Soil Dynamics and Earthquake Engineering 90 (2016) 74–87

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Optimal design of friction pendulum system properties for isolated structures considering different soil conditions

P. Castaldo [a,*], M. Ripani [b]

[a] Department of Civil Engineering, University of Salerno, Via Giovanni Paolo II (SA), Italy
[b] Universidad de Buenos Aires. Consejo Nacional de lnvestigaciones Científicas y Técnicas (CONICET). Instituto de Tecnologías y Ciencias de la Ingeniería "Hilario Fernández Long" (INTECIN). Facultad de Ingeniería, Buenos Aires, Argentina

ARTICLE INFO

Article history:
Received 28 June 2016
Received in revised form
12 August 2016
Accepted 19 August 2016

Keywords:
Seismic isolation
Friction pendulum isolators
Performance-based engineering
Non-dimensional form
Optimal isolator properties
Power spectral density method
Soil condition

ABSTRACT

This study aims at evaluating the optimal properties of friction pendulum bearings to be employed for the seismic protection of elastic isolated structural systems under earthquake excitations with different characteristics in terms of frequency content. A two-degree-of-freedom model is considered to describe the isolated system behavior while accounting for the superstructure flexibility and a non-dimensional formulation of the governing equations of motion is employed to relate the characteristic parameters describing the isolator and structure properties to the response parameters of interest for the performance assessment. Seismic excitations are modeled as time-modulated filtered Gaussian white noise random processes of different intensity within the power spectral density method. The filter parameters control the frequency content of the random excitations and are calibrated to describe stiff, medium and soft soil conditions, respectively. Finally, multi-variate regression expressions are obtained for the optimum values of the friction coefficient that minimize the superstructure displacements relative to the base mass as a function of the structural system properties, of the seismic input intensity and of the soil condition.

1. Introduction

Over the years, isolation systems have emerged as a very effective technique for seismic protection of building frames [1]. Friction pendulum system (FPS) bearings are often preferred to other types of bearings due to their capability of providing an isolation period independent of the mass of the supported structure, their high dissipation and recentering capacity, and their longevity and durability characteristics [2,3]. Many experimental and numerical studies have been carried out to investigate the behavior of these devices and to define reliable models for describing it [4–9]. Other studies have focused on the seismic response of structures isolated with FPS bearings by accounting for the variability of the seismic input characteristics [10–12]. In [13] the influence of friction pendulum system (FPS) isolator properties on the seismic performance of base-isolated building frames was investigated by employing a two-degree-of-freedom model accounting for the superstructure flexibility with a velocity-dependent model for the FPS isolator behavior. The variation of the statistics of the response parameters relevant to the seismic performance has been investigated through the nondimensionalization of the motion equation considering different isolator and system properties.

Few works (e.g. [14–22]) have been more oriented to develop design approaches for the isolators and to identify the optimal isolator properties. In this context, Castaldo et al. [14–16] and Palazzo et al. [17] proposed a seismic reliability-based design (SRBD) criterion to define the isolator dimensions in plan based on the evaluation of performance curves for the isolator and the superstructure. Bucher [22] proposed a reliability-based design approach for the bearings accounting for the probabilistic performance properties in terms of maximum and residual isolator displacements, and the maximum interstorey structural displacement. Jangid [18,19], considering a stochastic model of the earthquake ground motion, evaluated the seismic performance of a single shear type building isolated by FPS bearings whose behavior was described by a Coulomb model showing that there exists an optimal value of the friction coefficient for which the top floor absolute acceleration of the building is minimized. This value is influenced by the building properties and the isolation period, and it increases with the increase of the earthquake intensity. The minimization of the absolute accelerations of the isolated superstructure was employed as optimization criterion also in other

* Corresponding author.
E-mail addresses: pcastaldo@unisa.it (P. Castaldo), mripani@fi.uba.ar (M. Ripani).

http://dx.doi.org/10.1016/j.soildyn.2016.08.025
0267-7261/

works [20,21]. In [23], considering a ten-story shear type building as case study, a multi-objective optimization for the optimal design of sliding isolation systems for suppression of seismic responses of building structures is presented applying a genetic algorithm to minimize the building's top story displacement, its acceleration and also the base raft's displacement.

Although most of these abovementioned studies consider wide sets of ground motions to describe the seismic input uncertainty, they do not explicitly consider the effect of the frequency characteristics and its influence on the seismic response of base-isolated systems and on the optimal isolator properties. The problem has been addressed by other works (e.g., [24–26]) concerning isolated buildings and bridges and demonstrating that soft soil condition leads to a great alteration of the variances with large increment of the peak ratios, in terms of displacements and shear forces, by negatively affecting the isolated systems. Similarly, Kulkarni and Jangid [27] analyzed the effects of superstructure flexibility on the response of base-isolated structures subjected to non-stationary random processes by comparing the stochastic response of a base-isolated structure with superstructure modeled as flexible and rigid and highlighting that the seismic isolation is more effective for firm or rock type soil than the soft soils.

This work aims to further advance the studies of [13,18,27] by investigating the influence of soil characteristics in terms of frequency content on the seismic performance of elastic building frames isolated with FPS isolators and the optimal isolator friction properties. The two-degree-of-freedom model, already employed in [13], is used for this purpose, as it was shown to provide a reliable representation of the structural response of more complex systems, especially in the case of low values of the friction coefficient and high isolation degrees such that the effects of the higher modes are negligible. It is also useful because it leads to a condensed description of the problem in terms of few characteristic parameters representing the isolator and structural system properties. A parametric study of the system is performed for different values of these characteristic parameters by considering three different sets of artificial ground motion records, modeled as non-stationary stochastic processes and generated through the power spectral density method [28], with different frequency content corresponding to stiff, medium and soft soil conditions [29], respectively. The nondimensionalization of the governing equations of motions permits to investigate wide ranges of seismic intensities while limiting the required nonlinear response history analyses. For each set of random excitations, numerical simulations are first carried out to evaluate the relation between the characteristic system and isolator parameters and the structural performance. Successively, multi-variate regression expressions are derived for the optimal values of the friction coefficient that minimize the superstructure displacements relative to the base, as a function of the system characteristic parameters, of the seismic input intensity and of the soil condition. These equations can be useful for designing the friction properties of the isolators employed to seismically isolate regular building frames.

2. Non-dimensional equation of motion

The equations of motion governing the response of a 2dof model representing an elastic system on single concave FPS isolation bearings (Fig. 1) subjected to the seismic input $\ddot{u}_g(t)$, in the hypothesis of considering the horizontal component of the bearings displacement, is:

$$m_s\ddot{u}_s(t) + c_s\dot{u}_s(t) + k_s u_s(t) = -m_s\left[\ddot{u}_g(t) + \ddot{u}_b(t)\right]$$
$$m_b\ddot{u}_b(t) + f_b(t) + c_b\dot{u}_b(t) - c_s\dot{u}_s(t) - k_s u_s(t) = -m_b\ddot{u}_g(t) \quad (1)$$

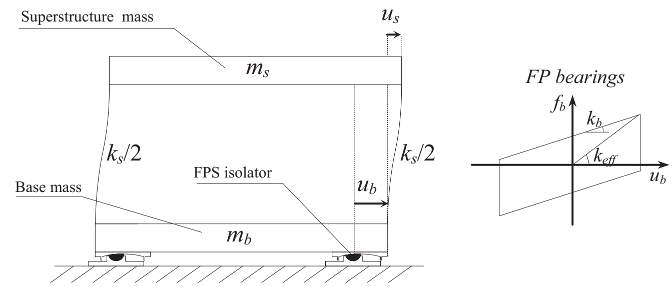

Fig. 1. 2d of model of elastic system isolated with FPS in the deformed configuration.

where u_s denotes the displacement of the superstructure relative to isolation bearing, u_b the isolator displacement relative to the ground, m_s and m_b respectively the mass of the superstructure and of the base floor above the isolation system, k_s and c_s respectively the superstructure stiffness and inherent viscous damping constant, c_b the bearing viscous damping constant, t the time instant, the dot differentiation over time, and $f_b(t)$ denotes the FPS bearing resisting force. This latter can be expressed as:

$$f_b(t) = k_b u_b(t) + \mu(\dot{u}_b)(m + m_b)gZ(t) \quad (2)$$

where $k_b = W/R = (m_s + m_b)g/R$, g is the gravity constant, R is the radius of curvature of the FPS, $\mu(\dot{u}_b(t))$ the coefficient of sliding friction, which depends on the bearing slip velocity $\dot{u}_b(t)$, and $Z(t) = \mathrm{sgn}(\dot{u}_b)$, with $sgn(\cdot)$ denoting the sign function. The fundamental period of vibration of a base-isolated system, $T_b = 2\pi\sqrt{R/g}$, corresponding to the pendulum component, is independent of the superstructure mass and related only to the radius of curvature R [13].

Experimental results [5–7] suggest that the coefficient of sliding friction of Teflon-steel interfaces obeys to the following equation:

$$\mu(\dot{u}_b) = f_{\max} - Df\cdot\exp\left(-\alpha|\dot{u}_b|\right) \quad (3)$$

in which $f_{\max}$ represents the maximum value of friction coefficient attained at large velocities of sliding, and $f_{\min} = f_{\max} - Df$ represents the value at zero velocity. In this study, to further simplify the problem, it is assumed that $f_{\max} = 3f_{\min}$ with the exponent α equal to 30 [13].

Moreover, note that, in the hypothesis of considering the maximum value of the sliding friction coefficient, it is possible to evaluate the effective stiffness of the isolation level $k_{eff} = W\left(1/R + f_{\max}/u_b\right)$ depending on the bearings displacement (Fig. 1) which leads to an effective isolated period $T_{b,eff}$ [30,31].

The non-dimensional form of the equations of motion can be derived by introducing the time scale $\tau = t\omega_b$, where $\omega_b = \sqrt{k_b/(m_s + m_b)}$ denotes the fundamental circular frequency of the isolated system with infinitely rigid superstructure, and the seismic intensity scale a_0, which has the dimension of an acceleration and it is such that $\ddot{u}_g(t) = a_0\lambda(\tau)$, where $\lambda(\tau)$ is a non-dimensional function of time describing the seismic input time-history. In [13], the following non-dimensional equations are obtained:

$$\ddot{\psi}_s(\tau) + 2\xi_s\frac{\omega_s}{\omega_b}\dot{\psi}_s(\tau) + \frac{\omega_s^2}{\omega_b^2}\psi_s(\tau) = -\left[\lambda(\tau) + \ddot{\psi}_b(\tau)\right]\ddot{\psi}_b(\tau) + \frac{1}{1-\gamma}\Bigg[2\xi_b\dot{\psi}_b(\tau) + \psi_b(\tau)$$
$$+ \frac{\mu(\dot{u}_b)g}{a_0}\mathrm{sgn}(\dot{\psi}_b)\Bigg] - 2\xi_s\frac{\omega_s}{\omega_b}\frac{\gamma}{1-\gamma}\dot{\psi}_s(\tau) - \frac{\omega_s^2}{\omega_b^2}\frac{\gamma}{1-\gamma}\psi_s(\tau) = -\lambda(\tau) \quad (4)$$

where $\omega_s = \sqrt{k_s/m_s}$ and $\xi_s = c_s/2m_s\omega_s$ denote respectively the circular frequency and damping factor of the superstructure; $\xi_b = c_b/2m_b\omega_b$ the isolator damping factor; $\gamma = m_s/(m_s + m_b)$ [30]