Evaluation of Response Factors for Seismic Risk Analysis of Nuclear Power Plants

Katsumi EBISAWA, Kiyoharu ABE
Japan Atomic Energy Research Institute, Tokaimura, Japan
Mamoru ITOH, Kunihiko KOHNO
Sato Kogyo Co., Ltd., Tokyo, Japan

1. INTRODUCTION

A level 1 seismic PSA consists of four tasks. They are seismic hazard analysis, realistic response analysis, component failure probability analysis, and system reliability analysis.

For the second task, analysis of realistic response of buildings, piping systems and components, two methods have already been provided. One is a detailed method developed in the course of Seismic Safety Margins Research Program (SSMRP) (Ref.1) and the other is a simplified method for the Zion PSA (Ref.2). In the simplified method, the safety margins included in the response analysis for seismic design are represented as "response factors".

In the JAERI's method, the realistic responses are evaluated by the response factor method but the fragilities of components are represented by functions of local responses similarly to SSMRP (Ref.3). Hence the realistic local responses must be evaluated for all the "elements" (structures, piping systems and components) in the system models. In order to make it possible, JAERI defined a set of response factors and quantified them based on the currently available data.

In this paper, the authors represent the outline of JAERI's method to evaluate the response factors as well as the evaluated results.

2. OUTLINE OF JAERI'S METHOD TO EVALUATE RESPONSE FACTORS

(1) Definition of response factors and classification of elements

The response factor (F_R) accounts for the difference between the design response with conservatism (q^D) and the realistic response (q^R) for each element in the nuclear power plant:

$$F_R = q^D / q^R \tag{1}$$

In evaluating the response factors, the elements were classified taking account of the differences in the geometries, sizes and installed places

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of the elements and in the vibration models used in their design response analyses. The classification is as follows:

- Elements
  - On ground
    - Inside the building
      - Decoupled on the building
        - One lumped mass model
        - Mult-lumped mass model
      - Coupled on the building
        - Mult-lumped mass model
    - Outside the building
      - Mult-lumped mass model
  - Underground
    - FEM model

(2) Decomposition of response factors into subfactors

The response factor for each element is derived from the product of several subfactors (F_i) which represent the margins introduced in various stages of the Japanese seismic design of a nuclear power plant.

F_1: generation of seismic wave
F_2: propagation of seismic wave
F_3: response of buildings
F_4: response of elements

These subfactors are illustrated in Figure 1.

Assuming that subfactors are independent on one another and has a probability density function represented by a logarithmic normal distribution, each response factor F_R is calculated by multiplying the subfactors:

$$F_R=F_1*F_2*F_3*F_4 \tag{2}$$

The logarithmic standard deviation of F_R is obtained from those of the subfactors using the SRSS (square root of the sum of the squares) method.

3 EVALUATION OF RESPONSE FACTORS AND SUBFACTORS

(1) Sample problem for quantification and evaluated results

The subfactors were evaluated for the following sample problem:
A BWR 5 with Mark II containment was assumed to be located at JAERI Tokai site. The vibration models were developed based only on the published data. The design responses of those elements were calculated using design response analysis codes.

The evaluated results are shown in Table 1. For some response factors or subfactors, the details of the evaluation methods are described below.

(2) Subfactor for generation of seismic wave, F_1

The response is a function of intensity, spectrum contents and duration time of the earthquake, which are functions of magnitude (M) and epicentral distance (Δ). Hence the subfactor for generation of seismic wave, F_1, should include the effects of these parameters (Ref.4).

The authors evaluated F_1 in two ways. First it was evaluated as a constant value. Second it was evaluated as a function of M, Δ and period (T):

$$F_1 = f(M, \Delta, T) \tag{3}$$

The magnitude and epicentral distance used in this function are "hazard-consistent magnitude" and "hazard-consistent distance" proposed by Kameda (Ref.5), which are defined as "conditional mean value given that the ground motion intensity exceeds the level specified by the annual probability of exceedance", respectively.

In this evaluation, F_1 was quantified by comparing the normalized design spectrum (S^D) for JAERI Tokai site with the normalized spectra (S^R) which were generated using 93 earthquake motion records (Ref.6), most of which were taken in Japan. The magnitudes and epicentral distances of these earthquakes are from 5.5 to 8.0 and from 35 to 300 km, respectively. Some records were for the ground motion and, in these cases, they were modified into the earthquake motions at bed rock by using the "Wave reflection-reaction theory".

S^D was calculated as the ratio of the design spectrum value to the maximum acceleration of the design ground motion at the bed rock. S^R were calculated as the ratio of the spectra values of the observed waves at bed rock to the maximum accelerations of these waves. These spectra were calculated for the period range from 0.04 to 0.4 second assuming 5% damping. The normalized spectrum of design earthquake motion and the normalized spectra of 24 records are shown in Figure 2 for 6.5 to 7.4 of magnitude and 29 to 40 km of epicentral distance.

Through this evaluation, it was found that F_1 depends significantly on magnitude and period but not so much on epicentral distance. The effect of M and Δ on F_1 is shown in Figure 3 for the low pressure core spray (LPCS) system pump which has a primary proper period of 0.123 second.

With F_1 and another subfactors, the failure probabilities of elements in various systems were calculated based on LaSalle seismic fragility data (Ref.7) using seismic PSA codes developed at JAERI (Ref.3). The failure probability of LPCS pump is shown in Figure 4.

(3) Response factor for control rod drive mechanism, $F_{R,CRDM}$

The design responses of the control rod drive mechanism (CRDM) are calculated by dynamic analysis using mult-lumped mass vibration model which takes account of the coupling to the reactor building.

The response factor for CRDM, $F_{R,CRDM}$, is calculated by Eq.(2). In this case, F_1 is the subfactor for the generation of seismic wave at the site and common to all the elements. F_2 to F_4 are specific to the buildings and elements. F_2 is for the propagation of seismic wave through the soil "under the reactor building", F_3 is for the response "of the reactor building", and $F_{4,CRDM}$ is "for the response of CRDM" to take account of the coupling to the the reactor building.

Through the evaluation of these subfactors, it was found that the soil-building foundation interaction and the usage of lumped mass vibration modeling would have large influence on $F_{R,CRDM}$. The response factors for the reactor pressure vessel and the fuel assembly, which are coupled on the reactor building, were also evaluated in the same manner.

(4) Response factor for sea water intake channel, $F_{R,SWIC}$

Since the vibration of underground structures follows the earthquake motions of the surrounding soil, the vibration of the underground structures such as the sea water intake channel (SWIC) is in general analyzed by the FEM model.

The response factor for SWIC, $F_{R,SWIC}$, was calculated as follows:

$$F_{R,SWIC}=F_1*F_{23} \tag{4}$$

where F_1 is the subfactor previously defined and F_{23} is the subfactor for the response of both soil and structure. The evaluation concluded that the shear modulus of soil would have a large influence on $F_{R,SWIC}$.

4. SUMMARY

In order to make it possible to evaluate the response factors for the structures, the piping systems and the components which appear in system models, these elements were classified into several groups according to the differences in their geometries, sizes, installed places and characteristics of the design response analysis. Then the response factors were evaluated for these elements, assuming that a BWR 5 with Mark II containment is located at JAERI Tokai site.

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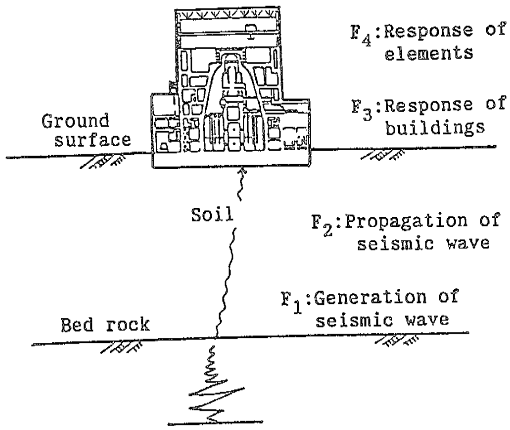

Figure 1 Illustration of response subfactors

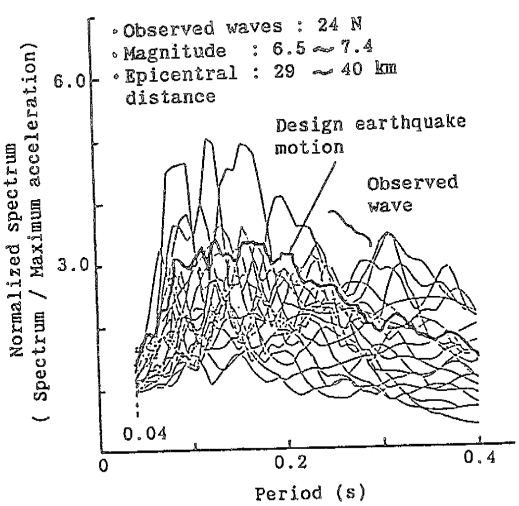

Figure 2 Normalized spectra of design earthquake motion and observed wave

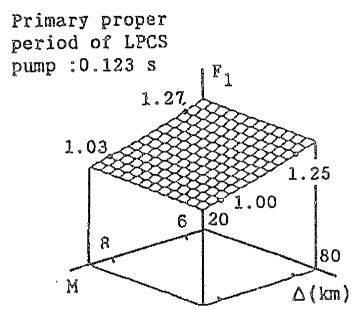

Figure 3 Effect of magnitude and epicentral distance on F_1

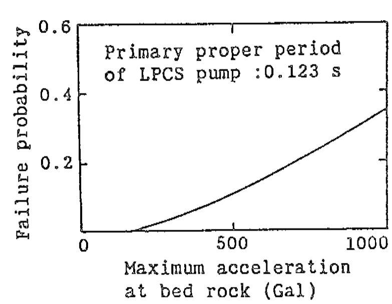

Figure 4 Failure probability of LPCS pump

Table 1 Evaluated results of response factors and subfactors

Installed places	Elements	Response subfactors: F1 Generation of seismic wave	F2 Propagation of seismic wave		F3 Response of buildings		F4 Response of elements		Response factors $F_{R,i}=\prod_{j=1}^{4} F_j$	
			$\overline{F_2}$	β_2	$\overline{F_3}$	β_3	$\overline{F_4}$	β_4	$\overline{F_{R,i}}$	β_{Ri}
On ground Inside the building (Reactor building)	Pump	·Constant							1.69	0.78
	Piping systems	$\overline{F_1}=1.22$					2.39	0.54	4.04	0.95
	Reactor pressure vessel	$\beta_1=0.13$	1.67	0.71	0.83	0.29	2.04	0.38	3.45	0.87
	Control rod drive mechanism	·Function					1.85	0.38	3.13	0.87
	Fuel assembly	$\overline{F_1}=aM+b\Delta+cT+d$					1.87	0.38	3.16	0.87
Outside the building	Transformer with ceramic insulator	a=-0.12 b=-0.0004	0.99	0.57			1.0	0.0	1.21	0.58
Underground	Intake channel	c=1.3 d=1.9	$\overline{F_{23}}=1.05$		$\beta_{23}=0.26$				1.28	0.29
	Intake pit	$\beta_1=0.13$	$\overline{F_{23}}=1.27$		$\beta_{23}=0.32$				1.55	0.35

$\overline{F_{1\sim4}}$: Median $\beta_{1\sim4}$: Logarithmic standard deviation
M:Magnitude, Δ:Epicentral distance (km), T:Period (s)
i:Elements j:Subfactors