20th International Conference on Structural Mechanics in Reactor Technology (SMiRT 20)
Espoo, Finland, August 9-14, 2009
SMiRT 20-Division 7, Paper 2566

Experience from a Seismic Probabilistic Safety Assessment of a German PWR

Theodor Bloem, Ralf Obenland

Westinghouse Electric Germany, D-68167 Mannheim, e-mail: bloem@westinghouse.com

Keywords: Earthquake, Probabilistic Safety Assessment, Seismic Hazard, Electrical Equipment, Mechanical Equipment, Fragility Analysis Method, Fragility Curve

1 ABSTRACT

The nuclear power plants in Germany have been subject to several deterministic seismic safety assessments. After each deterministic seismic safety assessment, components of the plant were upgraded. Additional deterministic assessments will not essentially improve the seismic resistance of the plant. In keeping with new requirement from the authority, seismic probabilistic safety assessments (seismic PSA) are to be conducted for some German nuclear power plants (BFS, 2005).

Experience from a seismic PSA of one of the latest erected German PWR will be presented. A full scale probabilistic analysis by evaluating safety products for structures, plant systems and components was performed in order to estimate the core damage frequency caused by earthquakes. Furthermore, limitations and benefits of a seismic PSA will be discussed.

2 INTRODUCTION

Nuclear power plants are designed to resist loads from an earthquake. The PWR investigated incorporated a lot of seismic experience learned from nuclear power plants erected before. Nevertheless from a probabilistic point of view there remains a risk:

- The earthquake may be stronger than the plant specific safe shutdown earthquake (SSE)
- Structures and equipment can have construction errors
- The component fails because of an unknown damage

If the SSE upon which the plant design is based corresponds to earthquake intensity $I_{EMS} > 7$, the core damage frequency induced by earthquakes has to be determined for German nuclear power plants. The full scope fragility analysis method (FA) was applied for conducting the seismic PSA. In the 1980s the procedure for performing a seismic PSA of nuclear power plants was evaluated in the USA. For safety relevant equipment accessible to analytic investigation of earthquake resistance, safety products can be evaluated. A safety product is a random variable expressing the conditional probability of failure as function of the earthquake horizontal peak ground acceleration (pga). For equipment which are not amenable to an analytic investigation of seismic ruggedness, generic High Confidence of low Probability of Failure (HCLPF) accelerations and Generic Equipment Ruggedness Spectra (GERS) are used.

In addition to the investigation on equipment strength, a plant walkdown is necessary. Thereby equipment to be more precisely checked can be separated from inherently rugged equipment. At the plant walkdown the equipment were checked according to the EPRI guidelines and to an IAEA safety report (EPRI, 1991b; IAEA, 2003).

For assessing the seismic risk, a seismic hazard curve must also be prepared by a seismologist. A seismic hazard curve gives the earthquake recurrence relationship in dependence of its intensity I_{EMS}. As stress reports use the acceleration as a measure for earthquake strength, a relation between the earthquake intensity I_{EMS} and the horizontal earthquake peak ground acceleration had to be evaluated too. Furthermore, the seismologist evaluated site specific ground motion response spectra.

By the seismic hazard curve and by safety factors of structures and equipment, the core damage frequency induced by earthquakes was determined.

3 FRAGILTY CURVE

The objective is to determine the earthquake horizontal peak ground motion acceleration A for which the seismic response of a component exceeds the component capacity resulting in its failure. By assumption, A is a log-normally distributed random variable which is the product of its median $\breve{A}$ and two normalized log-normally distributed random variables ε_R und ε_U:

$$A = \breve{A} \cdot \varepsilon_R \cdot \varepsilon_U$$

The random variable ε_R has the median 1. Its logarithmic standard deviation is denoted by β_R. The logarithmic standard deviation β_R expresses inherent randomness variability. Inherent randomness variability cannot be reduced by additional effort. The random variable ε_U also has the median 1 and its logarithmic standard deviation is denoted by β_U. The logarithmic standard deviation β_U expresses uncertainty variability caused by inadequate knowledge. The logarithmic standard deviation β_U can be reduced by additional analyses, tests or investigations.

For components and for structures, the conditional probability of failure at the non-exceedance probability level Q is expressed by

$$F_{\text{Failure}}(a,Q) = \Phi\left(\frac{\ln(a/\breve{A}) + \beta_U \cdot \Phi^{-1}(Q)}{\beta_R}\right) ,$$

where a is the horizontal peak ground acceleration and $\Phi(\cdot)$ is the standard Gaussian cumulative distribution function.

It is A_{SSE} the peak ground acceleration of the earthquake used for the plant design. The random variable A can be expressed as product of the peak ground acceleration A_{SSE} and a random variable F denoted factor of safety:

$$A = A_{\text{SSE}} \cdot F$$

Due to the random variables here being considered as log-normally distributed, a similar equation is also valid for their medians:

$$\breve{A} = A_{\text{SSE}} \cdot \breve{F}$$

The factor $\breve{F}$, the median of the factor of safety, is a measure for the ground acceleration capacity above the safe shutdown earthquake level A_{SSE} upon which the design is based.

For components accessible to determination of a seismic safety factor, fragility curves were evaluated. They give a conditional probability of failure $F_{\text{Failure}}(a,Q)$ in relation to the earthquake horizontal peak ground motion acceleration a. Fragility curves were determined for structures, pipes, core internals, buildings, cabinets, heat exchanger supports, and pump supports. For each component analyzed, fragilities for two non-exceedance probability levels Q were evaluated: The fragility curve for Q = 0.5 holds a conditional probability of failure determined with no conservatism. The fragility curve for Q = 0.95 delivers a probability of failure with 95 % probability of non-exceedance. Figure 1 shows fragility curves for a low pressure pipe with DN 600.

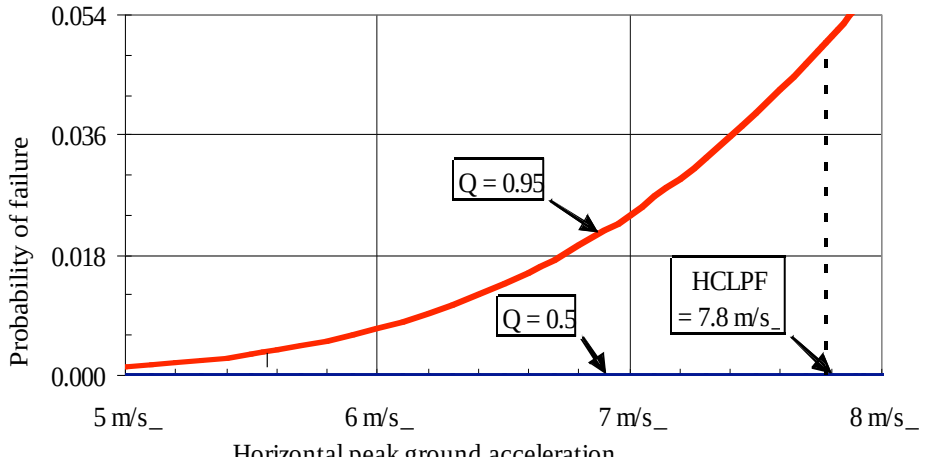

Figure 1. Low pressure pipe with DN 600, fragility curves for Q = 0.5 and Q = 0.95

At the non-exceedance probability level $Q = 0.5$, the probability of failure caused by an earthquake with horizontal peak ground acceleration $a = 7.8$ m/s² is less than 0.01 % for the pipe analyzed. At the probability level $Q = 0.95$, the probability of failure by this acceleration is 0.05. The horizontal peak ground acceleration for less than 5 % probability of failure at 95 % non-exceedance probability level is denoted by HCLPF.

Pipes are very resistant to earthquake loading because of threefold reason:
- ductile materials are used,
- their cross sections ovalize at a high bending moment,
- they are stabilized by their supports.

The good earthquake resistance of pipes was demonstrated by extensive studies conducted in the USA (NUREG, 1985; IAEA-Tecdoc-1333, January 2003).

The seismic resistance quality of pipes, pump supports, cabinets, heat exchangers, motor supports, generator supports, core internals, tanks, supports of HVAC equipment, and battery racks was analyzed by investigating stress reports and material data sheets. All components analyzed in this way have a HCLPF acceleration above $A_{SSE} = 2.1$ m/s², which is the peak ground motion acceleration of the SSE used for the plant design. Fragility curves were not evaluated for components and structures having a HCLPF acceleration more than twice the pga of the SSE.

The lesson learned from the seismic PSA was, that components, which are designed for SSE will withstand an earthquake loading much stronger than that encountered at SSE.

4 GENERIC HCLPF ACCELERATIONS AND GENERIC GERS SPECTRA

For instance the seismic ruggedness of electrical components cannot be determined only by analytic tools. The seismic capability of those components was proved by shake table tests at the time of the plant erection. If a component was too large for a shake table, its appurtenances had been shaken separately, while the integrity of the enclosing structure was proved by a stress analysis. Generally, a shake table test results in overtesting. A component whose seismic ruggedness was proven by a shake table test will resist an earthquake much stronger SSE. For components whose seismic resistance was proven by a shake table test and who maintain their seismic resistance over the plant lifetime, fragility curves were not evaluated.

A shake table test provides no assurance, that the equipment maintains its function at and after an earthquake occurring tens of years after the plant erection. The strength of electrical components can deteriorate by the passage of time. Electric contacts may oxidize, ceramic parts and circuit boards may become brittle, and cable insulation may flake. Those parts can fail during the earthquake. At the plant walkdown the equipment was checked against any sign of ageing. No visible ageing was detected after more than 20 years of plant operation. Nevertheless ageing was considered in the probability assessment. In a NUREG-report generic medians $\bar{A}$, generic logarithmic standard deviations β_R and β_U, and generic HCLPF accelerations are listed for motor control centers, breakers, battery chargers, transformers, inverters, and switchgears (NUREG 1985). The report EPRI NP 5223-SL lists GERS-spectra for battery chargers, contactors, motor starters, distribution panels, inverters, manual control switches, motor control centers, switches, switchgears, transformers, and transmitters. For considering ageing too, generic values from the NUREG-report and from the EPRI report, assessing the electrical function during and after an earthquake, were used for the seismic PSA. The zero period acceleration of the GERS-Spectrum was used as HCLPF acceleration.

Not all components of a nuclear power plant receive in-service inspections. For instance, small bore pipes get no radiographic examination. A hidden crack in a small bore pipe can break during an earthquake. A pipe bellows expansion joint of rubber can become brittle in the course of time. Large movement between two buildings or between the building and the surrounding soil can cause a bellows expansion joint to break. Seismic fragilities of small pipes and pipe bellows joints were taken into account by considering generic values.

5 PLANT WALKDOWN

In addition to investigations of stress analyses and shake table test reports, safety relevant components were checked by a plant walkdown. Walkdowns are necessary to check the as-built-situation, the design quality and the hazard for safety relevant components posed by non-safety relevant components. A detailed walkdown is an effective way to uncover seismic vulnerabilities in essential equipment and identify seismic spa-

tial system interactions. If the system has redundancies, only one redundancy was checked by the walkdown. For instance, we looked at one of the four emergency feedwater pumps including the diesel engine with starting equipment, electric motor, generator, cabinets, fuel tanks, heat exchangers, chillers, valves and pipes.

In the appendix F of the report EPRI NP-5223-SL guidelines and data sheets for a plant walkdown are presented (EPRI, 1991b). Also the IAEA safety report no. 28 provides recommendations and data sheets for a plant walkdown (IAEA, 2003). At the plant walkdown components were checked according to these recommendations. In addition to the recommendations from EPRI and IAEA, electrical contacts were checked for high load from the cable mass. Own specific protocol sheets have been developed and used for the walkdowns with component related criteria. Major deficits in seismic design were not observed at the plant walkdown.

6 SEISMIC HAZARD CURVE AND PLANT SPECIFIC SPECTRA

Germany is a region with some historical records of seismic activities. Damages from earthquakes have been chronicled for several centuries. On the other hand, there are only few instrumental strong motion seismicity records. Therefore the earthquake intensity I_{EMS} estimated from historical records instead of peak ground acceleration is a suitable parameter for the analysis. Figure 2 depicts the seismic hazard curve. It gives the recurrence relationship for various levels of earthquake intensity I_{EMS} at the plant site.

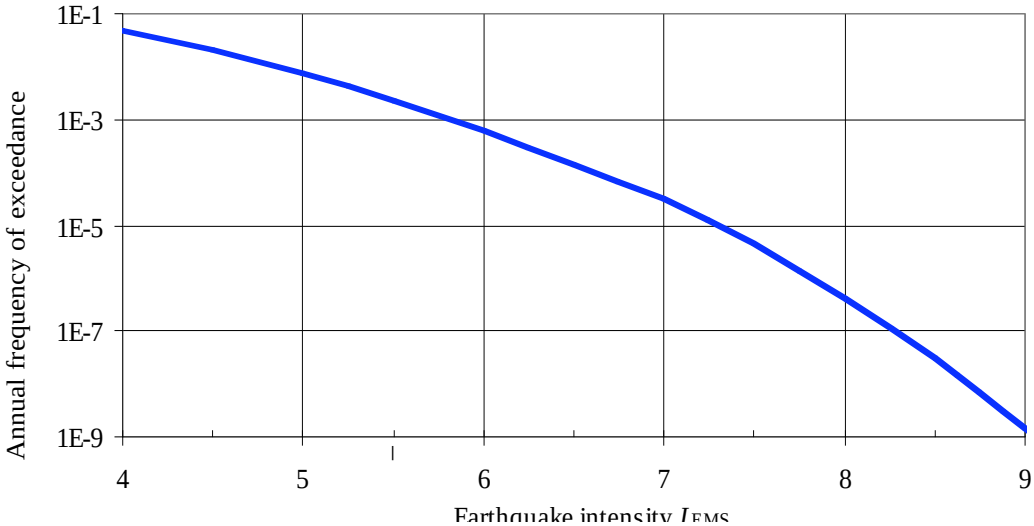

Figure 2. Seismic hazard curve at the plant site

Also plant specific ground motion response spectra for different levels of the earthquake peak ground acceleration are used for the seismic PSA. Figure 3 gives the four ground motion response spectra differing in intensity level I_{EMS} pga respectively. They were evaluated by a seismologist especially for the seismic PSA.

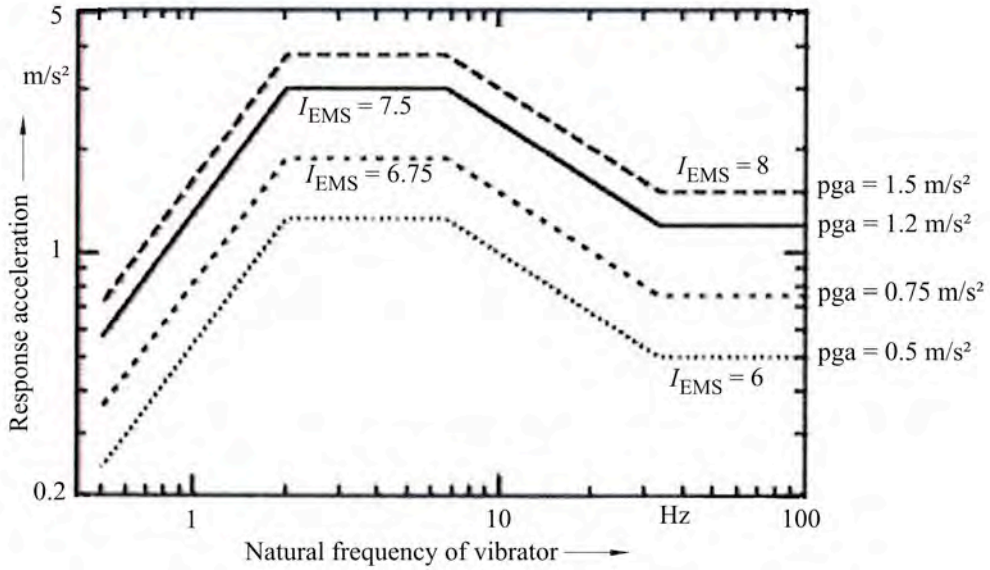

Figure 3. Four levels of site specific horizontal ground motion response spectra

From the four different ground motion response spectra of figure 3 a correlation between the earthquake intensity I_{EMS} and the horizontal earthquake peak ground acceleration was estimated.

The SSE on which the plant design is based has an intensity I_{EMS} = 7.5 and a pga of 2.1 m/s². According to figure 3, the site specific ground motion response spectrum for intensity I_{EMS} = 7.5 has a peak ground acceleration of 1.2 m/s². That shows that the result of a seismic PSA depends essentially on the site specific ground motion response spectra.

The annual frequency of component failure caused by earthquakes can be evaluated by the seismic hazard curve presented in figure 2, the plant specific horizontal ground motion spectra given in figure 3 and a fragility curve as seen in figure 1. From the knowledge of fragility curves for seismic critical components and structures as needed for reactor cooling and reactor shut down the annual frequency of core damage caused by an earthquake was determined.

7 RESULT

The calculated annual frequency of core damage caused by an earthquake is in the order of 10^{-7}. This low frequency of core damage was mainly affected by the fact, that the intensity of the site specific ground motion spectrum for 100,000 year return period is far below the intensity of the SSE, the basis of the plant design. Also the high seismic resistance of all plant components, structures and systems contributes to the low annual frequency of core damage.

Nevertheless the seismic PSA was conservative in some areas:

- Structures seem to be more resistant than calculated by the civil engineer. A NUREG report emphasizes a high seismic resistance of structures, especially for the rotational symmetric reactor building (NUREG 1985). Nuclear power plant structures seem to be non-critical components at an earthquake.
- The four site specific spectra in figure 3 are broadband ground motion response spectra. At an earthquake the soil at the plant site vibrates dominantly in a narrow frequency interval. A ground motion response spectrum calculated from measured accelerations has a narrow frequency band with amplified response acceleration. The spectral shape factor of the ground motion response spectrum is derived by comparing the design ground response spectrum with the “median site specific spectrum” (Kennedy and Ravindra 1984, NUREG 1978). Literature on seismic PSA does not explicitly allow determining a spectral shape factor from a realistic ground motion response spectrum, with a narrow interval of amplification.

There hardly arises a seismic risk from components which are designed against earthquake loads and which maintain their strength, ductility, and performance during the plant lifetime. Instead, attention was directed to:

- Ageing of electric equipment.
- Ageing of cable insulation.

- Failure of small, stiff pipes attached to large, flexible pipes or attached to other flexible supported components.
- Relay chatter and breaker trip. Examination is to be conducted to all circuits containing lockout (seal-in) and bypass logic to determine if non-recoverable failures are credible.
- Embrittlement of rubber flexible connections.
- Wear and corrosion of small pipes and heat exchanger tubes not receiving in-service inspections.
- Movement of plant buildings, with danger for buried pipes.
- Interbuilding pipe failure.
- Interbuilding cable failure.
- Sharp edges at the end of cable trays.
- Lateral soil pressure on buried structures. There might be a risk of pump flooding by cracks in pump houses below grade.
- Fault displacement at the site.
- Flooding of lower floors caused by rupture of pipes not designed against earthquake loads and subsequent failure of safety relevant equipment.
- Corrosion of anchor bolts.
- Anchorage failure, oil leakage and fire protection of transformers.
- Impact between buildings.
- Consequences of failures due to non-seismically designed conditions.
- Adverse human response caused by earthquake-induced stress.

8 LESSONS LEARNED

For each component investigated in a seismic PSA, a realistic median $\breve{A}$ of the earthquake ground motion capacity must be evaluated. That median expresses the peak ground acceleration with 50 % conditional probability of component failure. Usually, an engineer expresses his lack of knowledge on component strength by biasing the result conservatively. A seismic PSA requires a different working procedure: If the engineer does not know the median value for seismic component capacity, he nevertheless must give a non-conservative best estimate for the component capacity median. A lack of knowledge for the component strength could be expressed by a high value for the logarithmic standard deviation $_U$ describing uncertainty, but in no case by a lower value for the median $\breve{A}$.

The participants of the seismic PSA must be aware, that a conservative low median value $\breve{A}$ for seismic capacity of a component or structure distorts the final result, which is the frequency of core damage caused by earthquake. Thus rugged components may seem weak. More critical components may escape notice while supposedly critical components will draw undue attention.

Engineers may have a conflict with their professional obligation. Civil engineers are committed to give a reliable statement for the seismic capacity of a building. There is a temptation, to present the lower HCLPF acceleration instead of the median $\breve{A}$ as a best estimate for mean seismic capacity. Before starting the seismic PSA, all participating analysts should be obliged to evaluate realistic median ground acceleration capacities for systems, components and structures they are investigating. Also, the Codes should distinguish between conservative statements on strength for design and between median strength values for a probabilistic assessment.

Literature on seismic PSA does not always give precise instructions. For instance, the spectral shape safety factor F_{SA} for the ground motion response spectrum is defined as the relation between the site specific median ground motion response spectrum and the design ground motion response spectrum. The median ground motion response spectrum may be either a response spectrum determined from the most apparent property of the plant soil, or it may be a broadband response spectrum. Figure 3 shows the broadband horizontal site specific ground motion response spectrum for intensity I_{EMS} = 8 and a horizontal ground motion response spectrum compiled from an earthquake record. The spectrum compiled from the recorded Coalinga earthquake was scaled down to 1.5 m/s² pga. Naturally, the frequency interval with high response acceleration is wider for the broadband site specific spectrum.

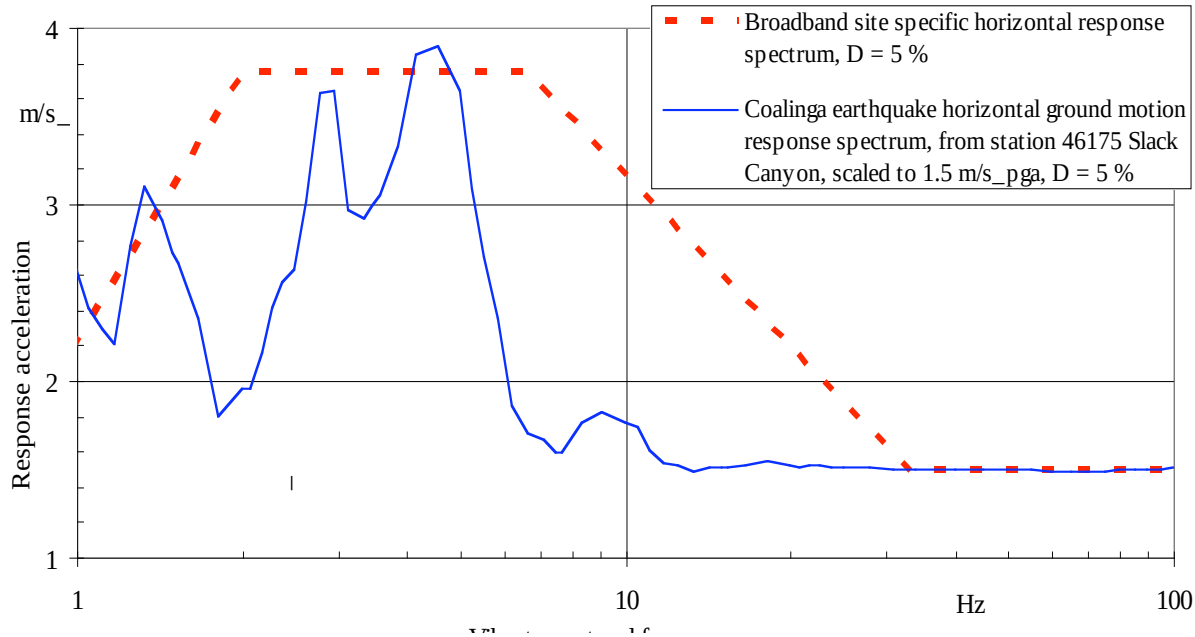

Figure 4. Broadband horizontal site specific ground motion response spectrum vs. horizontal ground motion response spectrum compiled from an earthquake record

At an earthquake, the soil at the plant site vibrates dominantly in a narrow frequency interval. Of course, there is an uncertainty for the real vibration frequency of the plant soil. It is consistent with probabilistic methods to compare a site specific spectrum derived from a mean soil property with the broadband design spectrum. By doing it that way the conservatism in the broadband response spectrum can be assessed.

9 PROBABILISTIC VS. DETERMINISTIC ANALYSYS

A deterministic safety analysis assesses code compliance of the component design. Load cases not covered by the code may not be considered in a deterministic analysis. Also, a nuclear power plant has components for which the code provides deficient rules for an adequate seismic design. Besides, a loss of seismic resistance caused by ageing may not be considered by the code. An earthquake stronger than the SSE might be disregarded in a deterministic safety analysis. A carefully conducted deterministic seismic safety analysis exhibits components, systems and structures with low seismic resistance, but it does not take care of all seismic risks.

The demand on a seismic PSA is quite simple: To determine the annual frequency of core damage caused by an earthquake. Accordingly all contributors to the risk of core damage, even with low probability, must be considered. Earthquakes stronger than the SSE must be assessed. Details of plant design not covered by a Code must be taken into consideration. Degradation by ageing must be taken into account. Flooding of a plant building can be triggered by an earthquake.

In engineering there are reservations regarding probabilistic methods. It is not easy to check a probabilistic safety analysis. Also it turned out, that reasons for an accident in a nuclear power plant were not considered as events in probabilistic analyses conducted before.

A seismic PSA can provide more information on seismic risk than a deterministic analysis. But before performing a seismic PSA, the participants must be aware of:

- Knowledge of probabilistic methods, fault trees, mechanical component design, structural design, electrical component resistance, soil mechanics, and of seismic hazard is necessary. A seismic PSA needs a wide scope of knowledge. Engineers from different disciplines must contribute to it.
- A seismic PSA must consider all contributions to the risk of core damage. A component remained intact so far can fail at an earthquake. Components with a low probability of failure must be taken into account. Failure modes not listed in Codes should be incorporated in the analysis. A seismic PSA is costly in terms of time.
- Not all components of a nuclear power plant are needed to safely shut down the reactor. But it must be kept in mind, that safety systems can be affected through the damage of non-safety relevant systems.
- Modelling of non-safety equipment in a seismic PSA is recommended to take advantage of successes.

10 CONCLUSION

A seismic PSA by the fragility method must consider all contributions to the seismic risk. This analysis is tedious and time consuming. All participants must agree in evaluating median values for the earthquake peak ground acceleration exceeding the component or structure seismic capacity.

Engineers usually publish their statements with a safety margin. They are reluctant to release median values of peak ground acceleration for component structural capacity. Codes should differ in rules for a design and for a probabilistic assessment.

The nuclear power plants erected in the 1980s are well designed against earthquake loads. There is hardly a need for upgrading the equipment. However, attention has to be drawn on the phenomenon of ageing of mechanical and electrical components.

ABBREVIATIONS AND SYMBOLS

A :	Horizontal peak ground acceleration
A :	Peak ground motion acceleration capacity
$\breve{A}$:	Median of A
A_{SSE} :	Horizontal peak ground acceleration of SSE
F :	Factor of safety
$\breve{F}$:	Median of F
$F_{Failure}(a,Q)$:	Conditional probability of failure
GERS :	Generic equipment response spectra
HCLPF :	High confidence of low probability of failure
HVAC :	Heating, venting, air conditioning
I_{EMS} :	Earthquake intensity by European macroseismic scale
pga :	Horizontal peak ground motion acceleration
PSA :	Probabilistic safety assessment
PWR :	Pressurized water reactor
Q :	Confidence level
SSE :	Safe shutdown earthquake used for plant design
$_R$:	Logarithmic standard deviation by randomness
$_U$:	Logarithmic standard deviation by uncertainty

REFERENCES

ANS (American Nuclear Society); External Events PRA Methodology Standard; ANSI/ANS-58.21-2003

BFS (Deutsches Bundesamt für Strahlenschutz); Facharbeitskreis Probabilistische Sicherheitsanalyse für Kernkraftwerke; Methoden zur Probabilistischen Sicherheitsanalyse für Kernkraftwerke; Stand August 2005, BfS-SCHR-37/05.

EPRI (U.S. Electric Power Research Institute); Generic Seismic Ruggedness of Power Plant Equipment; EPRI NP-5223-SL Revision 1; Final report, August 1991

EPRI; A Methodology for Assessment of Nuclear Power Plant Seismic Margin; EPRI NP-6041-SL Revision 1; Final report, August 1991

IAEA (International Atomic Energy Agency); Earthquake Experience and Seismic Qualification by indirect Methods in Nuclear Installations; IAEA-TECDOC-1333; Vienna, January 2003

IAEA; Seismic Evaluation of Existing Nuclear Power Plants; Safety Reports Series No. 28; Vienna 2003

R. P. Kennedy, M. K. Ravindra; Seismic Fragility for Nuclear Power Plant Risk Studies; Nuclear Engineering and Design 79, pp. 47 – 68 (1984)

NUREG (U.S. Nuclear Regulatory Commission); Development of Criteria for Seismic Review of Selected Nuclear Power Plants; NUREG CR-0098, May 1978

NUREG; An Approach to the Quantification of Seismic Margins in Nuclear Power Plants; NUREG-CR 4334, UCID-2044; August 1985

PEER Strong Motion Database, Processing by Pacific Engineering; Data from Coalinga Earthquake at 1983/05/02, Recorded at Station 46175 Slack Canyon; from http://peer.berkeley.edu/smcat/