAFETY EVALUATION

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7. Systems analysis and safety evaluation

The major steps for accomplishing a Seismic PSA are:

1. Development of a seismic hazard curve;
2. Structure and component seismic response determination;
3. Assessment of structure and component fragility;
4. Random failure data development;
5. Event/fault tree construction and solution;
6. Risk quantification incorporating results of steps 1) to 5)

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7. Systems analysis and safety evaluation

1. **Accident sequence definition/event trees:**
   - Initiated plant states
   - Facility functional response
2. **Systems analysis and fault tree development:**
   - Safety system failure criteria
   - Fault tree development

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8 – RESULTS OF SEISMIC PSA

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8. Interpretation of Seismic PSA results

- The results of a Level 1 seismic PSA consists of the "*frequency of occurrence of core damage in case of earthquakes*".
- The information is synthesized into a central value (median or mean) and two fractile values (lower and upper) defining a range of frequencies within 90% of the frequency contained.
- The central value can be roughly thought to reflect the contribution to the risk due to *intrinsic randomness*, while the confidence interval gives the *measure of the uncertainty* involved in the process.

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Example of Seismic PSA results

	Probability of core melt			
	5th	Median	95th	Mean
Case NPP A				
(*) LLNL	3.92E-7	1.48E-5	4.38E-4	1.16E-4
(*) EPRI	3.00E-7	6.12E-6	1.03E-4	2.50E-5
Fire	2.20E-6	8.32E-6	3.08E-5	1.13E-5
Internal	6.80E-6	2.30E-5	1.30E-4	4.10E-5
Case NPP B				
(*) LLNL	5.33E-8	4.41E-6	2.72E-4	7.66E-5
(*) EPRI	2.30E-8	7.07E-7	1.27E-5	3.09E-6
Fire	1.09E-6	1.16E-5	6.37E-5	1.96E-5
Internal	3.50E-7	1.90E-6	1.30E-5	4.50E-6

(*) Seismic PSA.

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8. Interpretation of Seismic PSA results

- Results of a seismic PSA are typically compared to results from internal events and other external events (e.g. fire).
- It is an IAEA requirement that the *radiological risk associated with external events* should not exceed the range of *radiological risk associated with the accidents of internal origin.*
- When this comparison is made by a PSA requires a Level 3 analysis.
- When comparing Level 1 results, the comparisons may be misleading due to the fact that the uncertainty in the seismic induced core damage frequency may be much greater than for internal events or other external events.
- The analyst must be objective in his evaluation of the results and actions that he may recommend for improving plant safety.

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Interpretation of Seismic PSA results

TABLE II. CONTRIBUTION OF INITIATING EVENTS TO MEAN ANNUAL CORE MELT FREQUENCY FOR PUBLISHED PSAS WITH COMPLETE SEISMIC ANALYSIS

Plant	Date	Contribution (%)					
		Seismic	Internal	Fire	Wind	External	Mean annual core melt frequency
Zion	1981	8	85	7	-	-	6.7×10^{-5}
IP2	1983	6	58	10	26	-	1.4×10^{-4}
IP3	1983	2	88	9	1	-	1.4×10^{-4}
Seabrook	1983	13	75	11	-	1	2.3×10^{-4}
Limerick	1983	13	34	53	-	-	4.4×10^{-5}
Millstone 3	1984	15	77	8		-	5.9×10^{-5}
Oconee 3	1984	25	56	4	5	10	2.5×10^{-5}

Notes:
- Contribution to core melt is not necessarily indicative of public health risk contribution.
- Seismic events that initiate core melt accident sequences are generally more likely to also cause damage to containment than other initiating event.
- Comparison of median (rather than mean) seismic risk to median core melt frequency would indicate in most (but not all) cases lower seismic contribution.

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Interpretation of Seismic PSA results

- A warning! :

  In case of the seismic re-evaluation, and consequently possible upgrading, of an operating existing NPP, for a newly defined seismic input exceeding the original design basis . . .

  . . . special care should be taken on the decision about the opportunity to conduct a Seismic PSA and the real physical actions for improving plant safety . Easy to perform fixes can be more cost-efficient and safety-effective, as well they will also have influence on the fragilities of the plant systems and items, on the basis of which the results of the seismic PSA are obtained.

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Interpretation of Seismic PSA results

Another warning! :

- The output of a PSHA can never be better than its input, or
- "*the output of a PSHA is only as good as its input. To improve the value and credibility of PSHA, one must* ***improve the quality*** *and* ***increase the quantity*** *of earth science information related to seismic hazards...*" (*)

(*) Panel on Seismic Hazard Analysis – PSH Analysis – US National Research Council, 1988.

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