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Determination of Proportional Damping Matrix in Dynamic Analysis using Direct Integral Method under Simultaneous Excitation in Three Direction

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1. Introduction

In the recent technical standards (KEPIC STC, ASCE 4-16), when performing the nonlinear seismic response analysis of a nuclear power plant with seismic isolation, it is specified that three directional seismic components are simultaneously excited as shown in the Figure 1. There are no specific guidelines reported about the analysis method, but it may be necessary to apply the implicit direct integral method in time domain to make a rigorous seismic analysis. At this point, calculation of the proportional damping matrix may be difficult and may be a challenge. The reason for this study is that determining the proportional damping matrix using Equation-1 requires the dynamic mode and damping ratio of a structure system to be applied, so it may be difficult to determine the principal frequency (ω_i, ω_j) under the multiple excitations. That is, most structures get higher stiffness in the upright gravitational direction, while the transverse stiffness is relatively flexible in nature. This is called a two-way system. Two-way system varies the dynamic mode characteristics of the structure independently for each direction.

In addition, if the structure is laterally asymmetrical, more complex directional independent modes will appear. Thus, it is common for analysts in the field of practice to calculate the damping matrix with Rayleigh proportional coefficient (α, β) by applying the first frequency and cut-off frequency using equation $C= \alpha M+ \beta K$. With this obtained damping matrix, the seismic response of the structure may result in excessive lateral or distorted vertical responses.

Currently, there are no researches and technical standards on the determination of the proportional damping matrix considering the simultaneously multiple excitation. Commercial packages also do not provide Rayleigh coefficients with the considerations.

2. Methods and Results

In this study, Rayleigh proportional coefficients including vectored characteristic are proposed and the proportional damping matrix are calculated using the Equation-1. The proposed method was compared and verified in the other linear analysis methods such as frequency domain analysis or mode superposition method. And then the nonlinear seismic response analysis with simultaneous three-directional seismic excitation is performed to demonstrate its validity. In this study, KIESSI-TD was developed for the dynamic analysis.

Seismic response analysis was performed for typical NPP structure with non-linear seismic systems as shown in Figure 2. The nonlinear analysis was also carried out considering soil-structure interaction (SSI). Table 1 shows Rayleigh coefficients taking into account multiple dynamic modes (Case-1) and with two wide frequency ranges (Case-2). Seismic response analyses were performed for the same examples, and the results were shown in Figure 3.

3. Conclusions

The method to obtain the Rayleigh proportional coefficients with vectored characteristic under multiple excitations is discussed. The KIESSI-TD program used for solving this problem was specially developed and various analyses (linear and nonlinear) for the verification were performed using the program.

REFERENCES

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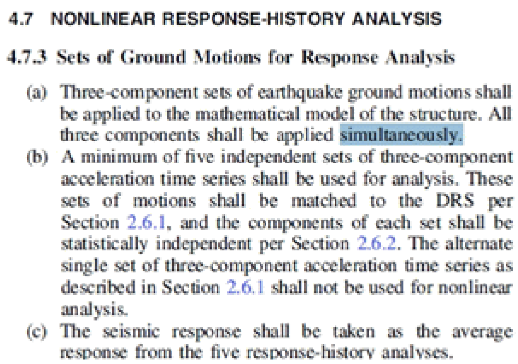

4.7 NONLINEAR RESPONSE-HISTORY ANALYSIS

4.7.3 Sets of Ground Motions for Response Analysis

(a) Three-component sets of earthquake ground motions shall be applied to the mathematical model of the structure. All three components shall be applied simultaneously.
(b) A minimum of five independent sets of three-component acceleration time series shall be used for analysis. These sets of motions shall be matched to the DRS per Section 2.6.1, and the components of each set shall be statistically independent per Section 2.6.2. The alternate single set of three-component acceleration time series as described in Section 2.6.1 shall not be used for nonlinear analysis.
(c) The seismic response shall be taken as the average response from the five response-history analyses.

Figure 1. Section 4.7.3 of ASCE 4-16

Table. 1. Rayleigh coefficients for each case

		Frequencies (rad/sec)	Modal damping	Coefficients
Case-1: Multi-directional Rayleigh coeff.	EW(X)	ω_{x1} = 3.14, ω_{x2} = 72.2	ξ_1 = 0.05, ξ_2 = 0.05	α_x= 0.30092, β_x= 0.00133
	NS(Y)	ω_{x1} = 3.14, ω_{x2} = 72.2	ξ_1 = 0.05, ξ_2 = 0.05	α_y= 0.30092, β_y= 0.00133
	VT(Z)	ω_{z1} = 98.07, ω_{z2} = 245.64	ξ_1 = 0.05, ξ_2 = 0.05	α_z= 7.00893, β_z= 0.00029
Case-2: Wide frequency range Rayleigh coeff.		ω_{n1} = 3.14, ω_c = 207.35	ξ_1 = 0.05, ξ_2 = 0.05	α = 2.98862, β = 0.00029

$$
\begin{aligned}
[C]^e &= \left[\sqrt{\alpha_x}\right]^T [M]^e \left[\sqrt{\alpha_x}\right] + \left[\sqrt{\beta_x}\right]^T [K]^e \left[\sqrt{\beta_x}\right] \\
&= \begin{bmatrix} \sqrt{\alpha_x} & & & \\ & \sqrt{\alpha_y} & & 0 \\ & & \sqrt{\alpha_z} & \\ & & & \ddots \\ 0 & & & & \ddots \end{bmatrix}^T
\begin{bmatrix} M_{11} & M_{12} & M_{13} & \\ & M_{22} & M_{23} & \\ & & M_{33} & \\ & & & \ddots \\ sym. & & & & \ddots \end{bmatrix}^e
\begin{bmatrix} \sqrt{\alpha_x} & & & \\ & \sqrt{\alpha_y} & & 0 \\ & & \sqrt{\alpha_z} & \\ & & & \ddots \\ 0 & & & & \ddots \end{bmatrix}
+ \begin{bmatrix} \sqrt{\beta_x} & & & \\ & \sqrt{\beta_y} & & 0 \\ & & \sqrt{\beta_z} & \\ & & & \ddots \\ 0 & & & & \ddots \end{bmatrix}^T
\begin{bmatrix} K_{11} & K_{12} & K_{13} & \\ & K_{22} & K_{23} & \\ & & K_{33} & \\ & & & \ddots \\ sym. & & & & \ddots \end{bmatrix}^e
\begin{bmatrix} \sqrt{\beta_x} & & & \\ & \sqrt{\beta_y} & & 0 \\ & & \sqrt{\beta_z} & \\ & & & \ddots \\ 0 & & & & \ddots \end{bmatrix} \\
&= \begin{bmatrix} \alpha_x M_{11} & \sqrt{\alpha_x\alpha_y} M_{12} & \sqrt{\alpha_x\alpha_z} M_{13} & \\ & \alpha_y M_{22} & \sqrt{\alpha_y\alpha_z} M_{23} & \\ & & \alpha_z M_{33} & \\ & & & \ddots \\ & sym. & & & \ddots \end{bmatrix}
+ \begin{bmatrix} \beta_x K_{11} & \sqrt{\beta_x\beta_y} K_{12} & \sqrt{\beta_x\beta_z} K_{13} & \\ & \beta_y K_{22} & \sqrt{\beta_y\beta_z} K_{23} & \\ & & \beta_z K_{33} & \\ & & & \ddots \\ & sym. & & & \ddots \end{bmatrix}
\end{aligned}
\qquad \text{(Eq.-1)}
$$

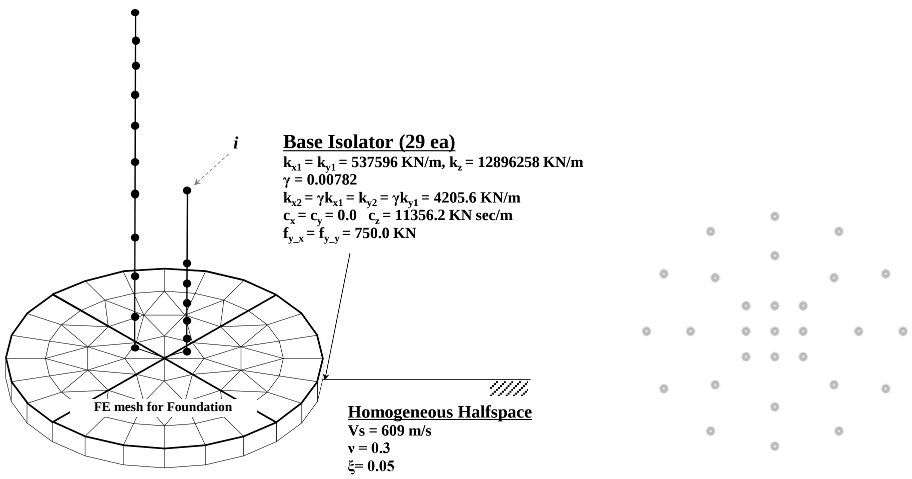
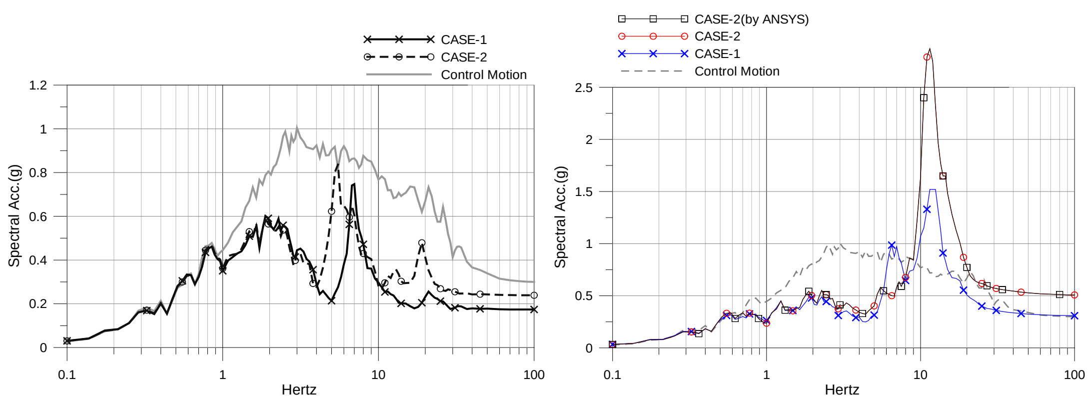


Figure 2. Non-linear analysis model with 29-bearing arrangement of typical NPP building



(a) without SSI (b) with SSI

Figure 3. Floor response spectrum at ‘i’ point of internal top