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FRAGILITY ESTIMATION FOR SEISMICALLY ISOLATED NUCLEAR STRUCTURES BY HCLPF VALUES AND BI-LINEAR REGRESSION

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ABSTRACT

A method for the fragility estimation of seismically isolated NPP structures is proposed, based upon both HCLPF (high confidence low probability of failure) values and bi-linear regression. LHS (Latin Hypercube Sampling) techniques are also involved.

1 INTRODUCTION

The fragility concept has been increasingly used in the seismic PRA (Probabilistic Risk Assessment) of nuclear plant structures during the last decade. Specific problems are encountered in the case of seismically isolated NPP structures [1,2], e.g., the necessity to consider both bi- and tri-linear hysteretic models for isolation layer / upper structure behaviour under earthquake input motion.

The method presented in [1,2] is based on the regression analysis between the response and the intensity of the input motion. The peak ground velocity V_{max} is taken as 'explanatory variable' in this regression analysis due to its strong correlation with the seismic response of isolated nuclear structures.The relationship between V_{max} and the response of the isolation layer and a member of super structure (respectively) is expressed by the bi-linear function

$$Q = b_o + b_1 x_{o1} + z \cdot b_2 x_{o2} \tag{1}$$

where b_o, b_1, b_2 = regression coefficients and x_{o1}, x_{o2} are independent variables given by

$$\begin{aligned} x_{o1} &= V_{max} \\ x_{o2} &= 0 \qquad\qquad , \; z = 0 \quad \text{if} \quad V_{max} \leqq V_{max_h} \; . \\ &= V_{max} - V_{max_h}, \; z = 1 \quad \text{if} \quad V_{max} > V_{max_h} \end{aligned} \tag{2}$$

In Eqs.(2), z is a dummy variable and V_{max_h} is the value of

V_{max} at the intersection of two line segments, determined so that it will give the largest multiple correlation coefficient.

Assuming the the ultimate capacity R of both the isolation layer and the member of the upper structure, as well as the maximum response Q, are lognormally distributed, the reliability index β for each component is given as a function of V_{max} by

$$\beta(V_{max}) = \frac{E[\ln R - \ln Q(V_{max})]}{\sqrt{D^2[\ln R] + D^2[\ln Q(V_{max})]}} \tag{3}$$

It is specified in [2] that the uncertainty of response Q (or its linear equivalent Q*) is assumed as resulting from: (i) randomness of response due to material randomness, (ii) modeling uncertainty, and (iii) randomness of response due to random characteristics of earthquake wave. As for (i), it is quantified by $D[\ln Q(V_{max})]$ in Eq.(3), (ii) is neglected while the effect of (iii) is evaluated from the estimation interval for the response Q in the multiple regression analysis (expressed by Eq.(1)). The response corresponding to a non-exceedence level a% is evaluated by

$$Q_a = \hat{a}_o + \hat{a}_1 x_{o1} + z \cdot \hat{a}_2 x_{o2} + \mathbf{t}(n-p-1,a)\sqrt{[1+1/n+D_o^2/(n-1)]V_e} \tag{4}$$

where $\hat{a}_o$, $\hat{a}_1$, $\hat{a}_2$ are the least squares estimates of regression coefficients, $\mathbf{t}(n-p-1,a)$ is the a-percentile of Student's $\mathbf{t}$ distribution with $n-p-1$ degrees of freedom (n = number of data/ waves, p= number of explanatory variables in regression analysis) D_o is Mahalanobis' distance given by

$$D_o^2 = \sum_{i=1}^{2}\sum_{j=1}^{2}(x_{oi} - x_i)(x_{oj} - x_j)s^{ij} \tag{5}$$

with s^{ij} = the current entry of the inverse of sum of products of deviations. Finally V_e is the unbiased estimate of conditional variance given by

$$V_e = \sum_{i=1}^{n}[Q_i - (\hat{a}_o + \hat{a}_1(x_{o1})_i + z \cdot \hat{a}_2(x_{o2})_i)]^2/(n-p-1) \ . \tag{6}$$

The fragility is defined in [2] as the conditional probability of failure under given peak ground velocity :

$$P_f(V_{max}) = 1 - \Phi[\beta(V_{max})] \ . \tag{7}$$

2 ALTERNATIVE FRAGILITY ESTIMATIONS FOR ISOLATED NPP STRUCTURES

The above presented fragility estimated method (due to Hirata et al [2]) has to be compared with other fragility models developed in, e.g., [3,4,5], in view of several reasons. For instance, the

HCLPF (high confidence low probability of failure) values have been rather widely used in seismic margins study (according to [6], for instance), and the approach in [1,2] is essentialy based on seismic margins. On another hand, it is argued in [7] that the LHS (Latin Hypercube Simulation / Sampling) method reduces the number of required trials and it can better handle partial correlation in uncertainty between components than the classical MCS (Monte Carlo Simulation). That is why we are going to propose a way to make use of HCLPF values and LHS in fragility estimation for seismically isolated nuclear structures.

The HCLPF values are introduced in terms of the so-called double lognormal format. The PGA (peak ground acceleration) A is usually accepted as the intensity parameter of the earthquake and a fragility curve is expressed (as in [5]) by

$$F(A) = \Phi\left[\frac{\ln(A/C)}{\beta_R}\right] \tag{8}$$

where Φ is the standard normal cdf (as in Eq.(7), too), C is the median PGA capacity and β_R is the variability of the fragility associated with randomness. The median capacity C is assumed to be itself lognormally distributed, with its pdf given by

$$f(C) = \frac{1}{\sqrt{2\pi}\,\beta_U C} \exp\left[-\frac{1}{2}\left[\frac{\ln(C/A_m)}{\beta_U}\right]^2\right] \tag{9}$$

where A_m is the median and β_U is the Log-N standard deviation of C. Now, the HCLPF value (of the component fragility) can be expressed as

$$HCLPF = A_m \exp[-1.645(\beta_R + \beta_U)] \; . \tag{10}$$

With the composite variability β_C defined as the norm of (β_R,β_U) the probability of failure P_f can be determined as follows :

$$P_f = \Phi\left[\frac{\ln HCLPF - \ln A_m}{\beta_C}\right] \; . \tag{11}$$

Let us now compare Eqs.(3),(7) with Eqs.(8),(11) but taking care of possible misleading notations : β in (3) and (7) is a reliability index, while subscripted β's in Eqs.(8) thru (11) are variabilities or (more precisely) logarithmic standard deviations and R in (3) is the ultimate capacity, while R in (8) and (10) stands for 'randomness'. Eq.(7) may be equivalently written as

$$P_f(V_{max}) = \Phi[-\beta(V_{max})] \tag{12}$$

where $\beta(V_{max})$ is given by Eq.(3). Since $\ln(A/C) = \ln A -$

- ln C, a difference appears between Eqs.(3) and (8) : the expectation E is not taken in the latter one. Instead, the numerator under Φ in Eq.(11) may be considered as an average logarithmic safety margin since both HCLPF and A_m are central values. As regards the denominators in the two equations, the similarity becomes clear as the composite variability β_C is given by

$$\beta_C = \sqrt{\beta_R^2 + \beta_U^2} \ . \qquad (13)$$

These remarks (and other details not given here) have led us to a proposal for an alternative method for fragility estimation of seismically isolated NPP structures. The main points are given below.

1° Both ultimate capacity R and structural response (of isolation layer / upper structure component) Q are assumed to be lognormmaly distributed, and included in a fragility model as the one given by Eqs.(8) and (9). A is replaced by R and its variability (due to randomness) is quantified by D[ln R]. C is replaced by the median response Q with the variability (due to model uncertainty) quantified by D[ln Q].

2° The regression coefficients b_i in Eq.(1) are estimated by LHS (instead of MCS) and they are employed in evaluation of the response for a non-exceedence level a% like in Eq.(4), that is,

$$Q_a \doteq \hat{b}_o + \hat{b}_1 x_{o1} + z\ \hat{b}_{o2} x_{o2} + \ldots \qquad (14)$$

where $\hat{b}_i$ are the LHS estimates of b_i (i = o,1,2).

3° Tolerance intervals including three response values evaluated by Eq.(14) are determined ; the middle one corresponds to the point where the regression line changes its slope (see Eqs.(2)). A lower and an upper bilinear regression lines are thus obtained, corresponding to non-exceedance levels $a-\delta$ and $a+\delta$, respectively. The resulting regression lines are illustrated in Fig.1.

4° The probability of failure (of isolation layer / upper structure component) is evaluated using an equation of the form (11), where HCLPF(Q) is taken for a of 2° and A_m is replaced by $\tilde{Q}$ (the median of Q). A lower and an upper bound on P_f are also obtained replacing a by $a-\delta$, respectively $a+\delta$ in determining HCLPF(Q).

3 CONCLUDING REMARKS

We proposed a modified version of the fragility estimation method presented in [2]. It avoids the use of the reliability index (Eq.(3)), which is not typical for fragility models. Instead, a doubdouble lognormal format is employed, together with HCLPF values for the structural response. The regression coefficients are estimated by the LHS method. Lower and upper regression lines and failure probabilities are determined.

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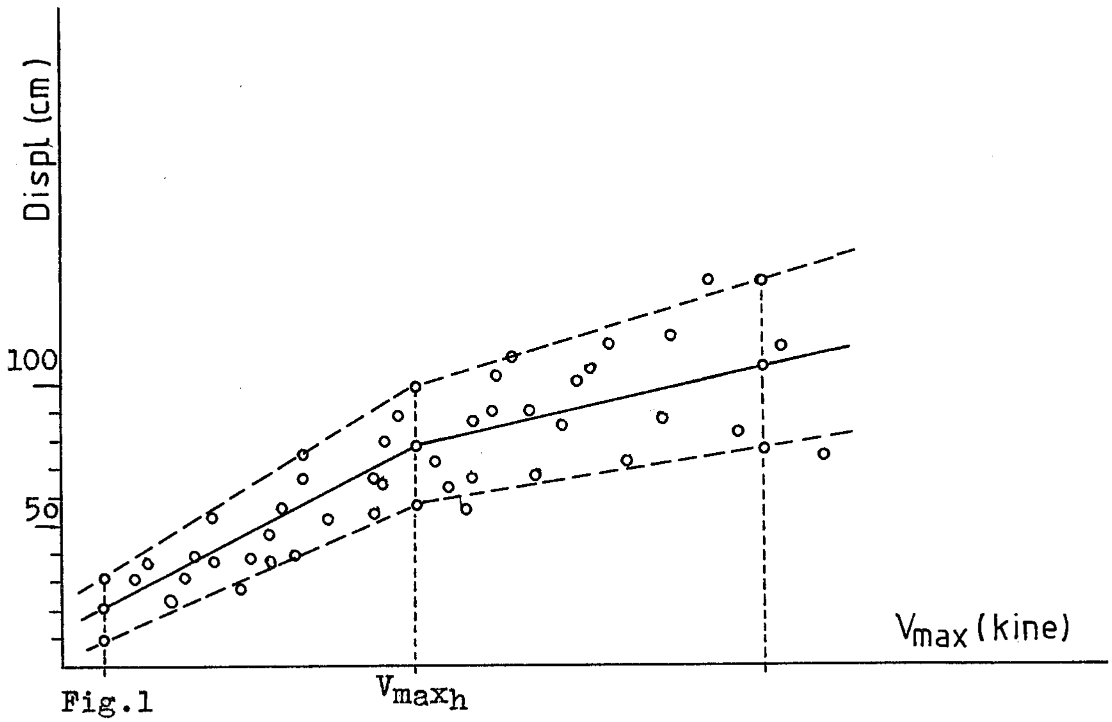

Fig.1

V_{max} vs maximum displacement of isolation layer : Estimated bi-linear regression line and lower / upper bounding lines