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Influence of various parameters on effectiveness of seismic base isolation of nuclear equipments

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ABSTRACT: Authors developed a methodology and EBISA code for evaluating the applicability and the effectiveness of seismic base isolation of nuclear equipments.In order to investigate the influence of various parameters on the effectiveness of seismic base isolation, a sensitivity analysis was carried out for an emergency transformer with the base isolation devices. It was proved that seismic base isolation of equipment is very effective.This effectiveness can be influenced by the differences of the base isolation devices and the direction of the input seismic wave.

1 INTRODUCTION

Authors proposed a methodology for evaluating the applicability and the effectiveness of seismic base isolation for nuclear equipments [1].This methodology is based on the theory of Reliability Engineering and the method used in seismic Probabilistic Safety Assessment (PSA).Based on the above procedure, an Equipment Base Isolation System Analysis (EBISA) code was developed for evaluating the applicability and the effectiveness of seismic base isolation of equipments.

An emergency transformer which was identified to be important by previous seismic PSA [2] and usually used in Japanese commercial nuclear power plants was selected for the analysis.The transformer was seismically isolated by the base isolation devices of various types.In order to investigate the influence of various parameters on the effectiveness of seismic base isolation, a sensitivity study was carried out using the EBISA code.

This paper describes the results of sensitivity study on the differences of the isolation structure, the seismic base isolation device, its viscosity, and the frequency characteristic and the direction of input seismic wave.

2 METHODOLOGY FOR EVALUATING THE EFFECTIVENESS OF SEISMIC BASE ISOLATION OF NUCLEAR EQUIPMENTS

The procedure to evaluate the applicability and effectiveness of seismic base isolation of equipments consists of two steps; (1) quantitative evaluation and (2) comparative evaluation, as shown in Fig. 1.

In the first step, to decide the applicability of base isolated structures, the functional failure probability, F(t), during the life time, t (year), of equipment without base isolation devices is quantified. In the case that F(t) is significant in the context of safety and replacement cost considerations, the comparative evaluation is carried out.

In the second step, the ratio of the functional failure frequency, λ(1/year), without base isolation devices to that with them is quantified.The effectiveness can then be judged based on the ratio as shown in Fig. 1.

These F(t) and λ are estimated based on the methodology used in Reliability Engineering and the seismic PSA. F(t) can be calculated according to the formula:

$$F(t) = 1 - \exp(-\lambda \cdot t). \tag{1}$$

Parameter λ can be calculated using the density function of seismic hazard [3], $H(\alpha)$, which represents the annual exceedance occurrence frequency of ground motion level above α, and the functional failure probability, $p(\alpha)$, of equipment under α as follows:

$$\lambda = \int_0^{\infty} \left[\left(-dH(\alpha)/d\alpha \right) \cdot p(\alpha) \right] d\alpha. \tag{2}$$

If the seismic response, $f_R(\alpha, x)$, that affects the equipment failure is independent of the seismic capacity, $f_C(x)$, of the equipment, $p(\alpha)$ can be expressed as follows:

$$p(\alpha) = \int_0^{\infty} f_R(\alpha, x) \left\{ \int_0^{x} f_C(x)\, dx \right\} dx, \tag{3}$$

where $f_R(\alpha, x)$ and $f_C(x)$ are the probability density function of the logarithmic normal distribution. x represents parameters of acceleration and stress etc.

After both failure mode and vulnerable part of equipment are identified, the realistic response of equipment at the vulnerable part is estimated based on the response factor method [4]. In this method, the realistic response, $f_R(\alpha^D, x)$, against the design ground motion level α^D is estimated by dividing the design response, q^D, to α^D by the response factor F_R. Assuming that $f_R(\alpha^D, x)$ is proportional to an acceleration level α, the realistic response, $f_R(\alpha, x)$, is estimated according to the formula Eq. (4).
Where F_R is introduced as a measure of conservatism in seismic design analysis.
It is defined as a ratio of conservative design response to realistic response and has a probability density function represented by the logarithmic normal distribution of the median $\overline{F_R}$ and the logarithmic standard deviation β_R.

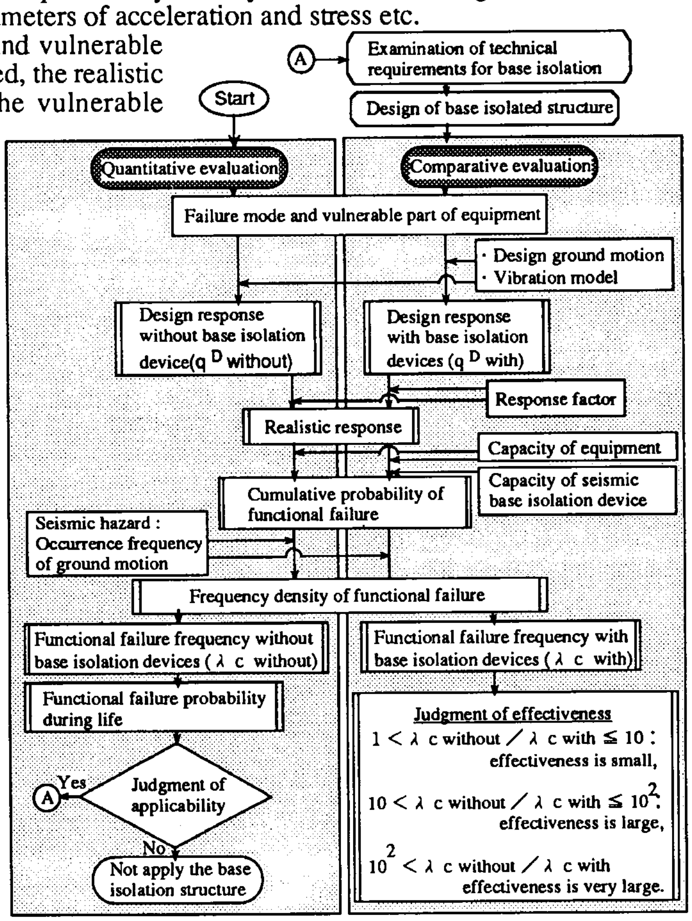

Fig.1 Evaluation methodology for applicability and effectiveness of seismic base isolated structure

$f_C(x)$ is also represented by the logarithmic normal distribution of the median M_C and the logarithmic standard deviation β_C to the formula Eq. (5).

$$f_R(\alpha, x) = \frac{1}{\sqrt{2\pi}\beta_R x} \exp\left[-\left(\ln x - \ln \frac{q^D \alpha}{\overline{F_R} \alpha^D} \right)^2 / 2\beta_R^{\,2} \right]. \tag{4}$$

$$f_C(x) = \frac{1}{\sqrt{2\pi}\beta_C x} \exp\left[-\left(\ln x - \ln M_C \right)^2 / 2\beta_C^{\,2} \right]. \tag{5}$$

3 CONDITUIONS OF SENSITIVITY ANALYSIS

3.1 SEISMIC BASE ISOLATION STRUCTURE

(1) Transformer with Ceramic Tubes
A high voltage type emergency transformer of 275 kV with ceramic tubes was selected for the analysis. This transformer was identified to be an important equipment by previous seismic PSA and usually used in Japanese commercial nuclear power plants. The transformer consists of three ceramic tubes charged with the isolation oil, the body and the foundation etc. as shown in Fig. 2. A weight of the ceramic tube and the body is about 1.9 and 78 tf, respectively.

The transformers are presumed to be in use for 40 years as a design life and to locate at Tokai site of the Japan Atomic Energy Research Institute (JAERI).

(2) Seismic Base Isolation Devices
The transformer was seismically isolated by the base isolation devices of three types; a high damping rubber bearings (HRB), a lead rubber bearing (LRB) and a ball bearing with coil springs and viscous dampers (BCV), which have a beneficial effect on base isolated structure of heavy equipment such as the transformer.They were installed on each pedestal of square corners between the body and the foundation as shown in Fig. 2.

Rated weight, horizontal stiffness corresponds to natural frequency and mean damping value for the above isolation devices are shown in Table 1.

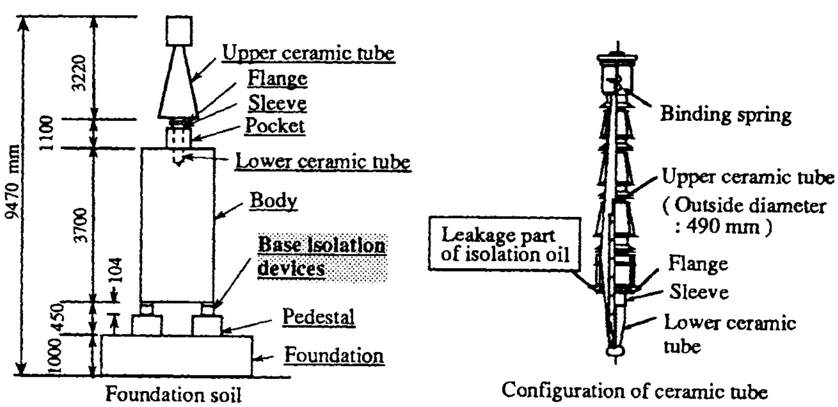

Fig.2 Geometry of transformer structure with ceramic tube and situation of base isolation devices

Table 1 Main specification of seismic base isolation devices

	Rated weight (tf)	Horizontal stiffness (Hz)	Mean damping value (%)
High damping rubber bearing (HRB)	20	1.0	14
Lead rubber bearing (LRB)		0.5	20
Ball bearing with coil springs and viscous dampers (BCV)		0.3	30

ł SEISMIC HAZARD, RESPONSE AND CAPACITY OF BASE ISOLATION STRUCTURE

Seismic Hazard
: seismic hazard at JAERI Tokai site which was estimated by one of the authors [3] (Fig. 3) was used in the analysis.

(2) Seismic Response
The realistic response of the transformer is estimated using its response factor F_R and design response q^D. The F_R estimated by one of the authors was used ($\overline{F_R}$ =1.21, β_R = 0.58) [5].The q^D was calculated by the direct integration method using the time history of design ground motion and the multi-lumped mass vibration model. In this model, the spring constants of sway and rocking represented the soil-transformer interaction have values of 1.6×10^4 ton/cm and 4.0×10^9 ton·cm/rad, respectively. The rocking spring constant between the sleeve and the upper ceramic tube has a value of 1.0×10^5 ton·cm/rad.

In the vibration model, the response of tube is considered to be dominated by the rocking spring between the sleeve and the upper ceramic tube.

(3) Seismic Capacity
The functional failure of the base isolation structure which consists of the transformer and isolation devices is supposed to be caused by at least one failure of the transformer and isolation devices.The smaller value between the functional failure value of the transformer and isolation devices was presumed to be the capacity of the isolation structure.

The vulnerable part of the transformer in section 3.1 was considered to be the area at the flange between the upper tube and the sleeve, and the functional failure mode was identified to be the leakage of isolation oil from at least one tube based on the records of disaster earthquake.The capacity of transformer were estimated by one of authors using the vibration test data for the functional failure of the transformer [1].

The functional failure mode of LRB or HRB was considered to be the shear rupture of rubber. One of BCV was presumed to be the leap of the ball bearings caused by the uplift of the ball bearing part. From comparing the capacity of the transformer with that of LRB or HRB, the capacity of the transformer with LRB or HRB was presumed to be derived from the transformer failure [6],[7]. In the same way, the capacity of the transformer with BCV was presumed to be derived from BCV failure [6],[7].

Each capacity of the transformer with LRB, HRB and BCV is shown in Table 2.

Table 2 Capacities of transformer with seismic base isolation devices

	Mean value (Gal)	Logarithmic standard deviation	Failure mode/ Vulnerable part
Transformer with high damping rubber bearing (HRB)	650	0.1	Leakage of isolation oil at flange between upper ceramic tube and sleeve
Transformer with lead rubber bearing (LRB)			
Transformer with ball bearing with coil springs and viscous dampers (BCV)	1440	0.2	Leap of ball bearings caused by uplift of BCV part

4 RESULTS OF SENSITIVITY ANALYSIS

4.1 PARAMETERS OF SENSITIVITY ANALYSIS

Parameters of the sensitivity analysis are as follows.

Case 1: the difference of structure; structure without and with base isolation devices,

Case 2: the difference of base isolation devices; LRB , HRB and BCV,

Case 3: the difference of BCV's viscosity by temperature; -3, 13.5 and 30 °C.,

Case 4: the difference of frequency characteristic of input seismic wave; S_1F^H (maximum acceleration: 287 Gal) of the predominant frequency of about 2.9 Hz by far earthquake, and S_1N^H (maximum acceleration: 267 Gal) of about 6.3 Hz by near earthquake, and

Case 5: the difference of direction of input seismic wave; S_1F^H of horizontal wave, and $S_1F^H_V$ that consists of both S_1F^H and S_1F_V (maximum acceleration: 137 Gal) of vertical wave.

4.2 RESULTS OF SENSITIVITY ANALYSIS

The results of the design response q^D and the functional failure frequency λ of transformer without isolation devices or with them for each case are shown in Table 3.

(1) Case 1: the difference of structure
The vulnerable part of transformer without isolation devices is the upper ceramic tube and $q^D_{without}$ at its part to S_1F^H was calculated to be about 755 Gal. An amplification to $q^D_{without}$ of maximum acceleration of S_1F^H is about 2.6.

By substituting $q^D_{without}$ and the estimated others values for Eq. from (2) to (5), the functional failure frequency, $\lambda_{without}$, of the transformer without isolation devices was calculated to be about 1.0x10^{-3}(1/year). From $\lambda_{without}$ and Eq. (1), F(40) during the life time of 40 years was about 4 %.

Assuming that this value is significant, the comparative evaluation was carried out.

(2) Case 2: the difference of base isolation devices
Each design response at the upper ceramic tube of transformer with LRB, HRB and BCV (temperature:13.5°C.) to S_1F^H was about 77, 185 and 49 Gal, respectively. Each amplification to q^D_{with} of maximum acceleration of S_1F^H ranges from about 1/2 to 1/6 for all the isolation devices. Thus, the effect of isolation system is very large.

Each vulnerable part of transformer with LRB and HRB is the upper ceramic tube and design response q^D_{with} at its part is about 77 and 185, respectively. The vulnerable part of transformer with BCV is the ball bearing part and q^D_{with} at its part is about 296 Gal.

Each functional failure frequency, λ_{with}, at the vulnerable part of the transformer with LRB, HRB and BCV was calculated to be about 2.0x10^{-8} (Case2-1), 4.7x10^{-6} (Case2-2) and 1.6x10^{-6} (1/year) (Case2-3), respectively. The ratio of $\lambda_{without}$ to λ_{with} for each devices is larger than about 10^3 for all the isolation devices. Fig. 3 shows cumulative probabilities and frequencies densities of functional failure of transformer with base isolation devices or without them as a function of the acceleration level at bedrock.
From these results, it is proved that seismic base isolation of equipment is very effective.

Table 3 Results of design responses and functional failure frequencies for each case on sensitivity analysis

Case	Base isolation devices	Seismic wave	Tempera-ture	Design response at upper ceramic tube qD (Gal)	Design response at vulnerable part qD (Gal)	Functional failure frequency l (1/year)
Case 1	without base isolation devices	S_1F^H	-	755	755	1.0×10^{-3}
Case2-1	with LRB	S_1F^H	-	77	77	2.0×10^{-8}
Case2-2	with HRB	S_1F^H	-	185	185	4.7×10^{-6}
Case2-3	with BCV	S_1F^H	13.5°C	49	296	1.6×10^{-6}
Case3-1	with BCV	S_1F^H	30°C	40	296	1.6×10^{-6}
Case3-2	with BCV	S_1F^H	- 3°C	78	296	1.6×10^{-6}
Case 4	with LRB	S_1N^H	-	52	52	5.2×10^{-9}
Case 5	with LRB	$S_1F^H_V$	-	191	191	1.3×10^{-5}

LRB : Lead rubber bearing HRB : High damping rubber bearing BCV : Ball bearing with coil springs and viscous dampers
S_1F^H,S_1N^H : Only horizontal direction of input seismic wave S_1F or S_1N
$S_1F^H_V$: Both horizontal and vertical direction of input seismic wave S_1F

(3) Case 3: the difference of BCV's viscosity by temperature
Each design response at the upper ceramic tube of transformer with BCV of temperature of -3 and 30°C. to S_1F^H was about 78 and 40 Gal, respectively. Each amplification to these design response of maximum acceleration of S_1F^H ranges from about 1/4 to 1/7, respectively. Then the effect of BCV system is larger than that of LRB or HRB.

Each λ_{with} for the above temperature are the same 1.6×10^{-6} (1/year) as case2-3. Because the design response at the vulnerable part is the same value 296 Gal as case2-3. In this case, the effectiveness of seismic base isolation is independent of the temperature.

(4) Case4: the difference of frequency characteristic of input seismic wave

The q^{D}_{with} at the upper ceramic tube of transformer with LRB to S_1N^H was about 52 Gal. λ_{with} estimated was smaller than that to S_1F^H (Case 2-1).

From this result, it is proved that the effectiveness of the seismic base isolation of equipment to the wave of high predominant frequency is lager than that to low frequency.

(5) Case 5: the difference of direction of input seismic wave

The q^{D}_{with} at the upper ceramic tube of transformer with LRB to $S_1F^H_V$ was about 191 Gal.The λ_{with} in this case was over three order larger than that to S_1F^H (Case 2-1).

From this result, it is proved that the effectiveness of seismic base isolation of equipment is influenced by the differences of direction of the input seismic wave.

5 SUMMARY

In order to investigate the influence of various parameters on the effectiveness of seismic base isolation of nuclear equipments, a sensitivity analysis was carried out using EBISA code. From the results of sensitivity analysis,it is proved that seismic base isolation of equipment is very effective.
Therefore it can be applied to improve the plant safety.

The effectiveness of seismic base isolation can be influenced by the differences of the base isolation devices and the component of the input seismic wave.

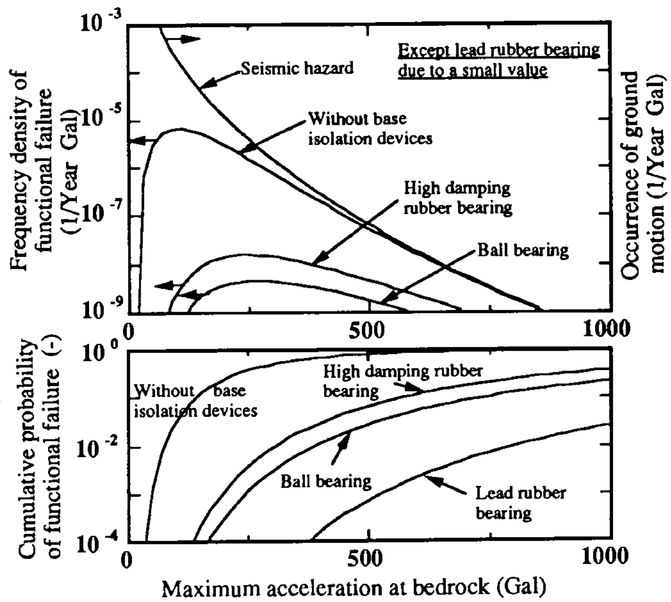

Fig.3 Calculated results of cumulative probabilities and frequency densities of functional failure of transformer with ceramic tube and with base isolation devices or without them

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