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Lifecycle cost–benefit analysis of isolated buildings

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ABSTRACT

Seismic isolation is effective in reducing seismic demand to buildings and mitigating seismic damage costs. To corroborate this fact quantitatively by taking all possible seismic events that occur during the service period of a building into account, this study investigates probabilistic characteristics of the peak ductility demand of inelastic superstructures with linear/bilinear base isolators subject to hundreds of strong ground motion records, and then assesses the cost-effectiveness of seismic isolation technology from the lifecycle cost–benefit perspective. Based on results from nonlinear dynamic analyses of two-degree-of-freedom systems with the Bouc–Wen hysteretic model, a prediction model for the peak ductility demand of isolated structures is developed and used in lifecycle cost analysis to assess the cost-effectiveness of seismic isolation systems. The analysis results show that seismic isolation reduces vibration in superstructures significantly and can be cost-effective in mitigating seismic risk.

1. Introduction

Strong earthquakes cause tangible and intangible losses and disrupt normal operation of structures and infrastructure. Such destructive seismic effects can be reduced by installing energy dissipation devices and seismic isolation systems. It is noteworthy that lifecycle cost–benefit assessments of seismic risk mitigation activities provide important information to decision makers [1–5]. The results are also valuable in performance-based and consequence-based earthquake engineering [6].

Seismic isolation has been successfully applied in practice to mitigate seismic risk [7]. The success of this technology is based on that an isolated structure, which includes a superstructure and isolator, has a much longer vibration period as compared with a fixed structure (i.e., structure without base isolation), and that strong ground motions (mostly, shallow crustal earthquakes in California) contain less energy in the long vibration period range. Consequently, seismic isolation systems are very effective. One exception could be when isolated structures are excited by near-fault motions containing strong velocity pulses. The performance of isolated systems subjected to near-fault motions has been investigated [8,9]. Assessments are usually carried out by considering that superstructures are rigid or elastic [7]; this consideration facilitates the design of isolated structures to limit seismic damage. However, to carry out cost–benefit analysis of isolated structures, it is necessary to characterize linear and nonlinear responses of a superstructure and base isolator by considering record-to-record variability of strong ground motions, which has a significant impact on the assessment results. A study of probabilistic characterization of these responses and cost-effectiveness of seismic isolation systems has not been reported in the literature, although Kikuchi et al. [10] carried out a parametric study on dynamic responses of yielding isolated structures by considering wide ranges of model parameters subjected to harmonic excitations and transient excitations (only three ground motion records).

This study investigates probabilistic characteristics of the peak ductility demand of inelastic superstructures with seismic isolation and assesses the cost-effectiveness of seismic isolation technology. The aims of this study are to develop a simple and generic lifecycle cost model of an isolated structure by taking all possible seismic events during its service period and nonlinear responses of superstructures into account, and to corroborate the empirically proven cost-effectiveness of seismic isolation from the lifecycle cost–benefit perspective. The hysteretic behavior of superstructures is represented by the Bouc–Wen model [11–13], which incorporates stiffness/strength degradation and pinching behavior due to cyclic loading. For the assessment, an isolated structure is modeled as a two-degree-of-freedom (2DOF) system, the bottom layer representing a seismic isolation system and the top layer representing a superstructure, and is subjected to a set of 381 California strong ground motion records (762 components) that were selected from the Next Generation Attenuation database [14] to account for record-to-record variability of strong ground motions. The considered isolation systems are low-damping rubber bearing systems (i.e., linear base isolators) and lead rubber

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bearing systems (i.e., bilinear base isolators). By carrying out nonlinear dynamic analysis, a prediction model for the peak ductility demand of isolated structures is developed, and is used in cost–benefit analysis to assess the cost-effectiveness of seismic isolation systems.

In the following, governing equations of motion for an inelastic 2DOF system are given, and nonlinear dynamic analysis is carried out to assess the effectiveness of seismic isolation in reducing seismic demand and to investigate probabilistic characteristics of the peak ductility demand. Subsequently, an empirical model for predicting the peak ductility demand of isolated structures is developed. The developed empirical model is used in illustrative lifecycle cost analysis to investigate the cost-effectiveness of seismic isolation for mitigating seismic risk.

2. Modeling of isolated structures subjected to seismic excitations

2.1. Equations of motion for isolated structures

In this study, isolated structures are represented by a 2DOF system with the Bouc–Wen model [11–13]. This simplification can be justified based on that isolated structures experience large deformation in isolation layers but small deformation in superstructures [7]; higher mode effects of superstructures are not significant [15]; and isolation layers are often modeled as a single-degree-of-freedom (SDOF) system [9,10,15]. A simplified 2DOF system is illustrated in Fig. 1, where the bottom subsystem represents a base isolation layer and the top subsystem represents a superstructure.

Let the subscripts B and S indicate the model parameters for isolation layers and superstructures, respectively. If a 2DOF hysteretic system is represented by the Bouc–Wen model that can deal with degradation and pinching behavior under cyclic loading, the governing equations of motion are given by,

$$\begin{aligned} &m_B\ddot{u}_B + c_B\dot{u}_B + \alpha_B k_B u_B + (1-\alpha_B)k_B z_B - c_S\dot{u}_S - \alpha_S k_S u_S \\ &\quad - (1-\alpha_S)k_S z_S = -m_B\ddot{u}_g \\ &m_S\ddot{u}_S + c_S\dot{u}_S + \alpha_S k_S u_S + (1-\alpha_S)k_S z_S = -m_S(\ddot{u}_g + \ddot{u}_B) \end{aligned} \tag{1}$$

where $\ddot{u}_g$ is the ground acceleration; u_i, $\dot{u}_i$, and $\ddot{u}_i$ are the translational displacement, velocity, and acceleration, respectively, relative to base of the subsystem i (i represents B or S) with the mass m_i, the viscous damping coefficient c_i, and the stiffness k_i; α_i is the ratio of post-yield stiffness to initial stiffness; and z_i is the hysteretic displacement of the subsystem i. The restoring force for the Bouc–Wen model equals $\alpha_i k_i u_i + (1-\alpha_i)k_i z_i$ [11–13]. The "fictitious" hysteretic displacement z_i is related to the total displacement u_i through the following differential equation [12,13],

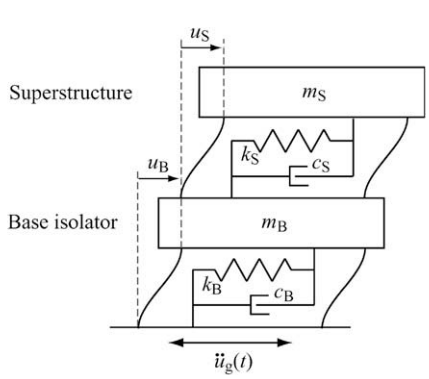

Fig. 1. Illustration of an isolated structure.

$$\dot{z}_i = \frac{h(\dot{u}_i, z_i, \varepsilon_i)}{1+\delta_{\eta i}\varepsilon_i}\left[\dot{u}_i - (1+\delta_{\nu i}\varepsilon_i)(\beta_i|\dot{u}_i||z_i|^{n_i-1}z_i + \gamma_i\dot{u}_i|z_i|^{n_i})\right], \quad i = B \text{ or } S, \tag{2}$$

in which $h(\dot{u}_i, z_i, \varepsilon_i)$ is the pinching function; β_i, γ_i, and n_i are the shape parameters; $\delta_{\nu i}$ and $\delta_{\eta i}$ are the degradation parameters; and ε_i is the dissipated energy through hysteresis of the subsystem i. The pinching function is given by [12,13],

$$\begin{aligned} &h(\dot{u}_i, z_i, \varepsilon_i) \\ &\quad = 1 - \zeta_i(1-e^{-p_i\varepsilon_i})\exp\left(-\left(\frac{z_i\,\mathrm{sgn}(\dot{u}_i) - q_i/\{(1+\delta_{\nu i}\varepsilon_i)(\beta_i+\gamma_i)\}^{1/n_i}}{(\lambda_i+\zeta_i(1-e^{-p_i\varepsilon_i}))(\psi_i+\delta_{\psi i}\varepsilon_i)}\right)^2\right), \\ &i = B \text{ or } S, \end{aligned} \tag{3}$$

where ζ_i, p_i, q_i, ψ_i, $\delta_{\psi i}$, and λ_i are the pinching parameters, and $\mathrm{sgn}(\cdot)$ is the signum function. The dissipated energy ε_i is given by,

$$\varepsilon_i = (1-\alpha_i)k_i\int_0^T \dot{u}_i z_i dt, \quad i = B \text{ or } S, \tag{4}$$

where T is the duration of structural response.

Under severe seismic excitations, it is expected that the ith subsystem responds inelastically with a displacement and force exceeding its yield displacement u_{yi} and yield force f_{yi}, respectively. To characterize inelastic responses, we will focus on the peak ductility demand of an isolated structure described in Eqs. (1)–(4), and use the normalized yield strength ϕ_i for each subsystem, defined as,

$$\phi_i = u_{yi}/u_{0i} = f_{yi}/f_{0i}, \quad i = B \text{ or } S, \tag{5}$$

where u_{0i} and f_{0i} are the peak values of the displacement and resisting force, respectively, of the linear elastic SDOF system with m_i, c_i, and k_i. These responses can be evaluated by solving Eq. (1) for a ground motion record with α_i set equal to unity. By using Eq. (5) and defining the following normalized displacement demand variables,

$$\mu_i = u_i/u_{yi} \quad \text{and} \quad \mu_{zi} = z_i/u_{yi}, \quad i = B \text{ or } S, \tag{6}$$

the governing equations for the system shown in Eqs. (1)–(4) become,

$$\begin{aligned} &\ddot{\mu}_B + 2\xi_B\omega_B\dot{\mu}_B + \alpha_B\omega_B^2\mu_B + (1-\alpha_B)\omega_B^2\mu_{zB} - 2\rho\Delta\xi_S\omega_S\dot{\mu}_S \\ &\quad - \alpha_S\rho\Delta\omega_S^2\mu_S - (1-\alpha_S)\rho\Delta\omega_S^2\mu_{zS} = \frac{-\Delta\ddot{u}_g}{\phi_S u_{0S}} \\ &\ddot{\mu}_S + 2(1+\rho)\xi_S\omega_S\dot{\mu}_S + \alpha_S(1+\rho)\omega_S^2\mu_S + (1-\alpha_S)(1+\rho)\omega_S^2\mu_{zS} \\ &\quad = \frac{2\xi_B\omega_B\dot{\mu}_B}{\Delta} + \frac{\alpha_B\omega_B^2\mu_B}{\Delta} + \frac{(1-\alpha_B)\omega_B^2\mu_{zB}}{\Delta} \\ &\dot{\mu}_{zi} = \frac{h(\dot{\mu}_i, \mu_{zi}, \varepsilon_{ni})}{1+\delta_{\eta i}\varepsilon_{ni}}\left[\dot{\mu}_i - (1+\delta_{\nu i}\varepsilon_{ni})(\beta_i|\dot{\mu}_i||\mu_{zi}|^{n_i-1}\mu_{zi} + \gamma_i\dot{\mu}_i|\mu_{zi}|^{n_i})\right] \\ &h(\dot{\mu}_i, \mu_{zi}, \varepsilon_{ni}) = 1 - \zeta_i(1-e^{-p_i\varepsilon_{ni}}) \\ &\qquad \times \exp\left(-\left(\frac{\mu_{zi}\,\mathrm{sgn}(\dot{\mu}_i) - q_i/\{(1+\delta_{\nu i}\varepsilon_{ni})(\beta_i+\gamma_i)\}^{1/n_i}}{(\lambda_i+\zeta_i(1-e^{-p_i\varepsilon_{ni}}))(\psi_i+\delta_{\psi i}\varepsilon_{ni})}\right)^2\right) \\ &\varepsilon_{ni} = (1-\alpha_i)\int_0^T \dot{\mu}_i\mu_{zi}\mathrm{d}t \end{aligned} \tag{7}$$

where ξ_i, $\xi_i = c_i/(2m_i\omega_i)$, is the damping ratio; ω_i, $\omega_i = (k_i/m_i)^{0.5}$, is the natural vibration frequency in rad/s; ε_{ni} is the dissipated hysteresis energy ε_i normalized by $f_{yi}u_{yi}$ for the subsystem i (i.e., $i = B$ or S); ρ is the ratio of m_S to m_B; and Δ is the ratio of u_{yS} to u_{yB} (i.e., $\Delta = u_{yS}/u_{yB} = (\phi_S u_{0S})/(\phi_B u_{0B})$). If all terms with the subscript B in Eq. (7) are ignored, the equations describe a fixed structure. It is noted that for each subsystem, the 12 Bouc–Wen model parameters α, β, γ, n, δ_ν, δ_η, ζ, p, q, ψ, δ_ψ, and λ are dimensionless. Therefore, the