Soil Dynamics and Earthquake Engineering 108 (2018) 111–129

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

Seismic demand of base-isolated irregular structures subjected to pulse-type earthquakes

Fabio Mazza

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

ARTICLE INFO

Keywords:
Pulse-type earthquake
Forward-directivity effect
Near-fault area
Wavelet analysis
Fixed-base irregular structures
Retrofitted base-isolated structures
Elastomeric and sliding bearings
Nonlinear dynamic analysis

ABSTRACT

Base-isolated structures may be subjected to severe seismic demand in the superstructure and/or in the isolation system at sites located near an active fault. Forward directivity effects with long-period horizontal pulses in the fault-normal velocity signals are the main cause of this behaviour. However, recent studies have identified pulses in arbitrary orientations along with false-positive classification of pulse-type ground motions. The aim of the present work is to evaluate the reliability of elastomeric (i.e. high-damping-laminated-rubber bearings, HDLRBs) and sliding (i.e. curved surface sliding bearings, CSSBs) base-isolation systems for the seismic retrofitting of in-plan irregular buildings located in the near-fault area. To this end, a five-storey reinforced concrete (r.c.) framed structure, with an asymmetric-plan and bays of different length, is chosen from benchmark structures of the Re.L.U.I.S. project. Attention is focused on the pulse-type and non-pulse-type nature of near-fault earthquakes and moderately-soft and soft subsoil conditions. First, a comparison between algorithms based on wavelet signal processing, that can identify pulses at a single (e.g. fault-normal) or arbitrary orientation in multicomponent near-fault ground motions, is carried out to classify records of recent events in central Italy and worldwide. Then, nonlinear seismic analysis of the fixed-base and base-isolated test structures is performed by using a lumped plasticity model to describe the inelastic behaviour of the r.c. frame members. Nonlinear force-displacement laws are considered for the HDLRBs and CSSBs, including coupled bi-directional motions in the horizontal directions and coupling of vertical and horizontal motions.

1. Introduction

First the detrimental effects of pulse-type near-fault ground motions on structural response are recognized in [1–4]. Next, near-fault ground motions worldwide (e.g. Chi-Chi in Taiwan, Northridge in U.S.A. and Kobe in Japan to name a few) exhibiting high-amplitude and long-period velocity pulses raise concerns about the reliability of the base-isolation as control system of existing framed buildings [5–8]. Amplification in the inelastic demand of the superstructure and large displacement at the base are generally expected for base-isolated structures located in the near-fault area [9,10], making it difficult and expensive to design optimal solutions [11,12]. In particular, forward directivity effects tend be maximum along the fault-normal direction, referring to the horizontal ground-motion components [13], although pulse-type earthquakes are also observed in different orientations [14]. However, not all near-fault ground motions experience pulse-type effects along with false-negative classifications that can occur when only one potential pulse is considered [14–16]. Moreover, the pulses caused by directivity effects arrive early in the velocity time history but pulse-type ground motions can be also caused by soft-soil effects. Finally, seismic sequences in near-fault area recorded during recent earthquakes in central Italy (i.e. L'Aquila in 2009 and Rieti in 2016) focus attention on the residual deformations of r.c. framed structures [17–19], giving rise to an interest in the retrofitting of existing structures with base-isolation systems to limit the accumulation of damage.

Coupled torsional-translational response of asymmetric-plan framed buildings adversely affects the nonlinear seismic behaviour, which results in irregular concentration of inelastic demand leading to structural collapse. Base-isolation is generally considered an effective means of reducing asymmetry if the stiffness (CS) and strength (CST) centres of the isolation system are directly under the centre of mass (CM) of the superstructure [20,21]. Significant sources of torsional motions in elastomeric [22] and sliding [23] base-isolated structures are the stiffness eccentricity (i.e. the distance between CS and CM) and the lateral and torsional flexibility of the superstructure. Mass-eccentric rather than stiffness-eccentric superstructures produce torsional amplifications [24], while an eccentric isolation system may adversely affect its effectiveness since the maximum displacement is increased [25]. Moreover, the maximum amplification of the response occurs at the stiff or flexible edge for torsionally flexible or rigid base-isolation systems,

---

E-mail address: fabio.mazza@unical.it.

https://doi.org/10.1016/j.soildyn.2017.11.030
Received 8 August 2017; Received in revised form 26 November 2017; Accepted 27 November 2017

respectively [26]. Finally, by observing the nonlinear behaviour of the superstructure one founds that CS ≡ CST ≡ CM is convenient only for accommodating torsional effects in the base isolation system but might cause more damage in the flexible side of the superstructure [27]. On the other hand, elastomeric and sliding bearings may suffer from tension or uplift, respectively, accompanied by large horizontal shear strain under violent near-fault earthquakes. Specifically, overturning moments during seismic excitation can induce undesirable tensile forces in elastomeric bearings [28,29] or uplift in sliding bearings [8,30], which are amplified when the height-width ratio of the superstructure is large or in-plan irregularity is considered.

Although the study of the retrofit of plan-irregular buildings with base isolation is not new [31,32], this discussion emphasizes the advisability of additional studies to clear up any misunderstanding and evaluate whether a base-isolation system may also be viable for the seismic retrofitting in the near-field area, also considering in plan-irregularities inducing torsional and overturning effects. With this aim in mind, a simulation is conducted in which a five-storey reinforced concrete (r.c.) framed structure, characterized by an L-shaped plan with bays of different length, is retrofitted by insertion of an isolation system at the base for attaining performance levels imposed by current Italian code (NTC08, [33]) in a high-risk seismic zone. Specifically, elastomeric (i.e. Elastomeric Base-Isolated, EBI, structure with high-damping-laminated-rubber bearings, HDLRBs) and sliding (i.e. Sliding Base-Isolated, SBI, structure with curved-surface-sliding bearings, CSSBs) base-isolation systems are considered. Four test structures are considered for each base-isolation system, considering: design seismic loads constituted of the horizontal component acting alone or in combination with the vertical one; subsoil classes C and D, corresponding to moderately soft- and soft-site, in accordance with the NTC08 classification. A comparison of the 3D nonlinear dynamic analysis for the original fixed-base (FB) and retrofitted base-isolated (EBI and SBI) structures subjected to near-fault earthquakes is presented. An algorithm based on the wavelet transform of a single component [13], typically the fault-normal orientation, or two orthogonal components [14] is adopted to classify near-fault ground motions as pulse-type or non-pulse-type in the horizontal direction. Next, 3D model of the fixed-base and base-isolated structures subjected to the horizontal and vertical components of near-fault earthquakes is considered. To this end, records of recent earthquakes in central Italy [34] and worldwide [35] are selected from the Italian Accelerometric Archive (ITACA) and the Pacific Earthquake Engineering Research (PEER) centre Next Generation Attenuation (NGA) database. To minimize the variability in the prediction of response parameters, a modified velocity spectrum intensity measure is evaluated and the selected earthquakes scaled in line with the NTC08 design spectra.

2. Pulse-type indicators for near-fault earthquakes

Pulse-type near-source ground motions may be the result of forward directivity effects, which result in a double-sided velocity pulse at the beginning of the time-history whose duration is expected to scale with magnitude [36]. This happens because seismic waves generated at different points along the rupture front arrive at a site at the same time when the fault rupture propagates towards the site and the slip direction is aligned with the site [37]. Evidence of impulsive features in near-source area are identified in recent earthquakes in L'Aquila (April 6th, 2009) and Rieti (August 24th, 2016) and their seismic sequences [13,18,19,38]. Elsewhere, rupture directivity effects can be also found in many worldwide strong near-fault records: e.g. Taiwan (Chi-Chi, September 20th, 1999), California (Northrdige, January 17th, 1999) and Japan (Kobe, January 16th, 1999). Leaving aside visually classified pulses, a broad algorithm used to classify these ground motions as pulse-type is based on wavelet analysis, by examining a single component of the original velocity time-history (typically that in the fault-normal orientation) to identify and extract the pulse, evaluating its period (T_P) and the residual motion after the pulse is removed [14]. A pulse indicator (i.e. a dimensionless real number PI varying in the range 0–1) is evaluated

$$PI = (1 + e^{-23.3+14.6(PGV\,ratio)+20.5(Energy\ \mathrm{ratio})})^{-1} \tag{1}$$

which is function of amplitude and energy of the residual and original (recorded) ground motions

$$PGVratio = \frac{PGV_{residual\ \ record}}{PGV_{original\ \ record}},\ \ Energy\ ratio = \frac{CSV\,(t_{tot})_{residual\ \ record}}{CSV\,(t_{tot})_{original\ \ record}} \tag{2a,b}$$

where the energy can be computed as the cumulative squared velocity of the signal during the total duration of the earthquake (t_{tot})

$$CSV\,(t_{tot}) = \int_0^{t_{tot}} V^2(\tau)d\tau \tag{3}$$

In particular, a ground motion is classified as pulse-type when a PI value in excess of 0.85 is scored together with a peak ground velocity (PGV) greater than 30 cm/s. Moreover, early pulses, produced by directivity effects, are distinguished by late pulses, due to soft-soil effects, using the time at which the CSV of the extracted pulse attains 10% of its total value (i.e. $t_{10\%,pulse}$) before the original ground motion reaches 20% of its CSV (i.e. $t_{20\%,original}$). However, this algorithm fails to capture pulse-type earthquakes in orientations different from fault-normal, and it is thus unusable when the fault-normal orientation itself is unknown. To overcome these problems, the ground motion can be rotated in all orientations (i.e. 0–180°, to avoid redundancy) and it can considered as pulse-type if a pulse is identified at least in one orientation [15]. On the other hand, this approach is computationally expensive and can lead to non-pulse-type ground motions being classified as pulse-type, because the PGV threshold is assigned arbitrarily. Finally, an improved algorithm avoiding false-positive classifications finds five potential orientations that are the most likely to contain strong pulses, also introducing a modified expression of the pulse indicator [16]

$$PI = 9.384(0.76 - PC - 0.0616PGV)(PC + 6.914.\ 10^{-4}PGV - 1.072) - 6.179 \tag{4}$$

with a principal component (PC) evaluated as linear combination of the PGV and energy ratios

$$PC = 0.63.\ (PGV\ \mathrm{ratio}) + 0.777.\ (Energy\ ratio) \tag{5}$$

The ground motion is classified as pulse-type when the PI value is positive and as non-pulse-type if negative. Moreover, the early pulses present $t_{5\%,pulse}$ greater than $t_{17\%,original}$.

Eleven recent near-fault ground motions in central Italy are selected from the Italian Accelerometric Archive [34]; recordings from ground motions with magnitude (M_w) between 5.9 and 6.5 and short epicentral distance (Δ_1) are considered. Worldwide, three strong near-fault earthquakes, with $6.7 \le M_w \le 7.6$ and closest fault distance (Δ_2), are selected from the Pacific Earthquake Engineering Research (PEER) centre Next Generation Attenuation (NGA) database [35]. The main data of the selected earthquakes (EQs) are shown in Tables 1a and 1b, respectively: i.e. earthquake, recording station, peak ground acceleration in the horizontal (PGA_{H1} and PGA_{H2}) and vertical (PGA_V) directions, maximum peak ground velocity ($PGV_{H,max}$) and displacement ($PGD_{H,max}$) in the horizontal direction. It should be noted that the Accumoli and Ussita EQs are also considered in the numerical study, although Baker's original classification [14] excludes these low-amplitude records because their $PGV_{H,max}$ value is less than 30 cm/s.

Firstly, the algorithm suggested by Shahi and Baker [14,15] is implemented at different orientations of the horizontal components of the selected earthquakes in the range 0–360°, with a constant step of 10°, using Eqs. 1–3 to evaluate the PI values for the Italian (Fig. 1) and worldwide (Fig. 2) EQs. The PI threshold (i.e. 0.85) is also reported in Figs. 1 and 2 with a dashed black line. As can be observed, Italian pulse-type ground motions occur in a range of orientations for all recording