Possibilities and Limitations of Simplified Methods for the Seismic Analysis of the HDR Reactor Building

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ABSTRACT

Data from seismic tests at the HDR reactor building were used for a systematic evaluation of possibilities and limitations of "simplified" seismic analysis methods. The models developed for this evaluation did not have more than 32 degrees of freedom. They were composed of two dimensional beams and lumped masses for the structures and of spring-dashpot elements for the soil. Eigenvalues, mode shapes and modal damping values of the soil-structure system were evaluated and compared with results from shaker tests. The structural response to an external blast excitation was analysed by the response spectrum method and compared with recorded data.

It was found that a rather accurate determination of the basic structural behaviour is possible by using simple beam models with soil springs. Simplified analysis methods were confirmed to be powerful tools for the design or review of nuclear power plant structures, provided certain modelling criteria are observed. In particular they are well suited for parameter studies.

1. INTRODUCTION

In addition to more sophisticated seismic analysis approaches, "simplified" methods are often used for the design or for the review of nuclear power plant structures. Earthquake simulation tests such as shaker and blast tests at the decommissioned HDR ("Heissdampfreaktor")-facilities in Kahl, Federal Republic of Germany, presented a unique opportunity for a systematic evaluation of possibilities and limitations of simplified seismic analysis methods.

The study presented in the following is part of the Swiss contribution to the HDR research project which is coordinated by the Federal Institute for Reactor Research (EIR) and sponsored by the National Energy Research Fund (NEFF). The project was realized in close cooperation with the German Nuclear Research Center (KfK). The complete study is reported in Ref. 1.

2. INVESTIGATED METHODS

For the selection and definition of the methods to be investigated, a subdivision into the aspects "analysis procedure", "load definition" and "modelling" was made (Table I). In respect to the analysis procedures, the main effort was spent on eigenvalue analysis and on modal response analysis. The eigenvalue analysis included the determination of eigenfrequencies, mode shapes, modal participation factors and, in addition, modal damping values. With the modal response analysis the peak accelerations of the structure were computed by applying the response spectrum method. Strongly simplified methods, like a pseudo-dynamic and a quasistatic analysis procedure, were also evaluated. Finally, floor response spectra generation was investigated by using two different approaches: the modal time history analysis (deterministic method) and a direct method based on power spectral density and frequency response functions (probabilistic method). The loads to the structure were defined mainly by acceleration response spectra or by selected spectral values. Acceleration time histories were used only to define the excitation for the deterministic floor response spectra generation.

3. MODELS

The main idea was to work out models with very few dynamic degrees of freedom (DOF) which still must be able to represent the essential features of the dynamic behaviour. All investigated models did not have more than 32 DOF. Most of them were composed of two-dimensional beams and lumped masses for the structure and of spring-dashpot elements for the soil. The modelling of the building structure and their components was based on original construction drawings and on equipment data. The soil model was derived from reports on soil investigations. A "basic model", a "reduced model" and a "modified model" were developed and used for the eigenvalue analysis and the modal response analysis (see also Table I).

3.1 Structure models

The basic model of the structure is shown in Figure 1. It consists of two vertical and concentric beam cantilevers, which are coupled at the level of 5.0 m below ground surface. One of the two beams represents the concrete containment, the other one the steel containment shell and the inner concrete structures with the components. The total mass is 24'660 tons. The model (including the connected soil springs) has 30 DOF for the horizontal direction and 15 DOF for the vertical direction. Decoupled horizontal and vertical analysis was considered justifyable.

The reduced model was derived from the basic model as illustrated in Figure 2 (upper part). It represents the condensation to a lower bound number of 14 horizontal and 7 vertical DOF. This number was considered to be a minimum for a reasonable modelling of the 10 basic modes of vibration in the frequency range up to 30 Hz. Reduction criteria and boundary conditions were established and observed carefully.

After first comparisons of eigenfrequencies and mode shapes with shaker test results, the basic model was slightly modified in the basemat area. The modified model (lower part of Figure 2) reflects a simple and rough estimate of the basemat flexibility. It thus allows for rotations of the two main structural beams relative to each other. This effect was achieved by introducing auxiliary beam elements with stiffness characteristics approximately equivalent to the elastic connection of the containment and the inner structure with the basemat.

3.2 Soil model and model combinations

The soil model essentially consists of elastic springs, dashpots (representing material- and radiation damping) and soil masses added to the base structural node. Spring stiffnesses and radiation damping values were determined by applying the well known compliance functions for the layered elastic medium and of the equivalent homogeneous halfspace respectively (Ref.3,4). The influence of embedment and the frequency dependency were investigated (Ref. 5,6). The embedment required an increase of stiffness and damping in the order of 10% (vertical) to 60% (rocking). Frequency dependency was found to be less important for the existing soil characteristics.

The significant soil model parameters were reasonably varied within the expected range of uncertainty. The variation of stiffness and damping around their best estimate values was based on an assumed deviation of ±20% for the shear wave velocities as the controlling soil properties. In this way the three main soil model types "soft", "best estimate" and "stiff" were established. All the three soil model types were combined with the basic and with the reduced structure model for the subsequent modal analysis. The best estimate type only was combined with the modified structure model.

4. MODAL CHARACTERISTICS

Eigenfrequencies, mode shapes and modal damping values for the described model combinations were computed with the structural analysis program BHSAP, a modified and expanded version of SAP IV (Ref. 8). They were compared with results from the shaker tests (Ref. 2) and with results from more sophisticated seismic analyses performed by other institutions engaged in the HDR research program. As representative examples the results for the first three modes are shown in Table II.

For the first mode - representing mainly a rocking rigid body motion - the range of the frequencies computed by the simplified models was between 1.2 and 1.7 Hz. Thus it was in good agreement with the recorded fundamental frequency of about 1.5 Hz. The modal damping values, determined as weighted average from contributions of material damping in the structure and the soil and of radiation damping (Ref. 7), were slightly lower than the values from the test results. For the second mode - representing the bending motion of the two structure cantilever beams in opposite directions - the approaches with the basic model and the reduced model resulted in significantly higher frequencies than the measured ones (4.2 - 4.4 Hz compared with 2.6 Hz). The main reason for this difference was considered to be an underestimation of the influence of the basemat flexibility. This gave rise to developing the modified model, as described in Chapter 3, which allows the vertical cantilever beams to rotate separately. With the modified model excellent agreement with the measured eigenfrequencies was observed, not only for the second mode, but also for other relevant higher modes. In particular, the frequencies of modes with motions of the two cantilever beams in opposite directions were found to be significantly more accurate.

The shell vibration modes identified by the shaker tests could not be represented by the beam models. However these modes usually do not contribute significantly to the overall seismic response of the structures.

5. RESPONSE TO BLAST EXCITATION

The structural response was analysed for data from an external blast test. Since no representative free field motion was definable from the tests, the excitation of the structure had to be described by the recorded basemat motion.

5.1 Peak accelerations

Figure 3 shows the horizontal peak structural response of the HDR-reactor building to the blast excitation computed by the response spectrum method with the modified model. It was found that a reasonably accurate assessment of peak accelerations can be achieved by simplified analysis methods. Consequently, also maximum global forces for the building can be determined rather realistically.

Reasonable estimates of peak accelerations were also obtained by the pseudo-dynamic method, whereas the quasistatic method (as was expected) provided very conservative results.

5.2 Floor response spectra

Simplified methods are not considered to be entirely suitable for computation of floor response spectra. Nevertheless an attempt was made to work out the possibilities and limitations of the modified model for floor response spectra generation.

Deterministic method

An example of a floor response spectrum computed by modal time history analysis is compared with the corresponding recorded spectrum in Figure 4. The analysis overestimated the structural amplification for the ranges of the eigenfrequencies represented by the model. On the other hand the influence of effects not reflected by the simple beam model (like shell vibrations) was underestimated. In general the simplified models tend to produce conservative floor response spectra, especially when the usual methods of peak broadening and smoothening are applied in order to obtain design spectra.

Probabilistic Methods

The investigated probabilistic method of floor spectra generation (also called the direct method, Ref. 9) is based on the assumption of a stationary Gaussian stochastic process. The assumption of stationarity is however not justified for a blast excitation of extremely short duration. Therefore a response spectrum as well as a corresponding artificial time history, reflecting an approximatively stationary excitation, were established. In the following, probabilistic and deterministic floor response spectra were generated. The comparison of the spectra showed a reasonable agreement of probabilistic results with the deterministic ones. The direct probabilistic method is more efficient and, moreover, it gives information about the confidence level of the final results.

6. CONCLUSIONS

Since the HDR reactor building represents an exceptional case - in particular with regard to its geometry and to the soil conditions - the generalization of the study findings had to be made carefully. The following possibilities and limitations of simplified methods were found and considered to be generally valid:

- A rather good determination of the basic structural behaviour is possible by using simple beam models, provided they are coupled with reasonably estimated soil springs and dashpots. Thus peak accelerations and global forces in the structure due to seismic excitation can be computed (or enveloped) quite accurately.
- Suitable modelling of important boundary conditions proved to be more essential than the number of dynamic degrees of freedom.
- Extensive and valuable parameter studies are feasible due to the limited computational effort.
- The degree of detailing referring to the aspects "analysis procedure", "load definition" and "modelling" are often more reasonably balanced by simplified methods than by the so called sophisticated methods.
- Limitations were found in the description of the frequency content of structural response. The agreement of the computed floor response spectra with the corresponding recorded spectra was not fully satisfactory. In general a trend to overestimation of the response in the frequency ranges of the basic structural modes was observed.
- The applied method for direct (probabilistic) determination of floor response spectra provided results which were - for approximately stationary excitations, but not for the non-stationary HDR blast excitations - well comparable with the deterministic results from modal time history analysis.

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Table I: Features of the investigated methods

SIMPLIFIED SEISMIC ANALYSIS METHODS

ANALYSIS PROCEDURES	LOAD DEFINITION	MODELS
- Eigenvalue analysis	No load	Building: 2d-beams + lumped masses
- Modal response analysis by response spectrum method	Acceleration response spectra	Soil: springs + dashpots
- Pseudo-dynamic method - Quasistatic method	Selected values from acceleration response spectra	- Basic model 30 DOF - Reduced model 14 DOF - Modified model 32 DOF
- Floor response spectra generation		and for pseudo-dynamic method:
. Deterministic method	Acceleration time histories	- Rigid-body on springs
. Probabilistic method	Acceleration response spectra	- Continuous beam models

Table II: Comparison of modal characteristics

		Test	Analysis						
			basic model			reduced model			modified model
			soft soil	best estimate	stiff soil	soft soil	best estimate	stiff soil	
Mode 1: Rocking 	Frequency f (Hz)	1.47	1.23	1.50	1.73	1.22	1.48	1.71	1.39
	Modal damping β (%)	5.2	2.9	2.8	2.6	2.9	2.9	2.8	3.9
Mode 2: Bending in opposite directions 	f (Hz)	2.62	4.17	4.24	4.26	4.31	4.37	4.38	2.57
	β (%)	3.1	7.5	2.9	2.1	6.0	2.7	2.2	1.8
Mode 3: Vertical 	f (Hz)	4.03	3.14	3.81	4.54	3.13	3.80	4.51	
	β (%)	?	52	50	49	52	50	48	

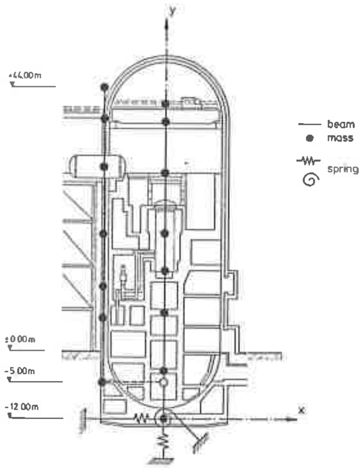

Figure 1: Basic model

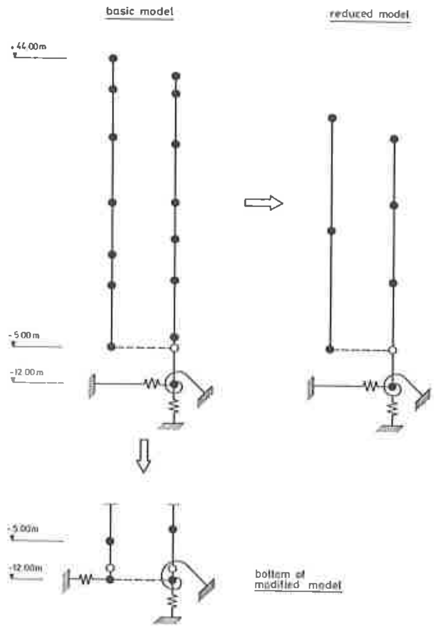

Figure 2: Derivation of the reduced and the modified model from the basic model

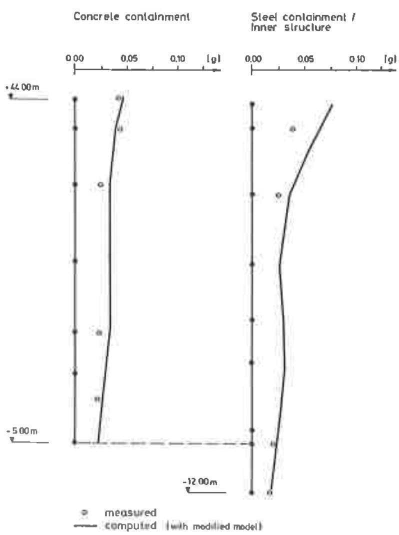

Figure 3: Computed and measured horizontal peak structural response to blast excitation

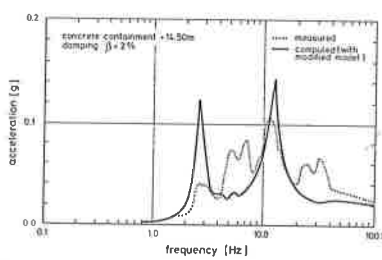

Figure 4: Example for comparison of floor response spectra