

Seismic Risk Analysis in The German Risk Study Phase B

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ABSTRACT

The paper discusses some aspects of the seismic risk part of the German Risk Study for Nuclear Power Plants, Phase B. First simplified analyses in Phase A of the study allowed a rough classification of structures and systems of the PWR reference plant according to their seismic risk contribution. These studies were extended in Phase B using improved models for the dynamic analyses of buildings, structures and components as well as for the probabilistic analyses of seismic loading, failure probabilities and event trees. The methodology of deriving probabilistic seismic load descriptions is explained and compared with the methods in Phase A of the study and in other studies. Some details of the linear and nonlinear dynamic analyses of structures are reported, in order to demonstrate the influence of different assumptions for material behaviour and failure criteria. The probabilistic structural and event tree analyses are discussed with respect to distribution assumptions, acceptable simplifications, special results for the PWR reference plant and, finally, the influence of model uncertainties.

INTRODUCTION

The German Risk Study for nuclear power plants was carried out in two Phases A and B. In Phase A of the study (GRS, 1980) only very preliminary investigations with respect to seismic risk had been carried out. The contribution of earthquakes to the overall core melt risk then was analysed in more detail in Phase B which is just ready for publication. This seismic risk part of the study included the following subtasks:

determination of realistic seismic load assumptions with

- site-specific intensity exceedance rates and
- site- and intensity-dependent engineering seismic input parameters

dynamic building analyses

- for different safety-related and non-safety-related buildings and
- different levels of site intensity with related input parameters
- yielding e.g. floor response spectra or time histories

dynamic and probabilistic failure analyses

- of safety related structures, components and systems
- using building floor response spectra or time histories as input

event sequence analyses

- for event sequences which could be influenced by an earthquake
- using intensity-dependent and -independent unavailabilities

- evaluation of core melt risk contributions due to earthquakes
- from different event sequences at different intensity levels
- including the effects of accident management measures and
- estimating the influence of statistical and model uncertainties.

SEISMIC LOAD ASSUMPTIONS

The seismic analyses in Phase A were based on seismic load assumptions taken from the licensing procedure, e.g. standard spectra, which were combined with regional annual exceedance rates of the peak ground acceleration (as scaling parameter for standard spectra). These (classical) assumptions which are also used in several other seismic risk studies did not account for site-specific influences, neither for the local subsoil conditions nor for the seismotectonic position. Therefore a more realistic procedure was applied in Phase B of the study (Hosser, 1985), originally developed in a former study for the fast breeder reactor SNR 300 (Hosser, 1983 a).

The makroseismic intensity I which is directly correlated with structural damage was now chosen as leading parameter for the determination of intensity-dependent seismic input parameters. The seismic input parameters - especially free-field response spectra and durations of strong motion - were determined for three selected ranges of site intensity covering all earthquakes important to the seismic risk of plant buildings and components at the site:

$I_1 = 6.5 \pm 0.5$	focal distances $R \leq 60$ km
$I_2 = 7.5 \pm 0.5$	focal distances $R \leq 40$ km
$I_3 = 8.5 \pm 0.5$	focal distances $R \leq 30$ km.

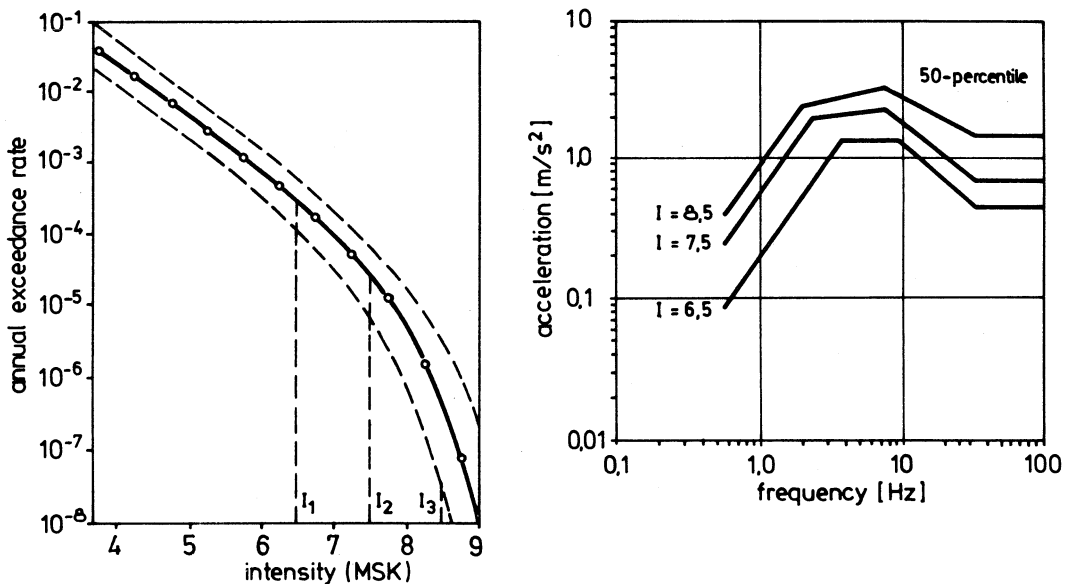


Fig.1 : a) Annual exceedance rates of makroseismic intensity I (with confidence bounds) and b) Intensity-dependent free-field acceleration response spectra for the three intensity ranges (damping 5 %.)

The related probabilities of occurrence of earthquakes within these ranges were calculated from annual exceedance rates of the makroseismic intensity I. The exceedance rates in Fig. 1 resulted from a probabilistic site analysis by Ahorner, based on a detailed seismic zone model according to the procedure in (Hosser, 1983 b). For the three intensity ranges also ranges of related makroseismic parameters were derived from Monte Carlo simulations. The local subsoil conditions at the reference site were classified "soft to medium stiff sediments". The ranges of makroseismic parameters and the subsoil class were used as criteria for selecting representative strong motion records from a strong motion data bank.

Realistic seismic input parameters for the three intensity ranges were defined by the help of statistical analyses of free-field spectra and durations of strong motion. In Fig. 1 b the smoothed 50-percentile acceleration response spectra (with 5 % damping) for the three intensity levels are plotted. The scattering amplitudes are described by a logarithmic normal distribution with a coefficient of variation of about 60 % in the whole frequency range. The average duration of strong motion in each intensity class is below 4 s. Based on this information, artificial acceleration time histories were determined to be used as seismic excitation for the buildings.

FAILURE ANALYSES

Selection of structures and components

The choice of the structures and components for detailed failure analyses is based on the following criteria:

- The earthquake loads contribute largely to the total stresses governing design.
- The seismic induced failure initiates an event sequence relevant to safety or contributes towards increasing the risk of a postulated event sequence.
- The choice should, as far as possible, be representative for the total behaviour of a large number of structures and components and, with respect to the components, be representative for all major systems.

The selected structures and components are listed in Tab. 1 below.

Dynamic building analyses

The respective buildings were dynamically analysed using the seismic input parameters for the three ranges of site intensity as defined above. The buildings were modelled by beams with generally linear-elastic material behaviour. Nonlinear material behaviour was taken into account e.g. for the stiffening transverse frames in the turbine building and for the stiffening shear walls in the switchgear building. In both cases local ductilities were analysed based on the actual design, the relevant failure mechanisms and the respective rotation or deformation capacities.

This shall be illustrated using as an example the transverse shear walls in the switchgear building. The most critical lower part of such a wall is shown in Fig. 2 a. Obviously, the wall has a lot of openings of different size reducing the shear capacity. Therefore shear failure was analysed in more detail yielding the shear force - deformation laws plotted in Fig. 2 b. The deformation capacity of the wall within the lower floor of the building was defined based on data from shear wall tests. For the dynamic analysis of the whole building it is sufficient to take into account such a nonlinear behaviour only for the

Tab. 1: Structures and components selected for seismic risk analysis in phase B of the German risk study.

Structures

- Reactor building: inner cylinder in the lower area
- Reactor building: inner cylinder under the polar crane
- Reactor building: separating wall between the fuel element (storage) pool and core structure wall
- Valve compartment wall
- Turbine building: transverse frame (beam)

- Reactor auxiliary building: stack
- Reactor auxiliary building: floor under the demineralized water tanks
- Switchgear building: transverse stiffening walls
- Switchgear building: floor under the emergency diesel generators

Components

- Demineralized water tank in the intermediate tract
- Emergency feed (water) pump in the intermediate tract
- Pumps and pipes of the secondary cooling water supply in the pump building
- Emergency cooling system and decay heat removal system inside the containment
- Emergency diesel generators in the switchgear building
- Heat exchangers between the nuclear intermed. cooling system and the auxiliary cooling water system in the reactor building
- Fuel storage
- Primary system including pressurizer
- Support structures for electrical or electronic components
- Containment vessel

beams representing the walls in the lowest story whilst all other beam elements of the oscillation model behave linearly (Fig. 3).

In the case of the transverse frames in the turbine building the rotation capacity in the area of beam-column connections is decisive for the ductile failure under dynamic loading. All other buildings are relatively stiff and are realistically analysed by a linear elastic model.

Dynamic analyses of structural elements

Several structures inside the buildings were analysed in more detail because of their importance for the function of safety-related systems or the global behaviour of the buildings. At first, the sensitivity to seismic action was checked with a linear elastic dynamic analysis. Except for the lower part of the inner cylinder in the reactor building, also nonlinear dynamic analyses were performed in a second step limiting the energy transfer to the structure due to local energy absorbing mechanisms, e.g. rotations of parts of reinforced concrete beams and frames or friction between the polar crane and its supporting ring beam. Taking into account this realistic material behaviour, the bearing capacity of the structural elements in terms of seismic excitation amplitude increased by a factor of 2 up to five.

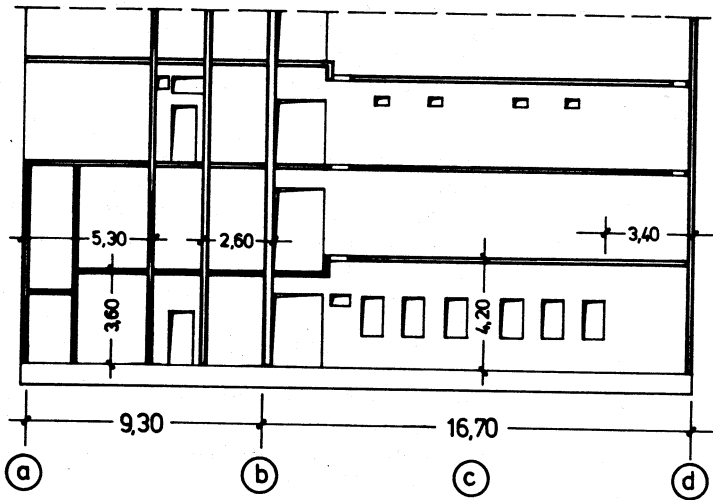


Fig. 2 a :
Lower part of the
transverse wall of
the switchgear-
building

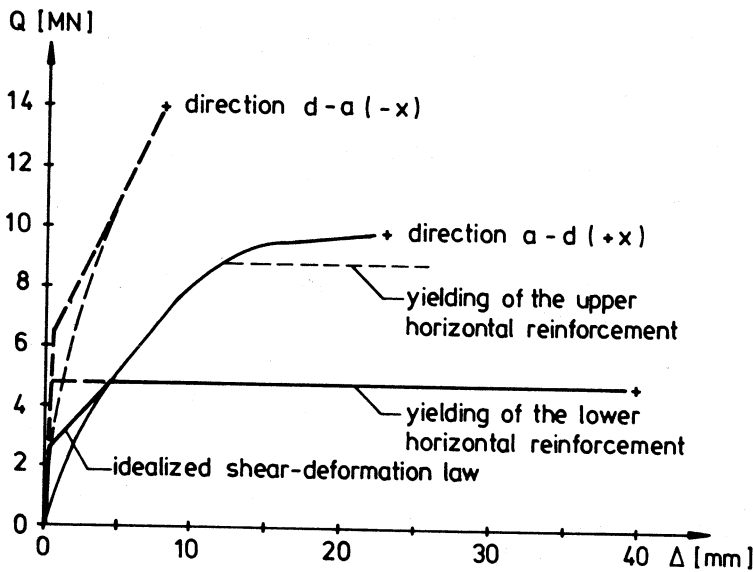
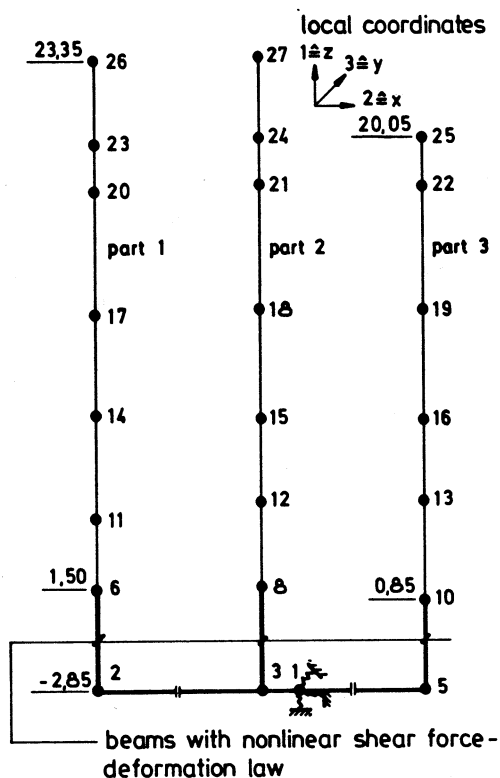


Fig. 2 b
Shear force - de
formation law for
the lowest story
of the transverse
wall

Probabilistic analyses of structural failures

Probabilities of seismic induced failure of the structures were determined with the help of well known first order reliability method which has already been applied in Phase A (GRS, 1980) and in (Hosser, 1983 a). In some simple cases - where the seismic action governs the design and is to be compared with a leading resistance parameter - the calculation could be reduced to the determination of the convolution integral of two logarithmic normal distribution functions. In other cases more detailed and sometimes nonlinear state equations with several stochastic parameter had to be analysed yielding a higher calculation effort.



Conditional probabilities of failure were determined for each of the three seismic intensity levels. In addition, total probabilities of seismic induced failure were evaluated by multiplying the conditional probabilities of failure with the probabilities of occurrence of the intensity ranges and summing up the three contributions. The highest contribution was generally at the mean intensity level or between the lowest and the mean level, depending on the individual design of the structures.

Tab. 2 gives an overview of all total probabilities of failure p_f of the structures and compares with some results from Phase A. Generally, the improved seismic load assumptions result in a decrease of p_f by one order of magnitude and the improved failure models in another one.

Fig. 3
Oscillation model of the switchgear building with partly nonlinear beams

Tab. 2: Total probabilities of seismic induced failure of structural elements analysed in the German risk study.

Building/structure	P_f	
	Phase A	Phase B
Reactor building:		
- inner cylinder, lower part	5 E-12	4 E-14
- inner cylinder under the polar crane	4 E-5	1 E-7
- separating wall between the fuel element storage pool and core structure wall	2 E-13	5 E-7
Valve compartment:		
- outer wall	4 E-6	4 E-9
Turbine building:		
- transverse frame	3 E-4	9 E-7
Reactor auxiliary building:		
- stack	-	1 E-6
- floor under the demineralized water tank	-	3 E-5
Switchgear building:		
- transverse wall	-	2 E-6
- floor under the emergency diesel	-	2 E-5

Component failure analyses

The component failure analyses in Phase B are documented in detail in (Klein, 1985) and are therefore not included in this paper.

EVENT SEQUENCE ANALYSIS

Depending on their consequences on plant structures and systems, earthquakes can influence or initiate different event sequences (see Fig. 4). Generally, all non-availabilities of operational and safety systems can be more or less influenced by an earthquake. A large variety of possible types of seismic induced failures have to be considered, e.g. global failures of structures, loss of integrity of a pressure-retaining system or functional failure of an individual component. However, according to the results of our failure analyses, only few failure types of particular structural elements and components really contribute to the risk of the plant. An earthquake can cause transients and loss of coolant accidents.

Seismic induced transients are mainly initiated by a failure of the offsite power supply, disturbances in the power supply inside the plant or a failure of components of the feedwater steam circuit. As opposed to sequences induced by internal events, the earthquake can affect several systems at the same time. In the study it is conservatively assumed that certain equipment in the turbine building (generator, turbine, main heat sink, components of the operational feedwater system including feed water tanks), which have not been explicitly designed against earthquakes, are not available. The possibility of restoring the offsite power supply within one hour after an earthquake-induced station blackout is considered.

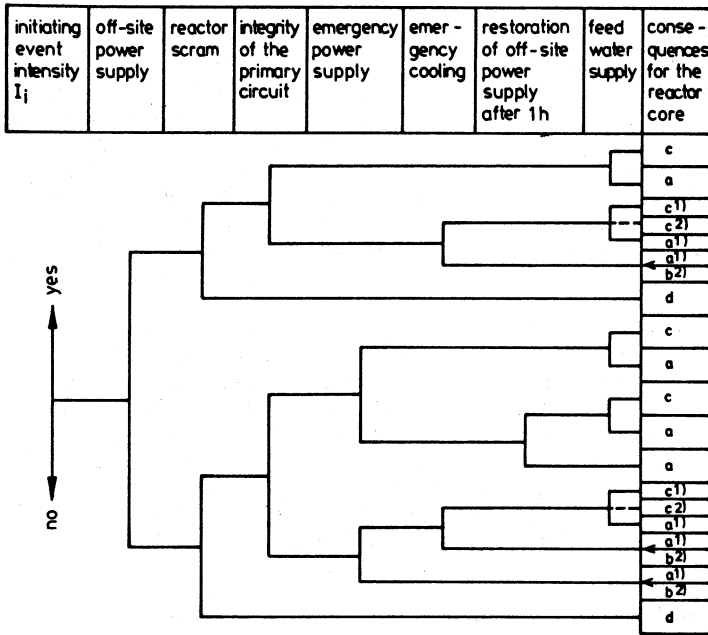
The probability of the event sequences generally results from both, non-availabilities independent of the earthquake and seismic induced failure probabilities of systems. The independent non-availabilities are important for low earthquake intensities. Sometimes, the seismic induced failure probability of one component governs the probability of a branch; this holds e.g. for the emergency power generators with respect to the loss of emergency power and for the demineralized water tanks in case of a loss of the feedwater supply.

Instead of a detailed analysis of the common mode case earthquake, the probability of consequences for the reactor resulting from an individual event sequence paths (branches) is calculated approximately on the assumption that the seismic induced events are either independent of each other (e.g. different types of components at different locations) or strongly dependent (e.g. similar structures and components with dominating influence of the earthquake). System-specific dependencies, e.g. on the power supply, are observed.

RESULTS AND CONCLUSIONS

The results of the event sequence analyses are expressed in terms of frequencies of plant conditions beyond design basis (core melt) as a consequence of earthquake induced transients and primary circuit leakages. More details will be dealt with, after publication of the risk study Phase B, during the presentation.

The contribution of the three seismic intensity levels to the frequencies shows that the intensity range I_2 is dominating. This proves that the intensity ranges were appropriately chosen. It also shows that earthquakes of intensities higher than those on which the plant design is based do not affect the results very much. The contribution from leakages to the seismic risk is negligible. Consequently, the uncertainties related to leakage assumptions resulting from a possible over-estimation of medium to large leakages and possible under-estimation of small leakages is of no practical importance.



- a core melt (high pressure path)
- b core melt (low pressure path)
- c no core damage
- d continuation: ATWS
- 1) sequence branch: small leakage
- 2) sequence branch: large leakage

Fig. 4 : Simplified event tree "earthquake"

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