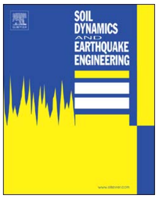
Soil Dynamics and Earthquake Engineering 90 (2016) 299–312

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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



Nonlinear seismic analysis of irregular r.c. framed buildings base-isolated with friction pendulum system under near-fault excitations

Fabio Mazza*, Mirko Mazza

Dipartimento di Ingegneria Civile, Università della Calabria, Rende, Cosenza, Italy

ARTICLE INFO

Article history:
Received 16 March 2016
Received in revised form
16 August 2016
Accepted 20 August 2016

Keywords:
R.c. base-isolated structures
Friction pendulum system
Torsional effect
Residual displacement
Uplift
Near-fault ground motions
Nonlinear dynamic analysis

ABSTRACT

The application of the friction pendulum (FP) system is increasing due to its conceptual simplicity; yet there are still aspects of its behaviour that need further attention. Long duration intense velocity pulses in the horizontal direction and high values of the ratio between vertical and horizontal peak ground acceleration are expected in the near-fault areas. Base-isolated structures subjected to near-fault earthquakes present variation of friction force and lateral stiffness of the FP system during the sliding phase which can induce torsion with residual displacement and uplift. To investigate these effects, a nonlinear dynamic analysis is carried out considering a six-storey reinforced concrete (r.c.) framed building, characterized by an L-shaped plan with wings of different length and setbacks at different heights along the in-plan principal directions. Twelve base-isolated test structures are designed in line with the Italian seismic code, considering (besides the gravity loads) the horizontal seismic loads acting alone or in combination with the vertical ones. Three design values of the radius of curvature and two in-plan distributions of dynamic-fast friction coefficient are assumed for the FP bearings, ranging from a constant value for all isolators to a different value for each. A nonlinear force-displacement law of the FP bearings is considered in the horizontal direction, depending on sliding velocity and axial load, while a gap model takes into account the vertical uplift of the FP bearings. The nonlinear seismic analysis is performed on near-fault ground motions with significant horizontal or vertical components, selected and normalized on the basis of the design hypotheses adopted for the test structure.

1. Introduction

Today a variety of structures are built using single Friction Pendulum (FP) bearings. Among these, the C.A.S.E. project in L′ Aquila (Italy), after the 6th April 2009 near-fault earthquake, represents the largest base isolation project ever carried out [1]. The single friction pendulum (FP) bearing is made with an articulated slider on a spherical concave surface, where the geometry and gravity allow a self-centring and a minimization of torsion of the base-isolation FP system for a wide range of frequency inputs [2]. However, the (low) constant isolation frequency, proportional to the curvature of the sliding surface, may induce resonance of base-isolated structures if it is close to the predominant vibration period of near-fault ground motions [3–5]. A number of analytical studies have been made to investigate the seismic behaviour of base-isolated structures, in order to pursue an optimum design of FP bearings under the horizontal components of strong near-fault earthquakes. Special attention was paid to the sensitivity of the structural response to modelling aspects of both the base-isolation system (e.g. [6,7]) and the superstructure (e.g. [8,9]), with reference to two- and multi-degree-of-freedom systems. However, little attention was paid to the effects of the in-plan distribution of friction coefficient for the FP bearings, due to its dependence on the sliding velocity and axial load. More specifically, long duration intense velocity pulses in the horizontal direction [10,11] may affect the friction force of the FP bearings, which results increasing with the velocity up to a constant value [12]. On the other hand, friction force and lateral stiffness of the FP system during the sliding phase are strongly influenced by the axial load variation induced by the high frequency vertical component of near-fault earthquakes [13–16]. This vertical motion is characterized by peak ground acceleration higher than the horizontal one and closer to this in time for decreasing values of the distance from the fault [17,18]. Thus, torsional effects with residual displacements and uplifts may happen for base-isolated structures with single FP bearings located in near-fault areas. However, the main conclusion of some studies is that coupled lateral-torsional response is negligible in sliding isolated structures, even in the presence of large mass and stiffness eccentricities [19–21]. On the other hand, further studies highlight that lateral-torsional coupling can be

---

* Corresponding author.
E-mail address: fabio.mazza@unical.it (F. Mazza).

http://dx.doi.org/10.1016/j.soildyn.2016.08.028

significant depending on the superstructure eccentricity and the lateral-torsional flexibility of both superstructure and base-isolation system [22].

In order to verify the occurrence of torsion with residual displacement and uplift of the FP system for base-isolated structures located in near-fault areas, this study investigates the nonlinear dynamic response of in-plan and in-elevation irregular structures base-isolated with FB bearings. To this end, a six-storey reinforced concrete (r.c.) framed building, characterized by an L-shaped plan with wings of different length and setbacks at different heights along the in-plan X (i.e. one setback, at the third-storey) and Y (i.e. two setbacks, at the second- and fourth-storey) principal directions is considered. In detail, twelve base-isolated structures are designed in line with the Italian seismic code (NTC08, [23]), considering (besides the gravity loads) the horizontal seismic loads acting alone or in combination with the vertical ones. Two in-plan distributions of low-type friction, ranging from a constant value for all isolators to a different value for each, are designed for three low-to-medium design values of radius of curvature of the FP bearings. An elastic-linear behaviour is considered for the superstructure. Moreover, a nonlinear force-displacement law of the FP bearings is considered in the horizontal direction, depending on sliding velocity and axial load, while a gap model takes into account the uplift of the FP bearings in the vertical direction. Thus, the in-plan distribution variability of the friction force and lateral stiffness of the FP system are taken into account as function of time, due to overturning effects and high values of the acceleration ratio $\alpha_{PGA}(=PGA_V/PGA_H)$, defined as the ratio between the peak value of the vertical acceleration (PGA_V) and the analogous value of the horizontal acceleration (PGA_H). Moreover, to evaluate the effects of the modelling assumptions related to the velocity dependence of the friction coefficient of the FP bearings, three cases are compared: (a) friction coefficient variability as a function of the sliding velocity [24]; (b) constant friction coefficient, at fast sliding velocity; (c) constant friction coefficient, at slow sliding velocity. Two sets of seven near-fault earthquakes, each with significant components in the horizontal or vertical direction, are selected from the *Pacific Earthquake Engineering Research Center Database* (PEER, [25]) and normalized on the basis of the design hypotheses adopted for the test structure. In detail, maximum and mean effects are evaluated for the orientation of the strongest pulse in the case of earthquakes with significant horizontal components, while accelerograms applied in line with the direction of the recording station are considered for earthquakes with significant vertical component. It is shown that lateral-torsional coupling and residual displacement and uplift of base-isolated structures with FP bearings subjected to near-fault ground motions can be significant, depending on the distribution of friction force and lateral stiffness of the FP system and its variation during the sliding phase.

2. Layout and design of the base-isolated buildings

A six-storey r.c. office building base-isolated with the FP system, characterized by an L-shaped plan with wings of different length (Fig. 1(a)) and setbacks at different heights (Fig. 1(b)), is considered as test structure. It is designed in line with the Italian seismic code [23] and besides the gravity loads, the horizontal seismic loads are assumed to act alone or in combination with the vertical ones. The following design assumptions are considered: elastic response of the superstructure (i.e. behaviour factor for the horizontal seismic loads, $q_H=1$; behaviour factor for the vertical seismic loads, $q_V=1$); stiff site (i.e. subsoil class B); medium-risk seismic region (i.e. peak ground accelerations: $PGA_{H,LS}=0.16\times g\times 1.2=0.19\times g$ and $PGA_{V,LS}=0.08\times g$, at the life-safety limit state for the superstructure; $PGA_{H,CP}=0.21\times g\times 1.2=0.25\times g$ and $PGA_{V,CP}=0.13\times g$, at the collapse prevention limit state for the base-isolation system). The gravity loads used in the design are represented by a dead load of 6.7 kN/m^2 and a live load of 2.0 kN/m^2, on all floors, and a perimeter masonry-infills of 2.7 kN/m^2, on the first five floors. A cylindrical compressive strength of 25 N/mm^2 for the concrete and a yield strength of 450 N/mm^2 for the steel are assumed for the r.c. frame members. Cross sections of beams and columns are reported in Tables 1 and 2, respectively.

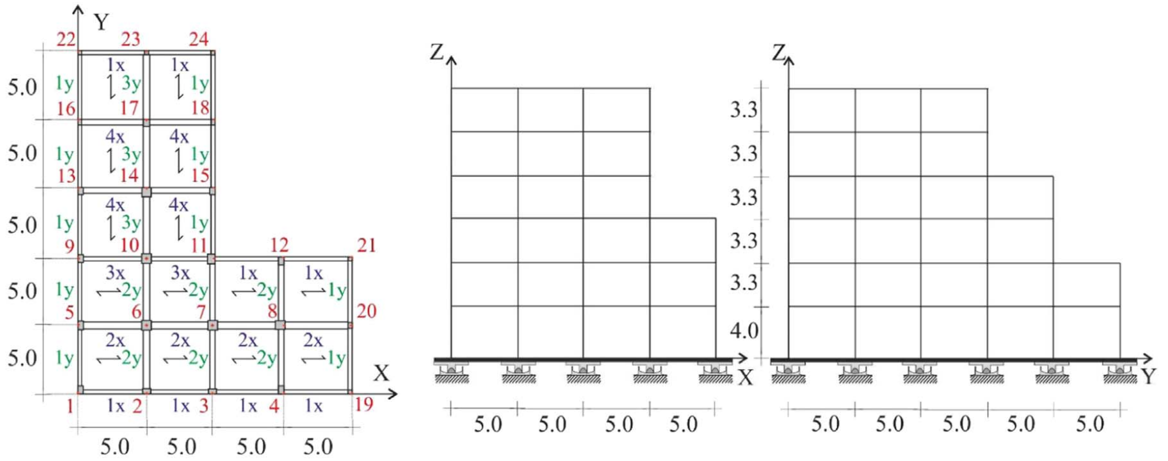
The FP system is designed at the CP limit state, requiring the fulfilment of the provisions imposed by NTC08: i.e. maximum compression axial load of the FP bearing less than its capacity; maximum horizontal displacements less than the spectral value; absence of tensile axial loads at the level of the FP system.

Three values of the effective fundamental vibration period of the isolation system

$$T_{e,I}=2\pi\sqrt{\frac{1}{g\left(\frac{1}{R}+\frac{\mu_{fast}}{u_{H,d}}\right)}} \tag{1}$$

are considered (i.e.=2 s, 2.5 s and 3 s), corresponding to the effective stiffness

$$K_e=N_{Sd}\left(\frac{1}{R}+\frac{\mu_{fast}}{u_{H,d}}\right) \tag{2}$$



(a) Plan (b) Elevations

Fig. 1. Base-isolated test structure (units in m).