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Comparison of different models for friction pendulum isolators in structures subjected to horizontal and vertical ground motions

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ABSTRACT

This research focuses on the different modelling approaches for the simulation of the seismic response of structures with friction pendulum isolation systems. The behaviour of such systems is strongly affected by several parameters, as for example the friction coefficient and the axial load. The latter has a particular importance in presence of seismic actions characterized by the simultaneous presence of high horizontal and vertical accelerations. To study these aspects, several nonlinear dynamic analyses have been performed considering a two degree of freedom model isolated at the base and subjected to recorded horizontal and vertical ground motions. The response of the selected isolation systems has been studied through different models, starting by the more simple ones based on a constant friction coefficient to the more complex ones based on a friction coefficient varying with the sliding velocity and axial force. A set of ground motions with near field records characterized by different values of the ratio between peak vertical and horizontal accelerations has been considered. The results have allowed to compare the different models and to study the effect of the vertical seismic component on the response of the isolators.

1. Introduction

Among the seismic isolation techniques, the friction pendulum system (FPS) is increasingly used thanks to its special features such as the stability of the physical properties and durability [1,2]. The friction pendulum isolation system combines two fundamental mechanisms: the frictional sliding of steel surfaces, which is separated by a Teflon layer, and the pendular motion of the slider on a perfectly spherical surface. Through these mechanisms, the device is able to recenter by itself and can dissipate a large quantity of energy through the sliding on a curved surface. The kinetic energy is partially converted into thermal energy through the overheating of the surfaces in contact and partially in potential energy through the uplift of the structure; the latter pulls back the oscillating mass to its initial position of stable equilibrium, thus providing recentering. The definition of the friction coefficient allows an evaluation of the amount of energy that is dissipated through the isolation system [3,4]. Another important property is that torsional motions of the superstructure are minimized; this result is given by the fact that the horizontal stiffness and the frictional force in each single isolator are directly proportional to the normal force acting on them. In this way, the centre of rigidity of the devices constantly coincides with the centre of mass of the structure, compensating the mass eccentricity of the superstructure.

Several experimental and analytical studies presented in literature have been performed with the purpose to investigate the seismic behaviour of these devices [5–15]. The experimental data showed important aspects as the dependence of the friction coefficient on the vertical load, the sliding velocity and the direction of motion. The analytical studies proposed and used models with different levels of complexity in order to account for the different aspects characterizing the response of FPS isolators.

There are some problematic issues that are related to the choice of the FPS isolator; its large size, for example, or the influence of vertical movements that are inevitably related to horizontal displacements and that may produce parasitic effects on the structure, thus compromising its correct behaviour [16]. High values of the ratio $V/H=PGA_V/PGA_H$ between the peak ground acceleration in the vertical direction (PGA_V) and the corresponding peak in the horizontal direction (PGA_H), which are typical of near-fault earthquakes, can cause significant variations in the axial force in reinforced concrete columns, thus introducing adverse phenomena (like brittle collapse in compression or tensile collapse, instability of longitudinal bars, loss of bond between steel and concrete); other effects can be the creation of plastic hinges along the beam span, especially on the higher floors [17–23]. High values of V/H can lead also to dangerous tensile stresses on the bearings, causing unexpected mechanisms, which may affect the isolator response with unforeseen breaks or sliding elements coming out of their seat. Moreover, a study of the influence of this component together with

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bidirectional horizontal seismic action would be necessary in order to consider all three components of the seismic acceleration [9].

The objectives of this study are the comparison of different models for friction pendulum isolators in structures subjected to horizontal and vertical ground motions and the evaluation of the effects of the vertical component. In particular, a two degree of freedom system with friction pendulum isolators at the base has been studied considering various models for the isolator response with different assumptions regarding the friction coefficient and the axial force. Several systems have been analysed by varying the following parameters: mass of the structure, horizontal and vertical stiffness of both structure and isolation system. The analyses have been performed considering a set of ground motion with near field records that show different values of the ratio between the peak vertical and horizontal accelerations. All the records have been applied to such models two times: the first with the horizontal component alone, the second with the horizontal and vertical components together. The records have been also applied considering increasing values of intensity in order to determine the collapse acceleration of the selected systems.

2. Horizontal and vertical behaviour of the isolation system

The effects of seismic isolation can be studied through a linear elastic system with concentrated masses (Fig. 1), which is an extreme simplification of the model in which mass, stiffness and energy dissipation of the superstructure are distributed along the height of the building. The model is characterized by two degrees of freedom, which correspond to the horizontal displacements of the superstructure and of the substructure, indicated as u_s and u_b, while u_g represents the displacement of the ground. The relative displacements are $v_b = u_b - u_g$ and $v_s = u_s - u_b$. The basic equations of motion of the two degree of freedom model are [24]:

$$\begin{cases} (m+m_b)\ddot{v}_b + m\ddot{v}_s + c_b\dot{v}_b + k_b v_b = -(m+m_b)\ddot{u}_g \\ m(\ddot{v}_s + \ddot{v}_b) + c_s\dot{v}_s + k_s v_s = -m\ddot{u}_g \end{cases} \quad (1)$$

where m and m_b are the masses of the superstructure and of the substructure respectively; k_s and k_b are the stiffness of the superstructure and of the isolation system respectively; c_s and c_b are the damping coefficients of the superstructure and of the isolation system respectively. The fundamental equations are integrated step by step with the 4th order Runge Kutta explicit integration method, and the attention is focused on the parameters that are modelled with appropriate non-linear functions, such as the isolator stiffness k_b and the isolator damping coefficient c_b.

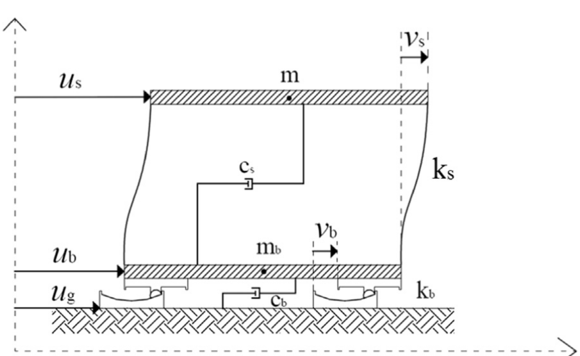

Fig. 1. Two degree of freedom isolated system.

Assuming small deformations, the unidirectional horizontal force-deformation response of the friction pendulum system (FPS) is given by Eq. (2) [25]:

$$F_H = N\left[\mu\, sign(\dot{v}_b) + \frac{v_b}{R}\right] \quad (2)$$

where N is the normal force on the isolator (equal to $(m+m_b)g$ in the absence of vertical accelerations, being g the gravity acceleration), R is the radius of curvature of the spherical surface, v_b is the sliding deformation, $\dot{v}_b$ is the sliding velocity and μ is the friction coefficient at the Teflon–steel interface (Fig. 2). The normal force N, acting on the FPS isolator, affects the horizontal force F_H and consequently the horizontal response of the entire system. An increase in modulus of N causes a large yielding force, which can delay the mobilization of the isolator under dynamic loads, and a high post-elastic stiffness, which can reduce the deformation of the isolator (bilinear behaviour). Besides, μ varies in modulus with N. The conventional FPS isolator does not resist to tensile load. This behaviour corresponds to the response of a "gap" element which is defined by the following relation:

$$F_V = N = \begin{cases} k_{b,v}v_{b,v} + c_{b,v}\dot{v}_{b,v} & \text{if } v_{b,v} \le 0 \\ 0 & \text{if } v_{b,v} > 0 \end{cases} \quad (3)$$

where $k_{b,v}$ is the compression stiffness and $v_{b,v}$ is the vertical displacement of the isolator; besides, it is necessary to specify the additional damping coefficient $c_{b,v}$ for the vertical degree of freedom. In the vertical direction we can estimate the damping coefficient that is needed to achieve a certain ratio, $\xi_{b,v}$, of critical damping (e.g. $\xi_{b,v}=0.05$) from Eq. (4):

$$\xi_{b,v} = \frac{c_{b,v}}{2\sqrt{k_{b,v}(m+m_b)}} \quad (4)$$

The equations of motion in the vertical direction are similar to those for the horizontal direction defined by Eq. (1).

3. Analytical models for the isolator stiffness and damping

This section illustrates a brief description of the various models adopted for the schematization of the stiffness and damping parameters of the FPS isolators, starting from the simplest to the most complex.

A) The first considered model is characterized by equivalent parameters for stiffness and damping (the procedure is currently used

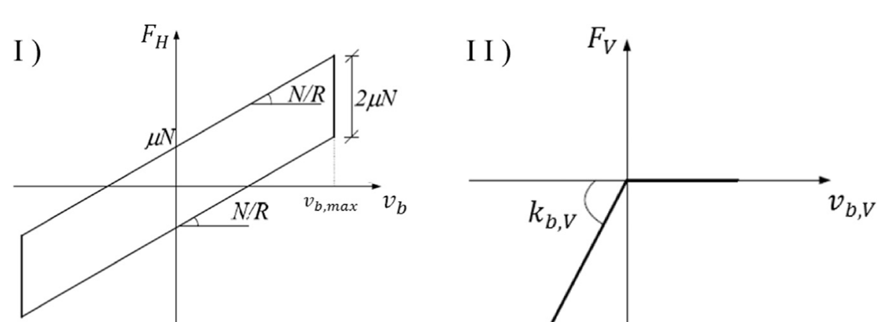

Fig. 2. I) Force-deformation diagram of the unidirectional rigid-plastic response of the FPS; II) force-deformation model of the “gap” element.