Seismic PSA of the Neckarwestheim 1 Nuclear Power Plant

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ABSTRACT

One of the first German nuclear power plants performing a seismic probabilistic safety assessment is the 840 MW pressurized water reactor plant Neckarwestheim 1 installed by Siemens/KWU in 1976. Some insights of the ongoing project are presented. Special focus is given to the requirements of the German methodology guideline, the seismic hazard analysis and the results of the plant walkdown.

KEY WORDS: seismic PSA, core damage frequency, seismic hazard analysis, fragility, seismic capacity, seismic-induced failure, plant walkdown.

INTRODUCTION

While probabilistic safety analyses have been performed for all German nuclear power plants since the 1990s seismic risks have not been assessed until now. Germany's new PSA methodology guide [1], published by the federal ministry for environment in 2005, requires a seismic PSA for all plants with a design basis earthquake of intensity $I_{MSK} \geq$ VII. One of the first plants evaluating its seismic vulnerabilities is the 840 MW plant Neckarwestheim 1 (GKN I), a 3-Loop pressurized water reactor installed by Siemens/KWU in 1976. A consortium of AREVA NP and ABS Consulting has been assigned by the plant operator EnBW Kernkraft GmbH (EnBW) to perform this study.

METHODOLOGY

Germany's PSA methodology guide assumes that a site-specific probabilistic seismic hazard analysis has already been carried out. However, for GKN I it was found that the existing analysis does not meet all requirements for a seismic PSA. EnBW had to assign some new investigations firstly: Site-specific ground motion spectra at different frequencies of occurrence were calculated in order to further the knowledge about the seismic hazard. Using the new spectra and the existing analysis, a seismic hazard curve could be obtained.

According to the methodology guide the subsequent seismic PSA shall be performed using a 3-step approach similar to the international well established procedures described in [2] and [3] for example:

1) The seismic plant walkdown where the components, structures and buildings included in the safe shutdown equipment list (SEL) are examined whether they are "typical" of their generic category or somehow non typical or even unique.
2) The seismic fragility analysis determining conditional probabilities of seismic-induced failure of the SEL items as a function of peak ground acceleration (PGA).
3) The probabilistic system analysis introducing equipment fragilities and initiating event frequencies derived from the seismic hazard analysis into the existing fault tree and event tree model for the at-power level 1 PSA in order to calculate core damage frequencies.

SEISMIC HAZARD ANALYSIS

Regional seismicity

The GKN I site is located at the river Neckar about 30 km north of Stuttgart. While there is a seismic zone of high seismic activity in the Swabian Alp about 100 km southeast, no earthquakes of major intensity have been recorded in Neckarwestheim in the recent past (Fig. 1). The design basis earthquake (DBE) was set to be characterized by an intensity I_{MSK} = VIII in the early 1970s considering that the DBE should be the earthquake of maximum intensity which may reasonably occur within 200 km from the site (comp. KTA 2201.1 [5]). The corresponding design basis spectrum was developed using earthquake recordings from rock sites in California. The spectral acceleration at frequencies > 30 Hz is 0.17 g.

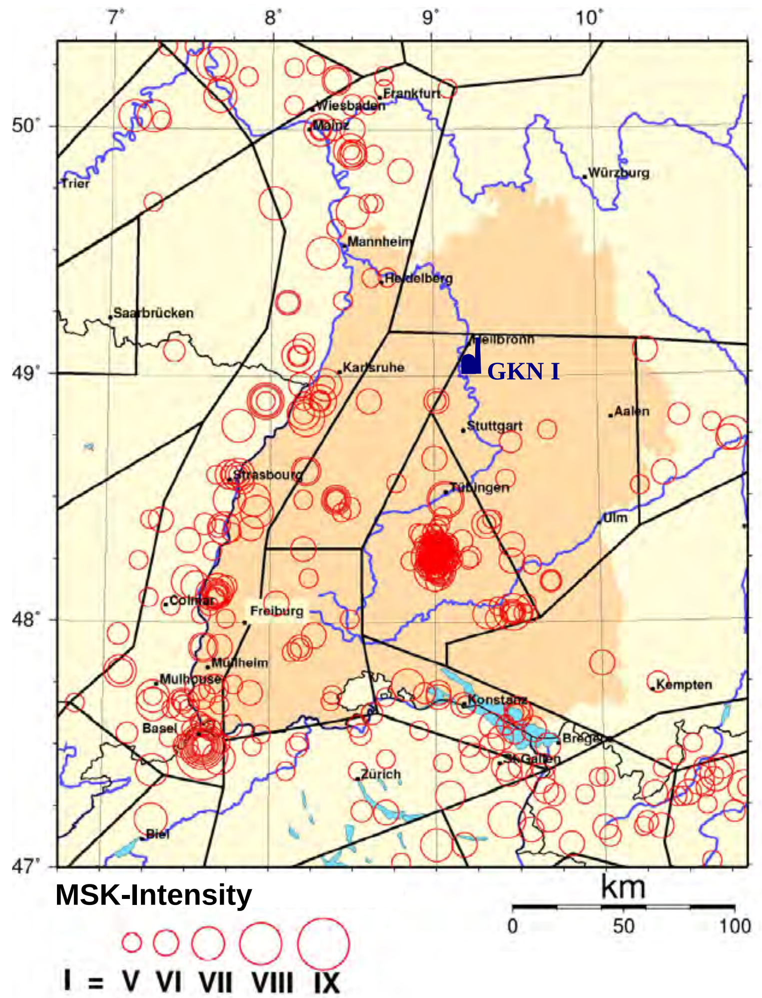

Fig. 1: Historical earthquakes in Baden-Wuerttemberg since 1000 AD [4]

Probabilistic Seismic Hazard Analysis

Probabilistic seismic hazard analyses have been performed for all German nuclear power plants in the 1980s and 1990s in order to confirm that the design basis earthquakes still match the state of scientific and technical knowledge. The existing analysis for GKN I is based on a seismicity analysis using the software code GUMBEL and a Monte Carlo simulation of the site impact applying the software code PSSAEL [6]. It predicts magnitude-distance bins of the most likely earthquakes for given intensities at the site. Furthermore a seismic hazard curve describing the annual frequency of earthquakes exceeding a certain intensity is presented (Fig. 2a). The intensity at a frequency of 1E-5/a, usually taken into account for the specification of the DBE today, is expected to be about VII. Thus it is shown that the design basis covers the seismic hazard conservatively.

The existing seismic hazard curve in terms of intensity cannot be used for the seismic PSA directly because the seismic fragilities are calculated as a function of peak ground acceleration. Hence, EnKK assigned Seismotec GmbH in Weimar (Germany) to calculate site-specific spectra for different frequencies of occurrence [7]. These spectra were determined considering the most likely magnitude-distance bins from the existing analysis and recently developed models for the spectral attenuation at rock sites. The subsoil at the site was classified taking into account recent measurements of the HVSR (Horizontal-to-Vertical Spectral Ratio) [8].

The peak ground accelerations obtained from these new spectra can be compared to accelerations calculated by empiric relationships between intensity and peak ground acceleration. The following relationships are used [9, 10]:

– Trifunac&Brady (1975): log PGA = 0.014 + 0.3 MMI (1)
– Murphy & O'Brien (1977) log PGA = 0.25 + 0.25 MMI (2)
– Richter (1958): log PGA = 0.33 MMI – 0.5 (3)

Additionally, an empirical relationship from Cancani, recommended in Germany's methodology guide [1], is applied. According to Cancani the acceleration is doubled when the intensity increases by one degree. Based on the characteristics of the GKN I design basis earthquake (I=VIII, PGA=0.17 g) a seismic hazard curve in terms of PGA can be constructed, too.

(Fig. 2b) shows that the spectral accelerations determined by Seismotec fall well within the range of these relationships obtained by analysis of worldwide earthquake recordings. Cancani's relationship fits the Seismotec data the best while the frequently used relationship from Murphy & O'Brien covers the Seismotec data more conservatively. Assuming a lognormal uncertainty distribution of the PGA at a given intensity uncertainty bounds for the seismic hazard curve can be constructed. The logarithmic standard deviation found by Murphy & O'Brien would lead to an error factor of 2.29 for example.

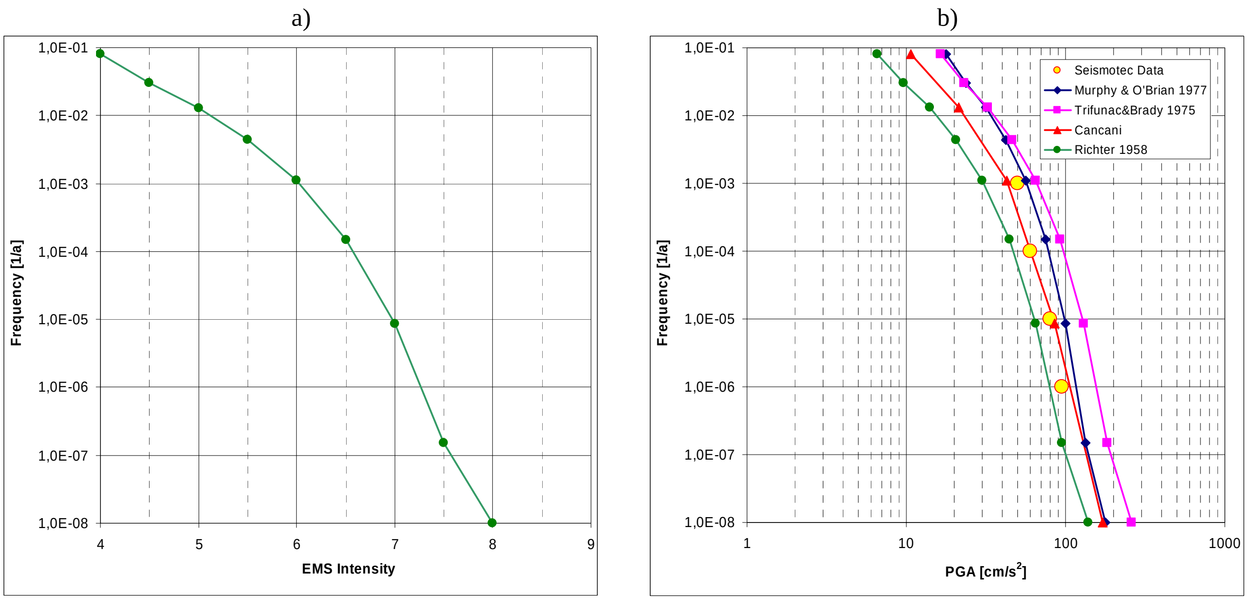

Fig. 2: Seismic hazard curve for GKN I:
a) in terms of intensity [6]
b) in terms of peak ground acceleration

SEISMIC PLANT WALKDOWN

Preparatory Work

Considerable preparatory work was performed prior to the seismic walkdown. The safe shutdown equipment list (SEL) was developed using the at-power Level-1 PSA as the main basis for the choice of the components. However, the fault tree model for internal events does not contain any passive components like heat exchangers, tanks and piping. The final equipment list was therefore developed considering the deterministic earthquake protection concept as well.

The Safe Shutdown Equipment List (SEL) contains 573 items. 289 SEL items are outside of the reactor building and the rest of the items are within the reactor building and the annulus. The items on the list were assigned to one of 27 generic component classes and for each item on the SEL, a specific seismic evaluation and walkdown data sheet (SEWS) was prepared covering the different caveats. Each SEWS consists of:

– General description of the equipment: equipment ID, name, system, equipment category, seismic qualification requirement, building/floor/room
– Equipment evaluation caveats
– Equipment anchorage
– Seismic interaction issues

A database of SEWS was developed in a Microsoft Access program called EQESEWS. The data collected in the inspection were later input into this database, too, resulting in an electronic record of all qualifications, observations and photographs made during the walkdown.

Walkdown methodology

The seismic walkdown of GKN-1 was performed following the procedures in EPRI NP-6041 Seismic Margin Methodology [11]. These procedures have been developed based on earthquake experience database, seismic qualification test database, and past seismic PSA of nuclear power plants. This methodology has been used in the U.S., Canada, Europe, and many other countries in the world to screen out seismically rugged equipment and to direct the budget and efforts to components that are more vulnerable to earthquake loadings.

The walkdown team reviewed all equipment on the SEL that were reasonably accessible and in non-radioactive or moderately radioactive environments. For components that were not accessible, the equipment inspection relied on alternate means such as photographic inspection. In the event the walkdown team had a reasonable basis for assuming that a group of components were similar and similarly anchored, a single component (i.e., lead item) out of this group was selected for inspection. The similarity of a group of SEL items was established based on equipment construction, dimensions, locations, seismic qualification requirement, anchorage type and configurations. The "similarity-basis" was confirmed during the walkdown. The members of the walkdown team did not review 100% of the subsystems (distribution systems such as piping, cable trays, and HVAC ducting). Selected samples of these subsystems were inspected.

In general, the equipment walkdown focused on the seismic ruggedness of the equipment, anchorage, mounting of internal devices, and potential systems interaction concerns. The following two examples illustrate the specific procedures that were used for the review of different classes of equipment inspected:

Pumps

- Verifying pump and motor anchorage including type of anchorage, foundation configuration and integrity.
- Reviewing potential nozzle loads and piping flexibility.
- Identifying interaction potential from overhead piping or adjacent components or structures.
- Reviewing long and unsupported casing or shaft of vertical pumps.

Electrical Equipment

- Reviewing and collecting anchorage details of the cabinet or enclosures for subsequent analytical review.
- Verifying that the internal instruments and components are positively attached to the cabinet framing or enclosure walls and that the device mountings are not excessively flexible. Also, structural integrity of the framing was assessed.
- Confirming cabinet that contains sensitive relays either has adequate gap or is bolted to the adjacent cabinets to prevent pounding.
- Identifying any system spatial interaction problems or flood or spray concerns.

Walkdown Results

Tables 2-3 and 2-4 in EPRI NP-6041 provide guidelines and caveats for structures and different classes of equipment to determine if the structure/equipment has a HCLPF (High Confidence, Low Probability of Failure) capacity of at least 0.3 g or 0.5 g PGA [11]. Table 2-3 pertains to the screening of civil structures whereas Table 2-4 provides guidelines for screening of mechanical and electrical equipment as well as distribution systems. This screening was conducted prior to and confirmed during the seismic walkdown. In some instances, the screening was done during the walkdown, or equipment data were collected during the walkdown and used to screen the component.

Applying the EPRI NP-6041 criteria most of the mechanical equipment like pumps, valves and tanks could be screened out. Some valves do not meet the screening criteria because their operator height and weight is not within the generic experience range included in the database. Some tanks and heat exchangers were insulated during the walkdown such that details of the anchor bolts could not be observed. The design calculation, vendor drawings, and foundation drawings of these components have to be reviewed to confirm the seismic margin of these components.

A large proportion of the electrical components included in the SEL meet the screening criteria, too. However, some switchgear, rectifiers, inverters, batteries, transformers and I&C cabinets need a plant-specific analysis due to the following reasons:

- Raised floor flexibility:
  The electrical equipment is installed on raised floors in many rooms. While the raised floor structural integrity and anchorage are judged to have high capacity the effect of floor amplification of input motion needs to be analyzed.

- Relay issues:
  The effect of relay chatter is always a crude point in the seismic margin assessment. A list of essential relays has been compiled. Shake table test of these relays need to be reviewed considering the effect of raised floor flexibility again.
- Masonry block walls:
  While only few issues of seismic interaction have been found in general, masonry block walls in the switchgear building could pose a seismic interaction concern to the electrical equipment installed there. With very few exceptions, all masonry walls have been retrofitted with floor-to-ceiling steel columns (i.e., strong-backs) that are tied to these walls. Further evaluations are necessary to ascertain that these block walls do not determine the seismic capacity of the electrical equipment.
- Anchorage:
  Anchorage details of the electrical and I&C cabinets are sometimes encased by a concrete covering and could not be visually inspected. Drawing and/or calculation review is required to ensure that the anchorage system for these cabinets has adequate seismic capacity.

A selected sampling of structures like ventilation ducts, cable trays and the main control room ceiling has been examined during the walkdown, too. Generally, only few critical issues were found due to extensive retrofits that have been performed in the past. Few cable trays in the turbine building and the switchgear building that have been not upgraded yet show questionable anchorage and need a critical review of design documents.

SEISMIC FRAGILITY ANALYSIS

The seismic fragility analysis is still in progress. Generic fragilities are assigned to the SEL items that meet a screening level of 2.0 g spectral acceleration at the equipment location. The HCLPF is determined considering the anchorage HCLPF according to Table 5 in EPRI NP-6041 and the ratio of the 2.0 g screening level to the probabilistic demand. The median ground acceleration capacity A_m is obtained by

$$A_m = \text{HCLPF} \cdot \exp(2.33\,\beta_c) \tag{4}$$

where β_c is a generic composite uncertainty.

Plant specific fragility calculations are performed for the buildings and all SEL items that do not meet the EPRI caveats. Germany's methodology guide recommends the use of an overall safety factor defined as the ratio of the median seismic capacity in terms of PGA and the PGA of the design basis earthquake. It represents the best estimate of the actual response and capacity as opposed to the design response and capacity. It is determined by the product of the factors of conservatism or unconservatism in each important variable that contribute to response and capacity, e.g.:

- Structural response of the buildings
- Response of the components
- Inelastic energy absorption

The randomness and uncertainty in each variable are combined to define an overall randomness and uncertainty in the median fragility level. The procedure is therefore identical to the scaling method described in [12] and [13].

Fragility curves describing the probability of seismic-induced failure P_F as a function of PGA can be generated using the following equation (Fig. 3):

$$P_F = \Phi\left(\frac{\ln\left(\frac{A}{A_m}\right) + \beta_U \Phi^{-1}(Q)}{\beta_R}\right) \tag{5}$$

where Φ is the standardized normal distribution, A is the PGA of interest, Q is the level of confidence and β_R and β_U are the logarithmic standard deviations representing randomness and uncertainty.

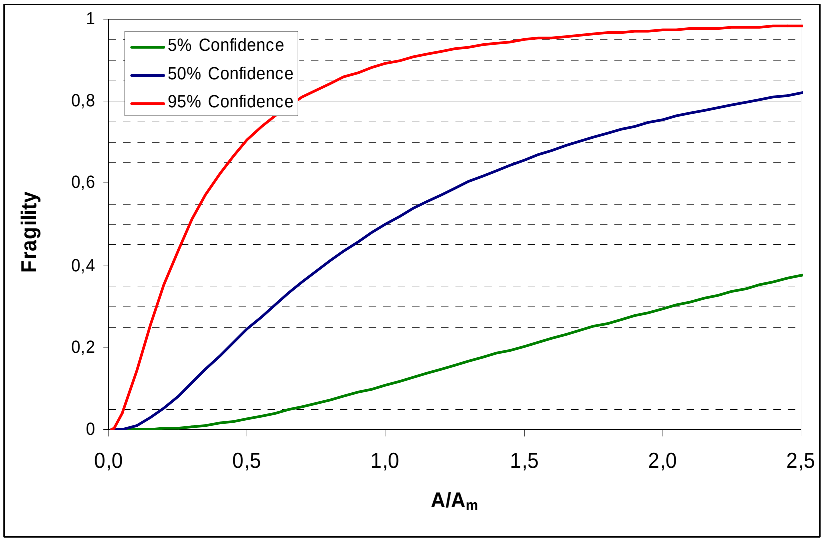

Fig. 3 Fragility curve representations (β_R=0.4, β_U=0.3)

SYSTEM ANALYIS

The software RISKSPECTRUM PSA PROFESSIONAL is used for the probabilistic system analysis. The existing fault tree and event tree model for the at-power level-1 PSA has been modified to account for location correlations and to introduce different seismic failure modes. The uncertainty distributions of component fragility at a given PGA are implemented in RISKSPECTRUM using the parameter distribution type "Discrete".

Seismic initiating event frequencies have been computed by splitting the seismic hazard curve into appropriate intervals. Each interval is characterized by its mean frequency of occurrence and its mean PGA. Taking into account the fragilities of components and structures at the mean PGA seismic initiator frequencies have been obtained splitting the mean frequency of each interval to the initiating events considered:

– Loss of coolant accidents (LOCA)
– Loss of offsite power
– Secondary side breaks

Propagating the initiating event frequencies through the modified event tree and fault tree model a point-estimate of the core damage frequency for each initiating event and for each earthquake size can be calculated. The minimal cut sets found in each analysis case can be combined in a "MCS Analysis Case" to obtain point estimates of the total risk of seismic-induced core damage. Uncertainty bounds of the result as well as some information about the dominant risk contributors can be estimated applying the uncertainty and importance analysis tools provided by RISKSPECTRUM, too.

Preliminary calculations using generic component and building fragilities from [14] indicate that seismic events do not contribute to the core damage frequency significantly.

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