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Influence of soil properties on response of seismic base isolation of nuclear equipments

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ABSTRACT: In order to investigate the influence of soil property on the performance of seismic base isolation for nuclear equipment, the response of emergency transformer without and with isolation devices is evaluated under the condition of the soil shear wave velocity (Vs) of range from 100 to 1500 m/sec. It was proved that the acceleration response of a component with devices is insensitive to the soil velocity except for Vs below 150 m/sec.

1 INTRODUCTION

Seismic base isolation of equipments is one of promising technique to reduce seismic risk of an existing or new plant. In order to establish design methodology of seismic base isolation of equipments, two studies have been carried out.

One is the study to develop a methodology for evaluating the effectiveness of seismic isolation of nuclear equipments. The methodology was developed by applying the theory of Reliability Engineering and the method used in seismic Probabilistic Safety Assessment (PSA) [1]. Based on this methodology, EBISA code has been developed [2]. An emergency transformer, which was identified to be an important equipment by previous seismic PSA [3], was selected for the case study of effectiveness evaluation by EBISA code. It was proved that the effectiveness can be influenced by the differences of the isolation devices and the direction of the input seismic wave [4]. In this study, however, an influence of soil property was not considered.

The another is the study to establish the design concept of seismic isolation of nuclear equipments. The equipments installed in various places both inside and outside the building were considered to be investigated. Thus various examinations corresponding to each installation condition are necessary. As for the equipments installed inside the building, it is important to evaluate the influence of building behavior on equipment response. From this viewpoint, the floor response in a BWR reactor building was studied [5].

On the other hand, as for the equipments outside the building, the influence of soil property on equipment response should be examined. In order to investigate the influence of soil property on the performance of seismic isolation for nuclear equipment, the above transformer was selected for the analysis. The influence of the shear wave velocity of soil property on the response of transformer with isolation devices was evaluated.

This paper describes the evaluation results of the influence of the soil shear wave velocity on the response of transformer with isolation devices.

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

The procedure to evaluate the applicability and effectiveness of seismic isolation of equipments consists of two steps; quantitative and comparative evaluations, 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.

$F(t)$ 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 [6], $H(\alpha)$, 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. The $f_R(\alpha, x)$ is estimated based on the response factor method [7].

3 CONDITIONS OF RESPONSE ANALYSIS

3.1 Seismic Base Isolation Structure

(1) Structure of Transformer with Ceramic Tubes

The high voltage type emergency transformer of 275 kV consists of three ceramic tubes charged with the isolation oil, the body and the foundation etc. as shown in Fig. 2. The ceramic tube has a length of 3.22 meters, the maximum outside diameter is 490 millimeters. A weight of the ceramic tube and the body is about 1.9 and 78.1×10^3 kgf, respectively.

(2) Seismic Base Isolation Devices

The transformer is seismically isolated by the base isolation devices of a lead rubber bearing (LRB) type, which is suitable for heavy equipment such as the transformer. It is installed on each pedestal of square corners between the body and the foundation as shown in Fig. 2.

The bearing has a rated weight of 20×10^3 kgf, the horizontal stiffness corresponds to the natural period of 1.98 sec and the mean damping is about 20 %.

(3) Failure Mode of Transformer

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 vulnerable part of the transformer is assumed to be the area at the flange between tube and sleeve, and the functional failure mode was identified to be the leakage of isolation oil at least one tube based on the records of disaster earthquake [1].

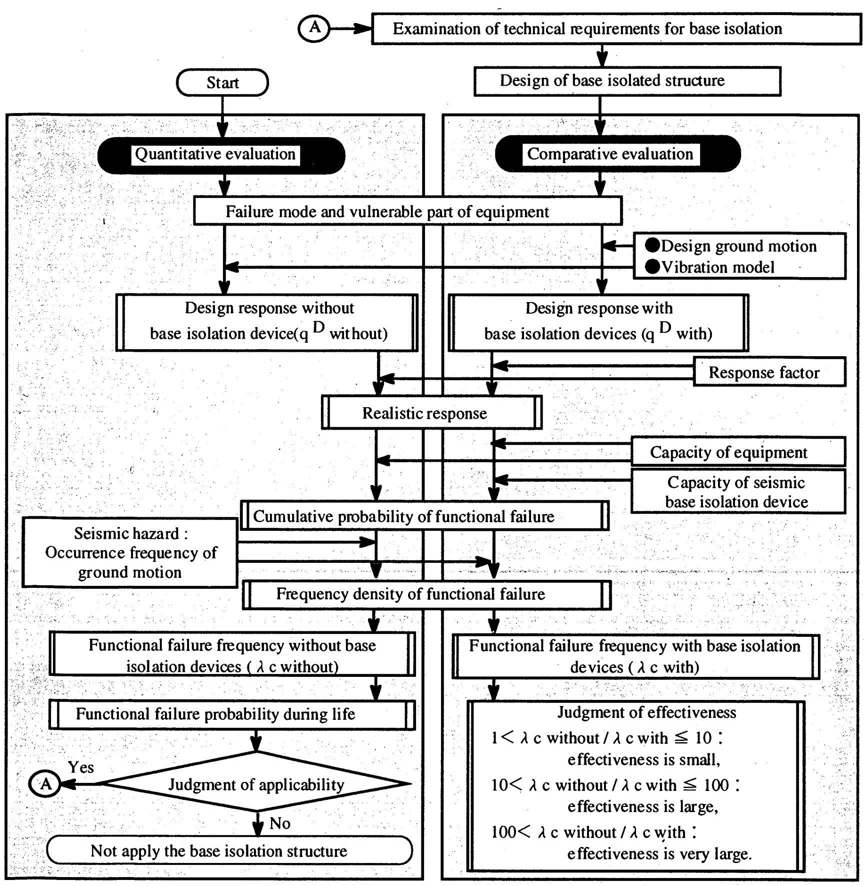

Fig.1 Evaluation methodology for applicability and effectiveness of seismic isolated structure

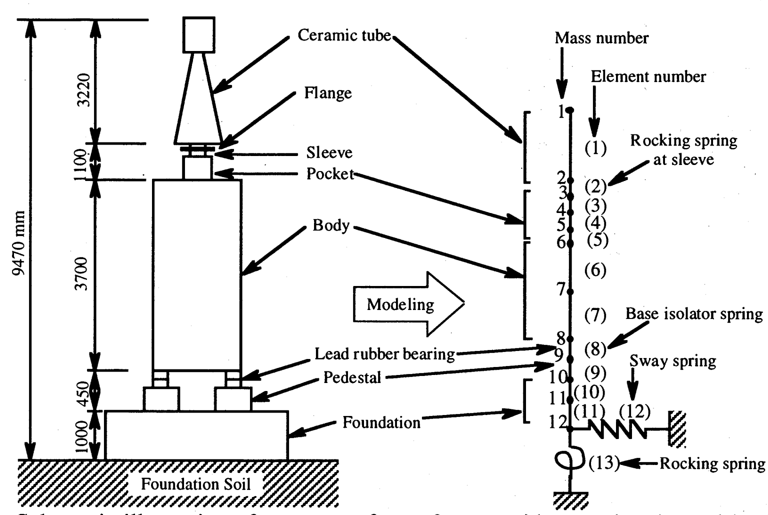

Fig.2 Schematic illustration of structure of transformer with ceramic tube and lead rubber bearing and multi-lumped mass vibration model

3.2 Response Analysis

(1) Procedure of Response Analysis

The responses of the transformer are calculated by the direct integration method using the time history of seismic motion and the multi-lumped mass vibration model as shown in Fig.2.

The main specification of the above vibration model can be described: The spring constants of sway and rocking, which represent the soil-transformer interaction, are estimated by the following Whitman and Richart theory [8] using the soil material values of the various shear wave velocities (Vs) of 100, 150, 300, 500, 1000 and 1500 m/sec.

$$K_S = 2(1+\nu)\cdot G\cdot \beta_x \cdot \sqrt{BL}, \qquad C_S = 0.576 K_S \cdot R_S \cdot \sqrt{\frac{\gamma}{g\cdot G}}, \tag{4}$$

$$K_R = \frac{G}{1-\nu}\cdot \beta_\phi \cdot B \cdot L^2, \qquad C_R = \frac{0.30}{1+\beta_\phi}\cdot K_R \cdot R_R \cdot \sqrt{\frac{\gamma}{g\cdot G}}, \tag{5}$$

$$G = \frac{\gamma\cdot (V_S)^2}{g}, \tag{6}$$

where K_S and C_S are stiffness (kgf/cm) and damping coefficient (kgf・sec/cm) of sway spring, K_R and C_R stiffness (kgf・cm/rad) and damping coefficient (kgf・cm・sec/rad) of rocking spring, and G shear modulus (kgf/cm^2). The nomenclature and values of the others parameters in the above equations are shown in Table 1. The spring constants of sway and rocking corresponding to each value of the above shear wave velocity are shown in Table 2.

The sway spring constant of LRB is 5.1×10^2kgf/cm. The rocking spring constant between the sleeve and the ceramic tube is based on data of the Society of Electrical Co-operative Research and has a value of 1.0×10^8 kgf・cm / rad [9].

Table 1 Nomenclature and Values of Each Parameter in Evaluation Equations of Sway and Rocking Constants

γ	Density of Soil	2.1×10^{-3}(kgf/cm^3)	R_S	Equivalent Radius of Foundation for Sway Spring	691(cm)
ν	Poisson's Ratio of Soil	0.438	R_R	Equivalent Radius of Foundation for Rocking Spring	2764(cm)
g	Acceleration of Gravity	980(cm/sec^2)	β_x	Correct Constant of Sway Spring depending on Ratio of L/B	1.1
B	Width of Foundation	1500(cm)	β_ϕ	Correct Constant of Rocking Spring depending on Ratio of L/B	0.46
L	Length of Foundation	1000(cm)			

Table 2 Evaluation Results of Shear Modulus, Sway and Rocking Spring Constants of Soil

		Shear Wave Velocity Vs (m/sec)					
		100	150	300	500	1000	1500
Sway	Stiffness $K_S\times10^5$ (kgf/cm)	8.3	18.7	74.7	207.5	830.0	1867.5
	Damping Coefficient $C_S\times10^3$ (kgf・sec/cm)	33.0	49.6	99.1	165.2	330.0	495.5
Rocking	Stiffness $K_R\times10^{11}$ (kgf・cm/rad)	2.6	5.9	23.7	65.7	262.9	591.4
	Damping Coefficient $C_R\times10^9$ (kgf・cm・sec/rad)	20.3	30.4	60.8	101.3	202.5	303.8
Shear Modulus $G\times10^2$ (kgf/cm^2)		2.1	4.8	19.3	53.6	214.3	482.1

(2) Input Seismic motions

Seismic motions, S_1F and S_1N, with different characteristics are chosen on input data. They are obtained from the maximum design earthquake in accordance with the Regulatory Guide [10] and used as the design basis ground motions for the structures and equipments of Japanese nuclear power plants.

S_1F has the predominant frequency of about 2.7 Hz, and the maximum acceleration of 287 Gal. S_1N has that of about 6.7 Hz, and 267 Gal.

These acceleration response spectra are shown in Fig. 3.

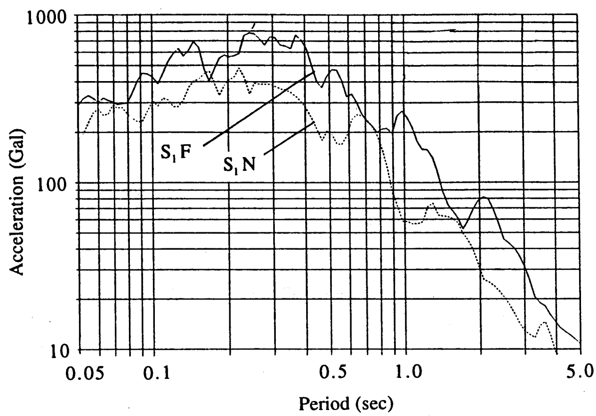

Fig.3 Acceleration Response Spectra of S_1F and S_1N

4 RESULTS OF RESPONSE ANALYSES

4.1 Natural Period of Transformer without and with Isolation Devices

The natural periods of the transformer without and with isolation devices under Vs range from 100 to 1500 m/sec are shown in Table 3.

From Table 3, the primary period of transformer without devices depends on the rocking of the ceramic tube and is the almost constant value of 0.15 and/or .013 sec. The secondary period depends on the sway of the foundation which represents the soil-transformer foundation interaction, and decreases gradually and settles down to the almost constant level of 0.02 sec with an increase of Vs. The primary and secondary periods at Vs of 100 m/sec are similar.

On the other hand, the primary and secondary periods of transformer with devices are 1.98 sec by the sway of the isolation devices and 0.14 sec by the rocking of the ceramic tube, respectively and are almost similar value for the range of Vs examined.

Table 3 Natural period of Transformer without and with Isolation Devices

Natural Period		Shear Wave Velocity of Soil Vs (m/sec)						Remarks
		100	150	300	500	1000	1500	
Without Isolation Devices	Primary (sec)	0.15	0.13	0.13	0.13	0.13	0.13	Rocking of Ceramic Tube
	Secondary (sec)	0.13	0.10	0.05	0.03	0.02	0.02	Sway of Foundation
With Isolation Devices	Primary (sec)	1.98	1.98	1.98	1.98	1.98	1.98	Sway of Isolation Devices
	Secondary (sec)	0.14	0.14	0.14	0.14	0.14	0.14	Rocking of Ceramic Tube

4.2 Responses of Transformer without Isolation Devices

The acceleration at the ceramic tube without isolation devices to S_1F and S_1N are calculated under Vs range from 100 to 1500 m/sec.

Fig.4 shows the acceleration response time histories at the ceramic tube at Vs of 100 and 1500 m/sec to S_1F. The maximum accelerations are about 1024 and 702 Gal, respectively. Fig.5 shows the relationship between the maximum acceleration and Vs to S_1F and S_1N.
As shown in Fig.5, the responses of transformer are very high at Vs of 100 m/sec, while it decreases steeply and settles to the almost constant level with an increase of Vs.

Under the response analysis conditions of this paper, the sway and rocking stiffness are considered to be soft in Vs range below 150 m/sec and to be rigid over 150 m/sec. Thus the influence of the soil property on the responses of transformer is large at Vs range below 150 m/sec but not over 150 m/sec.

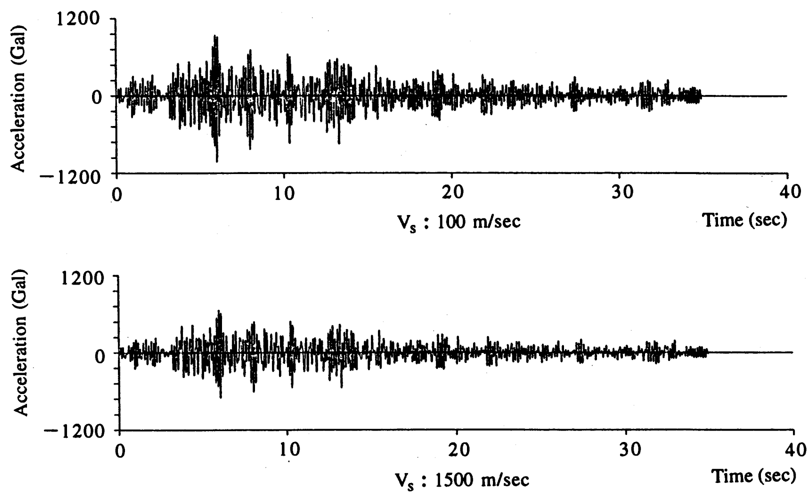

Fig.4 Acceleration Response Time Histories at the Ceramic Tube at Vs of 100 and 1500 m/sec to S_1F

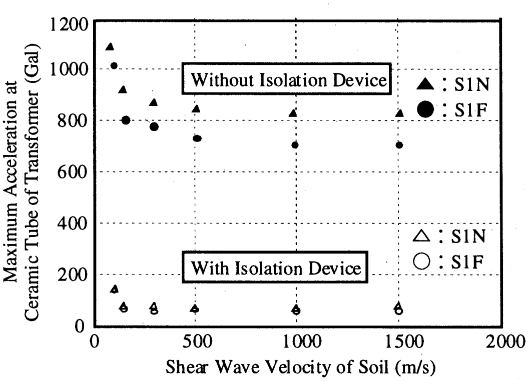

Fig.5 Relationship between Maximum Acceleration of Ceramic Tube and Shear Wave Velocity of Soil

4.3 Responses of Transformer with Isolation Devices

The acceleration responses of the transformer with isolation devices to S_1F and S_1N are calculated under the same condition as that without devices. The acceleration response time histories at the ceramic tube and the transformer body at Vs of 100 and 1500 m/sec to S_1F are shown in Fig.6 and Fig.7, respectively. The relationships between the maximum accelerationof the ceramic tube part and Vs to S_1F and S_1N are also shown in Fig.5.

The acceleration time histories of the transformer body as shown in Fig.6 and Fig.7 are dominated by the isolation devices that have natural period of 1.98 sec. On the other hand, it is shown that the time histories of the ceramic tube having that of 0.14 sec are superposed on that of the body.

From Fig.5, it is found that the acceleration responses of the transformer with devices are much smaller than that without devices and the acceleration values are almost constant for the range of Vs examined except for Vs below 150 m/sec.

These results indicate that the acceleration of a component with isolation devices is insensitive to the soil velocity except for Vs below 150 m/sec, since the stiffness of isolation devices are much smaller than that of soil.

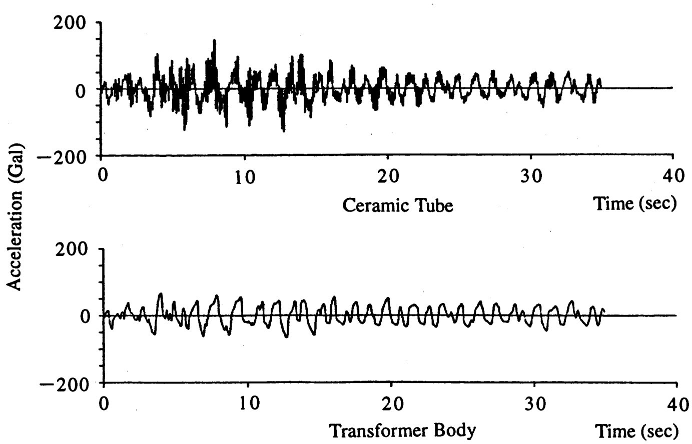

Fig.6 Acceleration Response Time Histories at Vs of 100 m/sec to S_1F

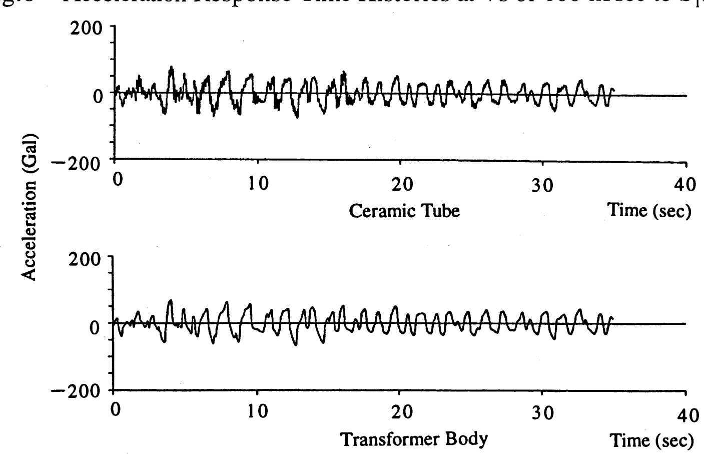

Fig.7 Acceleration Response Time Histories at Vs of 1500 m/sec to S_1F

5 SUMMARY

In this paper, it is indicated that the acceleration of a component with the isolation devices is insensitive to the soil velocity except for Vs below 150 m/sec.
Thus the shear wave velocity of soil is not important parameter except for Vs below 150 m/sec and its influence on the acceleration of a component outside the building may be ignored in the seismic base isolation design except for the above Vs range.

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