Reliability Analysis for Seismically Isolated FBR System

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INTRODUCTION

In recent years base isolation system has been applied for important structures such as those of nuclear facilities, and introducing the isolation system to FBR system to be constructed in seismically active region is planned. And for those structures evaluation of reliability for earthquakes is emerging as a matter of concern. For non-isolated LWR systems extensive studies have been conducted and the methodology regarding to seismic PSA has been developed so far[1][2]. However, for the isolated structures with natural period considerably longer than that of non-isolated structure and isolators behaving inelastically under design earthquake motion, the method developed for non-isolated structure can not be applied directly.

In this paper a simplified method for the evaluation of fragility of the isolated structure is presented, and the result of fragility analysis is shown.

Studies presented in this paper forms a part of a research project "Aseismic Proving Test of Seismic Isolation System for Fast Breeder Reactor(FY 1987-1993)" sponsored by Ministry of International Trade and Industry of Japan. Outline of the project is presented in Ref. [3].

SELECTION OF INPUT PARAMETER IN FRAGILITY ANALYSIS

In the seismic PSA of non-isolated structure, usually probability of failure is expressed as a function of peak ground acceleration Ap which is considered as the "best" parameter in describing ground motion intensity-response relationship. However, for the isolated structure of which the natural period is 1.0-2.0 second, and behaves inelastically under design earthquake motion, Ap might no more be the best parameter, and peak ground velocity Vp might be the best parameter. To verify this we conducted response analyses of isolated FBR building(Fig. 1) using 12 observed earthquake records and 3 artificial earthquakes, where restoring characteristics of the isolator is modeled with bi-linear model(Fig. 2). Natural periods of the isolated building corresponding to the first and the second stiffness K1, K2 of the bi-linear spring are 1.0 sec. and 2.0 sec., and the yield displacement δy of the bi-linear spring is 1.24 cm.

Observed earthquake records are scaled to 10 and 20 times as large as the original ones so that the isolator will deform beyond its elastic limit and the ductility factor (defined as the ratio of maximum displacement to yield displacement) will be considerably large. Maximum acceleration of the artificial earthquake waves is scaled to several levels, and 35 earthquake waves with different peak acceleration are used in all. The ratios of Ap to Vp of the input motion range from 4.1 to 25.6. For the artificial earthquakes which are rich in long period components, the ratio Ap/Vp is smaller than that of the observed ones(Fig. 3).

Result of non-linear response analyses shows the maximum displacement of the isolator has stronger correlation with Vp than with Ap (Figs. 4 and 5). Linear relationship between the maximum acceleration at the support level of the reactor vessel(Fig. 1) and the maximum displacement of the isolator(Fig. 6) indicates other response quantity such as inter-story shear force also has strong correlation with the peak ground velocity Vp(Fig. 7).

Description of Method

In the estimation of reliability for elasto-plastically behaving structure under strong earthquake motion, a method using reliability index is proposed by Kanda[4][5]. Here the method is applied in the estimation of the fragility of the isolated structure. Outline of the method is as follows.

Regression Analysis between Input Motion Intensity and Response

Using the results of non-linear response analyses, relationship between input motion intensity and the response is evaluated via regression analysis(e.g., linear regression). And in this case usually the response is converted to "equivalent linear response" which is defined as the response of linear system with the same potential energy as that of the elasto-plastic system(Fig. 2).

Estimation of Reliability Index under Given Input Motion Intensity

Safety margin of the member of the structure Sf which is defined as the ratio of the ultimate strength to the response is given as

$$Sf = R^*/Q^* \qquad [1]$$

where R* and Q* are the ultimate capacity and the response, and * stands for the equivalent linear response or equivalent linear capacity.

Assuming that R* and Q* follow log-normal distribution, reliability index β of the member is given as

$$\begin{aligned}\beta &= E[\ln R^*/Q^*(e)]/D[\ln R^*/Q^*(e)] \\ &= E[\ln R^* - \ln Q^*(e)]/\sqrt{(D^2[\ln R^*] + D^2[\ln Q^*(e)])} \qquad [2]\end{aligned}$$

where $E[\cdot]$ and $D[\cdot]$ mean the expectation and the standard deviation. From the assumption of log-normal distribution,

$$E[\ln R^*] = \ln E[R^*] - (1/2)D^2[\ln R^*], \quad D^2[\ln R^*] = \ln(1 + \delta^2{}_{R^*}) \qquad [3]$$

where δ_{R^*} is c.o.v. of R*. Equivalent response Q* is expressed as a function of intensity of input earthquake e(e.g., peak ground velocity Vp or peak ground acceleration Ap)by regression analysis (Figs. 7 and 8) and the reliability index is given as a function of e. Probability of failure Pf of the member is given using the reliability index β as

$$Pf(e) = 1 - \Phi(\beta(e)) \qquad [4]$$

where Φ is the normal distribution function. Using Eq.[4], fragility of the member of the structure is evaluated.

Confidence Interval of Probability of Failure

Functional relation between the response Q* and the intensity of earthquake motion is given by the regression analyses of sample of size n which is the number of earthquake waves used in the response analyses, where the regression curve is considered to give the best estimate. Scatter of Q* around the regression curve(Figs. 7 and 8) shows uncertainty of response for specified ground motion intensity, and the uncertainty is evaluated by confidence interval.

Suppose that the functional relation between Q* and e(intensity of earthquake ground motion) is linear as

$$Q^* = \alpha_0 + \alpha_1 \cdot e \qquad [5]$$

then the estimation interval of Q* for specified intensity of input motion e_0 with the confidence interval of $100(1-\alpha)\%$ is given as[6]

$$\hat{\alpha}_0 + \hat{\alpha}_1 \cdot e_0 \pm t(n-2, \alpha) \sqrt{[1 + 1/n + (\bar{e} - e_0{}^2)/S_{ee}]/V_e} \qquad [6]$$

where $\hat{\alpha}_0$ and $\hat{\alpha}_1$ are the least square estimates of α_0 and α_1, $t(n-2, \alpha)$ is the α percentile value of the t-distribution with (n-2) degrees of freedom, $\bar{e}$ is the mean of intensity of each input earthquake motion e_i, See is given by

$$S_{ee} = \Sigma (e_i - \bar{e})^2 \qquad [7]$$

And Ve is the unbiased estimate of variance of error given as

$$V_e = S_e/(n - 2) \qquad [8]$$

and Se is the sum of the squared errors given as

$$S_e = \Sigma (Q_i{}^* - (\hat{\alpha}_0 + \hat{\alpha}_1 \cdot e_i))^2 \qquad [9]$$

Estimation of Fragility

Modeling of the Isolated Structure

Reference FBR building for the fragility estimation is modeled with 17-lumped mass system(Fig. 1). Restoring characteristics of the isolator is given by bilinear model and the ultimate displacement of the isolator is 1.0m. The skeleton curve for the member of the upper structure is modeled with trilinear curve. And the result of response analyses shown in "SELECTION OF INPUT PARAMETER IN FRAGILITY ANALYSIS" is made use of in the estimation of fragility.

Although within the level of the input earthquake used in the analyses, upper structure behaved elastically, the skeleton curve is made use of in the assessment of the ultimate strength of the member in terms of the "equivalent elastic ultimate strength".

Result of Estimation

Linear regression analysis between peak ground velocity Vp and response of each member is conducted and the functional relation is evaluated(Figs. 7 and 8). The fragility estimated using Eqs.[2] through [4] and these functional relations gives median fragility(indicating 50% non-exceedance probability of failure)of the member. And the upper and lower limit of the confidence interval of the fragility is estimated by Eq.[6]. The confidence interval is 90% and the upper and the lower limits correspond to 95% and 5% non-exceedence probability of failure. Probability of failure for the upper structure is smaller than that for the isolation element(Figs 9 and 10), which is explained from the concentration of earthquake energy to the isolators indicating that the reliability of the isolation system is largely dependent on that of the isolator. As an example of sensitivity study, fragility of the isolator is estimated with median value of the ultimate displacement Dr as a parameter[Fig. 11]. Using the method prosed in this paper such parametric survey can easily be conducted once a set of response analyses are made.

CONCLUSIONS

Conclusions of this paper are summarized as follows.

(a)Response of the isolated reactor building has strong correlation with peak ground velocity Vp, and the fragility of the isolated building is proper to be estimated in terms of Vp rather than peak ground acceleration Ap.
(b)Estimation method of reliability for non-linear structure using reliability index is applied to the estimation of the fragility of the isolated FBR building and the reliability of the isolator proved to be influential in the total reliability of the isolated FBR system.

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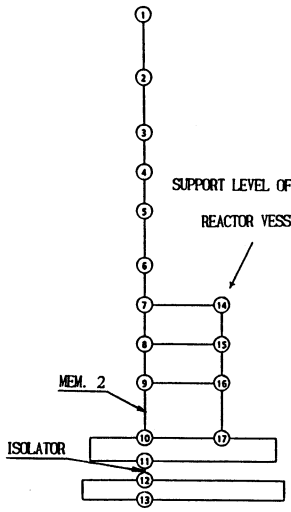

FIG. 1 LUMPED MASS MODEL FOR FBR BUILDING

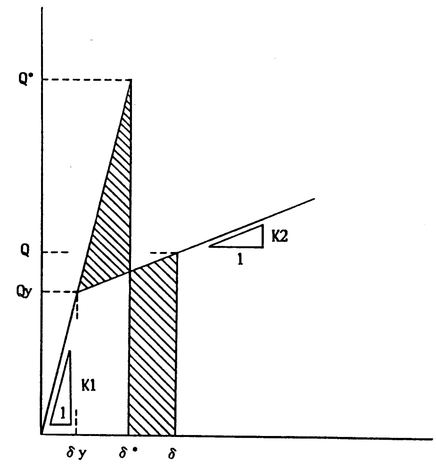

FIG. 2 BI-LINEAR MODEL FOR ISOLATOR AND CONCEPT OF EQUIVALENT LINEAR RESPONSE

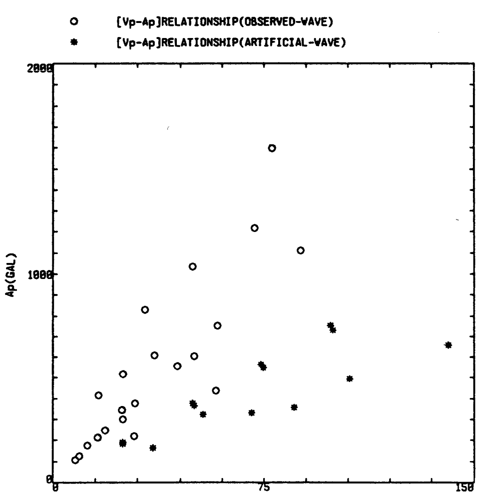

FIG. 3 V_P vs A_P OF EARTHQ. WAVES

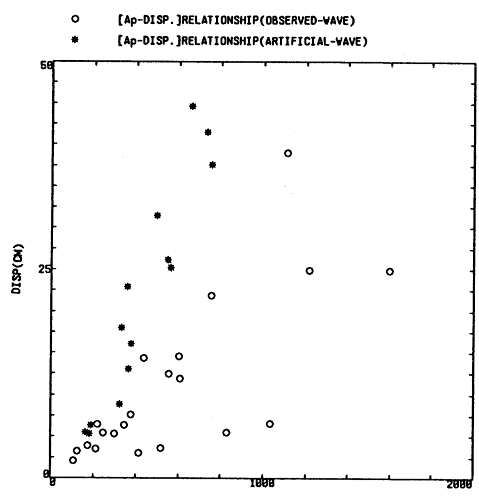

FIG. 4 A_P vs MAX. DISP. OF ISOLATOR

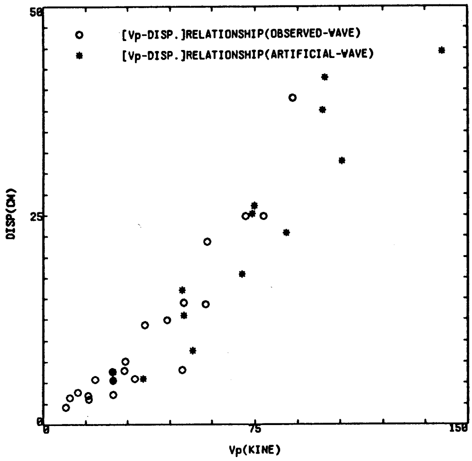

FIG. 5 V_P vs MAX. DISP. OF ISOLATOR

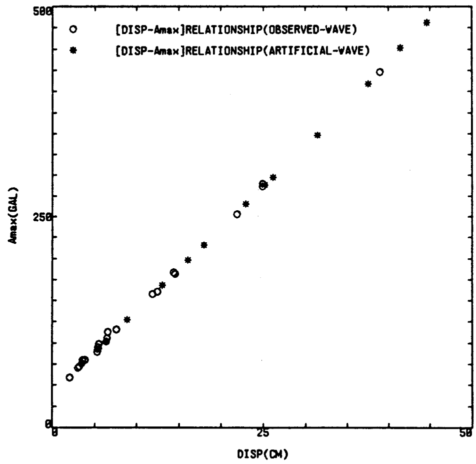

FIG. 6 MAX. DISP. OF ISOLATOR vs A_{MAX} AT SUPPORT LEVEL OF REACTOR

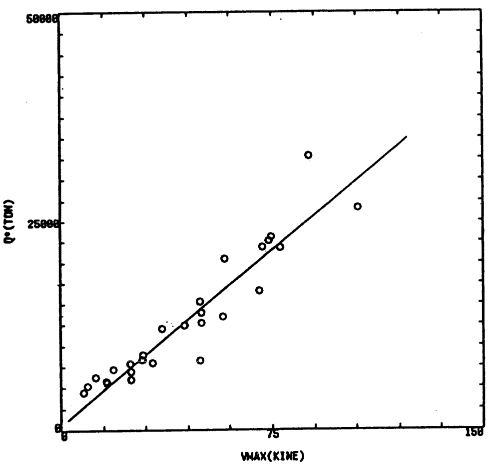

FIG. 7 LINEAR REGRESSION OF Q* ON V_P (BLDG. MEM. 2)

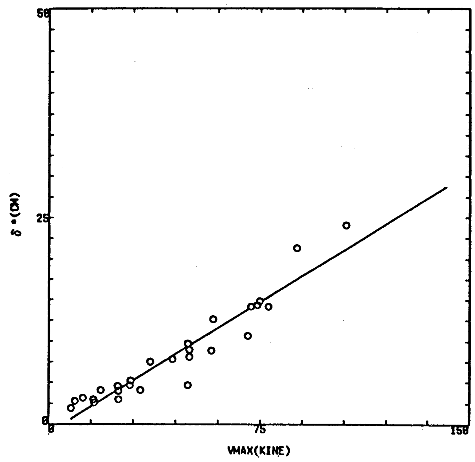

FIG. 8 LINEAR REGRESSION OF δ* ON V_P (ISOLATOR)

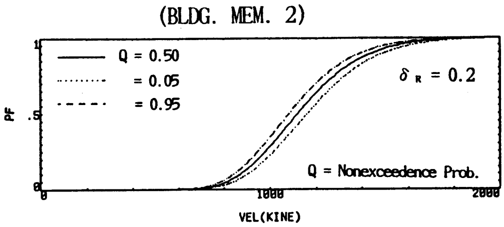

FIG. 9 FRAGILITY CURVE FOR BLDG. MEM. 2

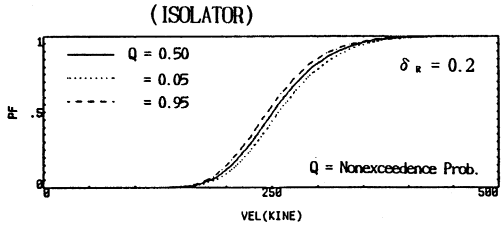

FIG. 10 FRAGILITY CURVE FOR ISOLATOR

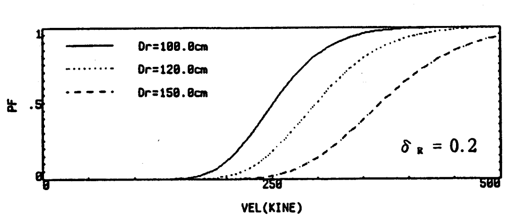

FIG. 11 FRAGILITY CURVE FOR ISOLATOR (PARAMETER: DISP. CAPACITY)