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Quantiles of critical separation distance for nonstationary seismic excitations

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Abstract

An assessment of quantiles of the separation distance to avoid the pounding of two adjacent buildings under seismic excitations is presented. The seismic excitations are modeled as a nonstationary random process, and the problem is formulated based on structural reliability methods and the random vibration theorem. The formulation includes the uncertainty in structural properties such as the natural vibration periods and damping ratios. Numerical analysis is carried out for assessing the quantiles of the critical separation distance between two adjacent buildings. These quantiles are compared with those obtained by using the complete quadratic combination (CQC) rule together with the quantiles of the structural peak responses that are calculated based on the two-sided crossing rate. The results obtained show that use of the CQC rule in this manner may significantly overestimate or underestimate the critical separation distance, depending on the damping ratios and the natural vibration periods of adjacent buildings. The trends of overestimation or underestimation on considering nonstationary excitations are similar to those obtained on considering stationary seismic excitations. However, the dispersion of the overestimation or underestimation for the former differs from that for the latter.

Keywords: Quantiles; Separation distance; Seismic pounding; Nonstationary random process

1. Introduction

Structural pounding during strong earthquakes is an often-observed phenomenon in metropolitan areas due to the inadequate separation distance between the adjacent buildings. The evaluation of this critical separation distance has been the subject of several studies [1–4]. Numerical analysis results given in [2,4] suggested that the risk of pounding for buildings satisfying the specified minimum separation distance in the Uniform Building Code [5] is not always consistent and varies with the vibration periods of adjacent buildings. The facts that the evaluation of the critical separation distance between two adjacent buildings to reduce risk of pounding is a one-sided crossing problem and that the assessment of the peak response for designing each individual structure subjected to seismic excitations is a two-sided crossing problem have been discussed and quantified in [4]. Therefore, the critical separation distance calculated based on a two-sided crossing rate could be conservative. However, since the peak responses considering the two-sided crossing rather than one-sided responses are used as the basis for the suggested response spectra or design response spectra in design codes, it would be ideal for a relatively accurate estimation of the critical separation distance to be obtained by using the ordinates of the spectra, the complete quadratic combination (CQC) rule and, if necessary, simply scaling factors. As a first step, the feasibility of such a proposed approximation is confirmed in [4] by considering that the seismic excitations could be modeled as a stationary process. However, the seismic excitation is inherently nonstationary. To further investigate the differences by using the one-sided and two-sided treatments and verify the feasibility of the proposed approximation for evaluating the critical separation distance, a systematic probabilistic analysis of the critical separation distance must be carried out by considering the seismic excitations as nonstationary processes.

The investigation carried out in this study extends the study shown in [4] by considering the seismic excitations as nonstationary stochastic processes. A procedure for evaluating the required separation distance between the adjacent buildings for a target safety level is presented for the ground motion modeled as a uniformly modulated nonstationary process.

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The analysis procedure incorporates the uncertain structural properties such as the vibration periods and damping ratios. The procedure presented is used to carry out numerical analyses aimed at verifying or providing suggestions for evaluating the required separation distance such that the probability of pounding will not exceed an allowable level.

2. Modeling of ground motion

Consider that the seismic ground acceleration $x(t)$ can be represented by a uniformly modulated nonstationary process. The modulated nonstationary process is given by

$$x(t) = A(t)\tilde{x}(t), \tag{1}$$

where $\tilde{x}(t)$ is a stationary process with zero mean and a known power spectral density (PSD) function; and $A(t)$ is the time modulating function. A few such modulating functions can be found in the literature for seismic excitations [6,7]. The present study adopts the so-called exponential modulating function given in [6],

$$A(t) = A_0(\mathrm{e}^{-b_1 t} - \mathrm{e}^{-b_2 t}), \qquad b_2 > b_1, \tag{2}$$

where the values of the shape parameters, b_1 and b_2, can be evaluated from a set of earthquake records with a strong motion duration T_0 and a rise time fraction ε [8]; and A_0 is the scaling factor. For simplicity and without loss of generality, the scaling factor A_0 is chosen to be equal to $1/\mathrm{Max}(\mathrm{e}^{-b_1 t} - \mathrm{e}^{-b_2 t})$ resulting in the maximum value of $A(t)$ equal to unit. Note that if $A(t)$ is a constant, the seismic excitation $x(t)$ becomes a stationary random process.

The evolutionary PSD function of $x(t)$, $G_x(\omega, t)$, is given by [9]

$$G_x(\omega, t) = |A(t)|^2 G_{\tilde{x}}(\omega), \tag{3}$$

where $G_{\tilde{x}}(\omega)$ is the PSD function of $\tilde{x}(t)$, and ω (rad/s) denotes the frequency. If $\tilde{x}(t)$ represents the white noise, $G_{\tilde{x}}(\omega)$ equals a constant G_0, and if the commonly used Kanai–Tajimi PSD function is considered, $G_{\tilde{x}}(\omega)$ is given by

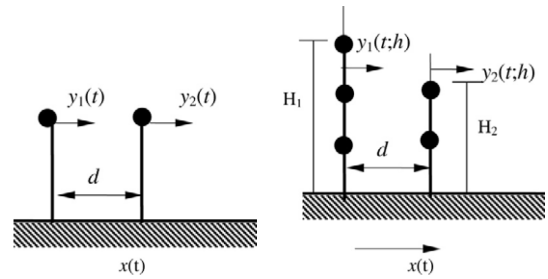
$$G_{\tilde{x}}(\omega) = \frac{\omega_g^4 + 4\xi_g^2\omega_g^2\omega^2}{(\omega_g^2 - \omega^2)^2 + 4\xi_g^2\omega_g^2\omega^2} G_0, \tag{4}$$

where G_0 is the intensity of the ideal white noise; ω_g (rad/s) is the filter frequency that determines the dominant input frequency; the damping coefficient ξ_g is a parameter that indicates the flatness of the power spectral density. Typical values of $\omega_g = 19.06$ and $\xi_g = 0.316$ for soil sites given in [10, 11] will be used for numerical analyses shown in this study. Without loss of generality, the value of G_0 is taken to be equal to 1.0 since it is a linear scaling factor for all the peak responses.

3. Quantiles of critical separation distance

3.1. SDOF systems

Consider that the adjacent buildings represented by viscously damped, linear elastic SDOF systems are subjected



(a) Modeled as SDOF systems.

(b) Modeled as MDOF systems.

Fig. 1. Two adjacent buildings separated by a distance d subjected to ground acceleration $x(t)$.

to the nonstationary ground acceleration $x(t)$ with zero mean and the PSD function $G_x(\omega, t)$ shown in Eq. (3) (see Fig. 1(a)). The displacement of the j-th building, Y_j, $j = 1, 2$, has zero mean and evolutionary PSD function given by [9]

$$G_{Y_j}(\omega, t) = |M_j(\omega, t)|^2 G_{\tilde{x}}(\omega), \tag{5}$$

where

$$M_j(\omega, t) = \int_0^t h_j(\tau) A(t - \tau)\mathrm{e}^{-i\omega\tau}\mathrm{d}\tau, \tag{6}$$

in which

$$h_j(\tau) = \frac{1}{\omega_j\sqrt{1 - \xi_j^2}} \mathrm{e}^{-\xi_j\omega_j\tau} \sin\left(\omega_j\sqrt{1 - \xi_j^2}\tau\right), \tag{7}$$

where ω_j and ξ_j are the natural frequency and the damping ratio of j-th structure, respectively.

If the relative displacement $d(t)$ defined by

$$d(t) = y_1(t) - y_2(t), \tag{8}$$

is greater than the separation distance d, pounding occurs. The evaluation of $d(t)$ is similar to the modal combination analysis of a two-degree-of-freedom system [7,12,13] except that the former is a one-sided crossing problem while the latter is a two-sided crossing problem [4].

The probability that the peak response of $d(t)$ over a duration τ, D_τ, is less than or equal to r, $L(r, \tau)$, can be approximately evaluated using [7]

$$L(r, \tau) = \exp\left(-\int_0^\tau \alpha(r, t)\mathrm{d}t\right), \tag{9}$$

where $\alpha(r, t) = \nu(r, t)\frac{1 - \exp(-\sqrt{\pi/2}\delta_e(t) r/\sqrt{\lambda_{D,0}(t)})}{1 - \exp(-r^2/\lambda_{D,0}(t))}$ represents the decay rate; $\delta_e(t) = \left(\sqrt{1 - \frac{\lambda_{D,1}^2(t)}{\lambda_{D,0}(t)\lambda_{D,2}(t)}}\right)^{1.2}$ where the quantity $\sqrt{1 - \frac{\lambda_{D,1}^2(t)}{\lambda_{D,0}(t)\lambda_{D,2}(t)}}$ is known as the shape factor that lies between 0 and 1 with small and large values representing the narrow-band and wide-band processes, respectively; $\nu(r, t) = \nu_0^+(t)\exp(-\frac{r^2}{2\lambda_{D,0}(t)})$ is the r-level up-crossing rate; and $\nu_0^+(t) = \frac{\sqrt{\lambda_{D,2}(t)/\lambda_{D,0}(t)}}{2\pi}$ is the zero up-crossing rate (i.e., one-sided crossing rate). $\lambda_{D,k}(t)$ representing the k-th moment