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First-passage Probability Estimation of an Earthquake Response of Seismically Isolated Containment Buildings

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1. Introduction

The awareness of a seismic hazard and risk is being increased rapidly according to the frequent occurrences of the huge earthquakes such as the 2008 Sichuan earthquake which caused about 70,000 confirmed casualties and a 20 billion U.S. dollars economic loss. Since an earthquake load contains various uncertainties naturally, the safety of a structural system under an earthquake excitation has been assessed by probabilistic approaches. In many structural applications for a probabilistic safety assessment, it is often regarded that the failure of a system will occur when the response of the structure firstly crosses the limit barrier within a specified interval of time [1]. The determination of such a failure probability is usually called the 'first-passage problem' and has been extensively studied during the last few decades [2]. However, especially for the structures which show a significant nonlinear dynamic behavior, an effective and accurate method for the estimation of such a failure probability is not fully established yet. In this study, we presented a new approach to evaluate the first-passage probability of an earthquake response of seismically isolated structures. The proposed method is applied to the seismic isolation system for the containment buildings of a nuclear power plant. From the numerical example, we verified that the proposed method shows accurate results with more efficient computational efforts compared to the conventional approaches.

2. Methods and Results

2.1 Methods for the First-passage Probability Estimation

A method is presented for evaluating the seismic failure probability of the seismic isolation system for containment building structures. We assumed that the failure of an isolation system will occur when the horizontal displacement response of a base level firstly crosses the predefined limit state during a strong motion duration. For the estimation of a first-crossing probability of a nonlinear structural system excited by an earthquake motion, we computed the average frequency of the crossings of the limit state. Generally, the average rate of barrier crossings (ν) is easily found by using Rice's formula [3].

$$\nu = \int_0^\infty \dot{y} p(b, \dot{y}) d\dot{y} \quad (1)$$

where y and $\dot{y}$ are displacement response and its derivative respectively. b represents the barrier and $p(\cdot)$ is a joint probability density function. For the nonlinear dynamic responses, it is well known that $p(\cdot)$ doesn't meet with the Gaussian function. We adopted the non-Gaussian closure method [4] for the approximation of the $p(\cdot)$. With the non-Gaussian closure method, $p(\cdot)$ can be estimated approximately by using higher order quasi-moments (b_{lm}) and Hermite polynomials (H_{lm}) as follows:

$$p_M(\mathbf{y}) = \left[1 + \sum_{s=3}^{M} \frac{1}{s!} \sum_{l+m=s} b_{lm} H_{lm}(\mathbf{y} - \mathbf{m}) \right] p_G(\mathbf{y}) \quad (2)$$

where $\mathbf{y} = (y, \dot{y})^{\mathrm{T}}$, M is an order of the non-Gaussian closure function, and $p_G(\cdot)$ is a Gaussian joint probability density function. Then, the probability of first-crossing, $P(t)$ can be estimated by using the Poisson distribution [5].

$$P(t) \to 1 - \exp(-\nu T) \ \text{as} \ b \to \infty \quad (3)$$

The proposed method was applied to the containment building of the Ulchin nuclear power plant units 5 & 6. Since that the Ulchin nuclear power plant units are not seismically isolated, we assumed the installation of isolation devices on the base of the containment building. The parameters for the seismic isolation devices are determined to optimize the seismic performance of the containment building [6]. For numerous iterative dynamic nonlinear analyses, seismically isolated containment building is simply modeled as a two-degree of freedom dynamic system (Fig. 1). The dynamic behavior of the isolation devices is modeled using a bilinear system.

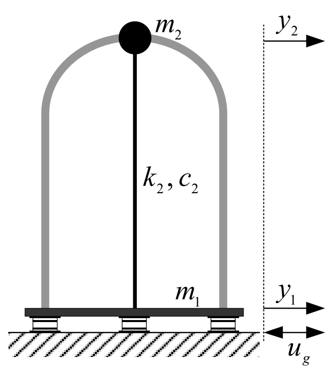

Fig. 1. Simple 2-dof dynamic model of containment building

2.2 Failure Probability of Seismic Isolation System

The failure probabilities was estimated according to the various artificial earthquake acceleration sets [7] representing specific seismic characteristics. For the verification of the accuracy and the efficiency of the presented method, we compared the estimated failure probabilities with the results evaluated from the conventional methods and the exact values which were estimated with the crude Monte-Carlo simulation method. Fig. 2 & 3 depict the results of failure probability estimation of the displacement response at the base level with respect to the variation of the predefined limit states. In Fig. 2, the seismic condition was assumed that acceleration coefficient (*A*) is 0.154 and the soil type is IV which represents the flexible soil profile. On the other hand, in Fig. 3, the soil profile was assumed as soil type I, and the acceleration coefficient is the same as the case of Fig. 3. In the Monte-Carlo simulation method, 100,000 iterative numerical simulations were used to evaluate the results while other methods used 200 simulations. It can be easily found that the proposed method shows more accurate results compared to the conventional approaches for the whole range of a variation of the limit states and corresponding failure probabilities.

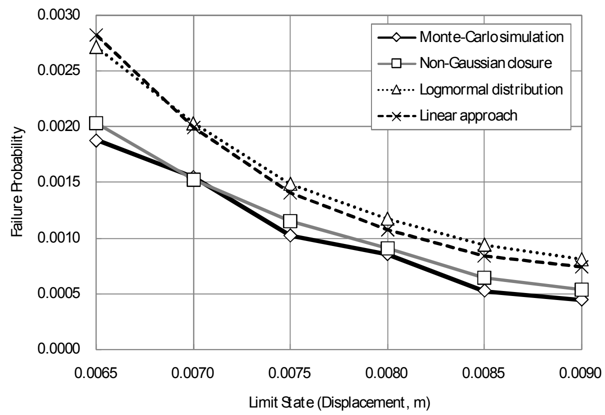

Fig. 2. Failure probabilities with respect to limit states (*A*=0.154, Soil type IV)

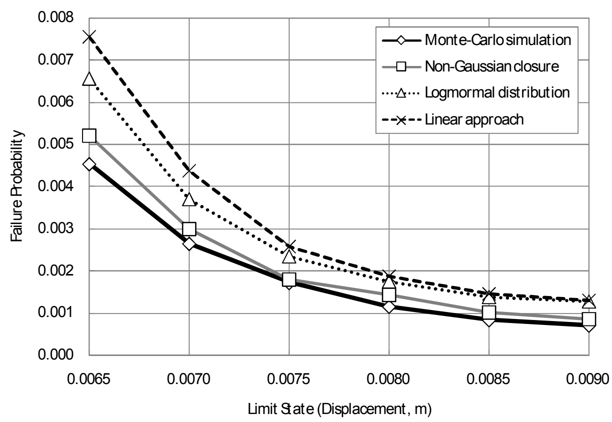

Fig. 3. Failure probabilities with respect to limit states (*A*=0.154, Soil type I)

Especially in Fig. 2, it can be noted that the results of the non-Gaussian closure are matched very closely with the exact ones, obtained by the Monte-Carlo simulation even though the failure probability is very small (less than 1/1000). Hence, we can conclude that the proposed method guarantees accurate results for the failure probabilities in the 'tail' region.

3. Conclusions

A new approach is presented for the evaluation of the first-passage probability of an earthquake response of seismically isolated structures. The proposed method is applied to the seismic isolated containment buildings of the Ulchin nuclear power plant units 5 & 6. The non-Gaussian closure method is introduced to the procedure for the estimation of the average crossing rate and the failure probability. From the numerical example, we verified that the proposed method shows accurate results with more efficient computational efforts compared to the conventional approaches.

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