Structural Engineering and Mechanics, *Vol. 75, No. 1 (2020) 33-47*
DOI: https://doi.org/10.12989/sem.2020.75.1.033

Dimensional analysis of base-isolated buildings to near-fault pulses

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(Received October 19, 2019, Revised January 10, 2020, Accepted January 11, 2020)

Abstract. In this paper the dynamic behavior of an isolated building subjected to idealized near-fault pulses is investigated. The building is represented with a simple 2-DOF model. Both linear and non-linear behavior of the isolation system is considered. Using dimensional analysis, in conjunction with closed form mathematical idealized pulses, appropriate dimensionless parameters are defined and self-similar curves are plotted on dimensionless graphs, based on which various conclusions are reached. In the linear case, the role of viscous damping is examined in detail and the existence of an optimum value of damping along with its significant variation with the number of half-cycles is shown. In the nonlinear case, where the behavior of the building depends on the amplitude of the excitation, the benefits of dimensional analysis are evident since the influence of the dimensionless Π-terms is easily examined. Special consideration is given to the normalized strength of the non-linear isolation system that appears to play a complex role which greatly affects the response of the 2-DOF. In the last part of the paper, a comparison of the responses to idealized pulses between a linear fixed-base SDOF and the respective isolated 2-DOF with both linear and non-linear damping is conducted and it is shown that, under certain values of the superstructure and isolation system characteristics, the use of an isolation system can amplify both the normalized acceleration and displacement of the superstructure.

Keywords: seismic response; near-fault pulses; base-isolation; dimensional analysis; non-linear analysis; earthquake engineering

1. Introduction

Base isolation has been one of the most effective and widely implemented seismic protection systems for the last 25 years. This system is intended to simultaneously reduce interstory drifts and floor accelerations through a reduction of stiffness and an increase in damping (Kelly 1997). Therefore, base-isolated buildings are characterized by relatively large fundamental periods.

In recent years the records from near-fault earthquakes (e.g. the 1995 Kobe Earthquake, the 1999 Chi-chi Taiwan Earthquake) have shown that the ground motions near the faults of major earthquakes may contain long period velocity pulses that can amplify the displacement demands of the isolation system. Although during the 1994 Northridge and the 1995 Kobe Earthquakes several isolated buildings with Lead Rubber Bearing (LRB) performed well and base isolation was effective in reducing the response (Nagarajaia and Sun 2000, Nagarajaiah and Sun 2001, Buckle *et al.* 2002), several researchers have pointed out the vulnerability of base-isolated buildings to large velocity pulses contained in near-source ground motions (Buckle and Mayes 1990, Heaton *et al.* 1995, Hall *et al.* 1995, Yang and Agrawal 2002, Castaldo and Tubaldi 2018). Under these motions there may appear such large displacement demands that could result in the failure of the isolation systems (Yang and Agrawal 2002, Nagarajaiah and Ferrell 1999). This topic has been challenging and, consequently, various studies have been reported (Makris 1997, Makris and Chang 2000, Jangid and Kelly 2001, Liao *et al.* 2004, Jangid 2005, Panchal and Jangid 2008, Ariga *et al.* 2006, Alhan and Gavin 2004, Ramallo *et al.* 2002, Shen *et al.* 2004, Rao and Jangid 2001, Kampas and Makris 2012, 2013, Makris 2014, Konstantinidis and Nikfar 2015, Chen *et al.* 2017). Ariga *et al.* (2006) revealed that the long-period ground motions recorded in Japan have the intensity to bring in resonance base-isolated high-rise buildings with long period components and that careful treatment is required in the structural design of these buildings. Shen *et al.* (2004) investigated the near-fault effects on the performance of a seismically isolated bridge. They revealed (i) an amplified seismic response when the pulse period was close to the effective period and (ii) a beneficial effect of bearing nonlinearity on the acceleration response.

Several researchers have suggested the use of supplemental energy dissipative mechanisms (to protect structures from near-fault earthquakes) (Hall 1999, Hall and Ryan 2000, Zhang and Iwan 2002, Sahasrabudhe and Nagarajaiah 2005), while others have shown that the addition of damping may reduce the isolator displacement but it may also increase the floor accelerations and interstorey drifts (Alhan and Gavin 2004, Inaudi and Kelly 1993, Sadek and Mohraz 1998). Jangid and Kelly (2001) reported the existence of a particular value of isolation damping that minimizes superstructure acceleration for a given structural system under near-fault motion. Some

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http://www.techno-press.com/journals/sem&subpage=7
ISSN: 1225-4568 (Print), 1598-6217 (Online)

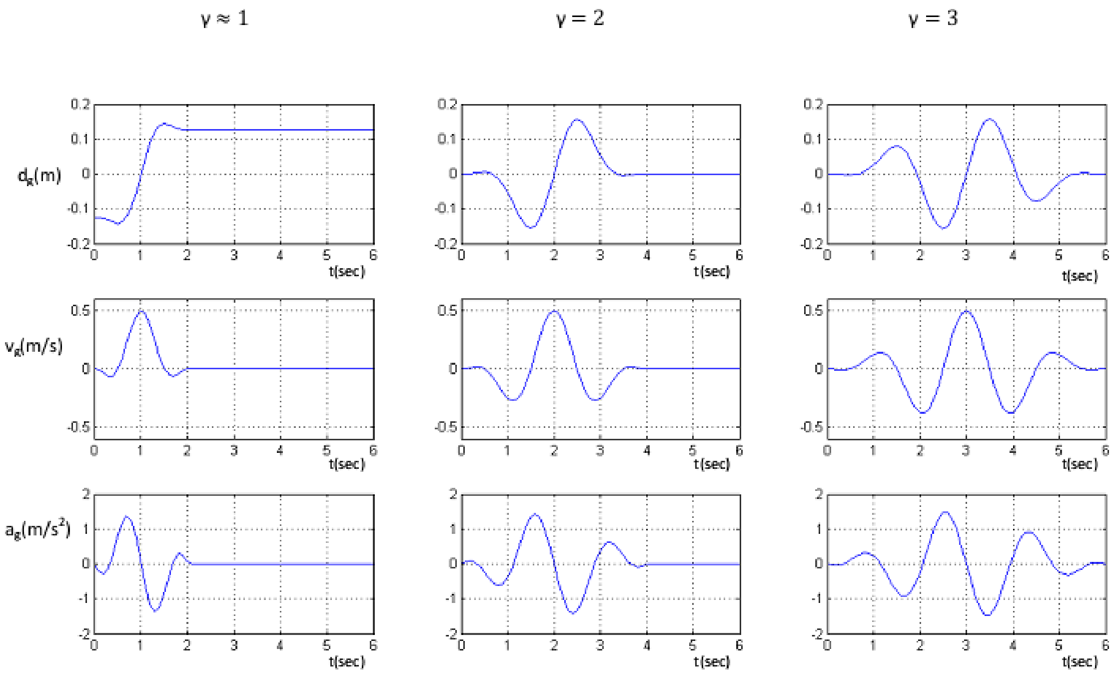

Fig. 1 Ground motions time histories (displacement, velocity, acceleration) given by the mathematical model of Mavroeidis & Papageorgiou for Tp=2s, A=0.5m/s, v=0 and different values of γ

researchers have investigated various passive isolation systems and dissipative mechanisms and showed the existence of optimum values of the parameters of the isolation system for near-fault earthquakes (Jangid 2005, Alhan and Gavin 2004, Jangid 2007), while others have proposed the use of semi-active dampers (Makris 1997, Ramallo *et al.* 2002) to effectively protect structures from near-fault ground motions.

Many of the aforementioned studies made use of recorded ground motions (Jangid and Kelly 2001, Jangid 2005, Ariga *et al*. 2006, Alhan and Gavin 2004, Ramallo *et al.* 2002, Jangid 2007), while others additionally used simple pulses along the recorded data (Makris 1997, Panchal and Jangid 2008, Makris and Chang 2000, Shen *et al*. 2004, Mazza and Vulcano 2009) since such an approach can lead to a better understanding of near-fault phenomena. Makris and Chang (2000) found that there is a resemblance between the structural response for near-fault ground motions and the one caused by a harmonic pulse only for buildings with moderate to large periods. Using the same harmonic pulses in conjunction with dimensional analysis, Makris and Black (2004) and Makris and Psychogios (2006) managed to specify dimensionless parameters which uncover the physics of the behavior of rigid-plastic, elastoplastic and bilinear SDOF systems (Makris and Black 2004, Makris and Psychogios 2006) and the physics of the behavior of yielding structures with first-mode dominated responses (Makris and Psychogios 2006), respectively.

In this study, the behavior of a base-isolated building with both linear and non-linear behavior of the isolation system, under idealized near-fault pulses, using dimensional analysis is investigated. A 2-DOF model is used, where for simplicity the superstructure will be assumed to remain in the elastic range during the earthquake excitation. The aim of this study is to specify dimensionless variables for the 2-DOF, similar to the ones found in (Makris and Black 2004)for the SDOF, that will allow to plot dimensionless graphs in order to shed light on the dynamic behavior of a base-isolated building subjected to pulse-type excitations resembling near-fault ground motions.

2. Analytical model for near-fault ground motions

Base isolation has been one of the most effective and widely implemented seismic protection systems for the last 25 years. This system is intended to simultaneously reduce interstory drifts and floor accelerations. Since the early study of Jacobsen and Ayre (1958) that examined the behavior of a SDOF under different types of acceleration pulses, several other researchers have used simple pulses in their studies (e.g. Hall *et al*., 1995, Makris & Chang, 2000, Mylonakis & Reinhorm, 2001, Mylonakis & Voyagaki, 2006). In recent years, that near-fault seismic ground motions comprise an active research topic for seismologists and earthquake engineers, various analytical models for the representation of near-fault ground motions have been introduced (Makris and Chang 2000, Menun and Fu 2002, Mavroeidis and Papageorgiou 2003). These mathematical models can approximate the main kinematic characteristics of near-source ground motions and have the potential to facilitate the study of the response of structures subjected to these motions. The minimum number of parameters is 2, that is: the duration T_p and either the acceleration amplitude ap or the velocity amplitude v_p. The present study employs both the simple harmonic pulses (used in Makris and Chang 2000, Makris and Black 2004, Makris and Psychogios 2006 among others] that employ only the 2 input parameters T_p

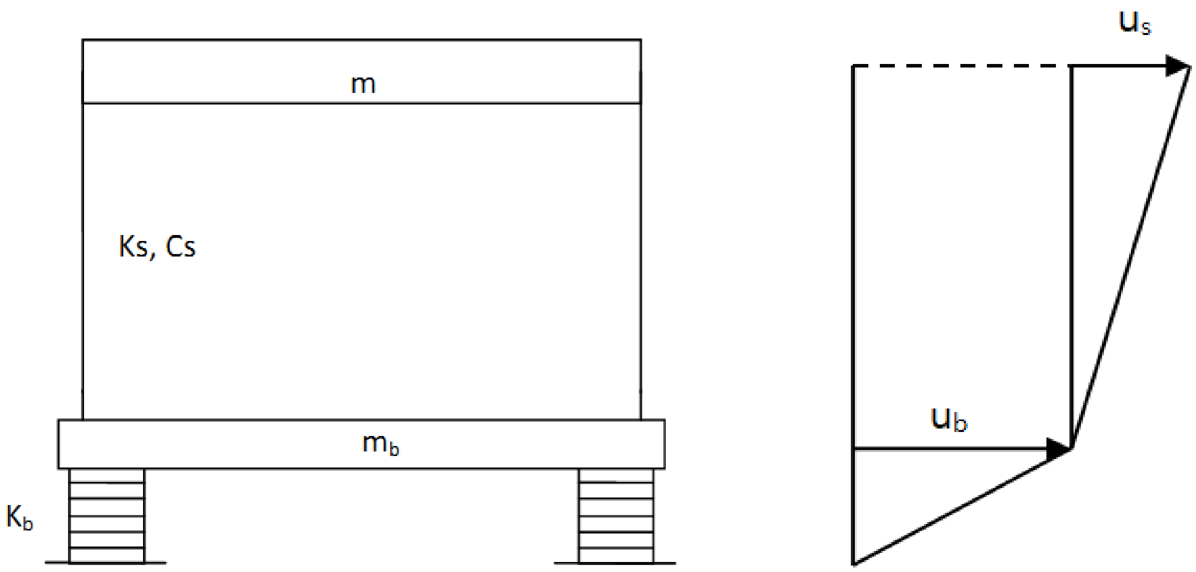

Fig. 2 Base isolated system and corresponding displacements

and a_p (or v_p), as well as the more sophisticated model of Mavroeidis and Papageorgiou (2003, 2004) that involves 4 input parameters which are the pulse period T_p, the velocity pulse amplitude A, the number γ and the phase v of the half cycles. However, because of limited space only the graphs from the latter model are presented. This model is also selected because of the large set of related near-fault ground motions that were used for its calibration and verification. The models are described by Equations (1) and (2). It must also be clarified that the pulse velocity is represented with v_p according to Makris and Black (2004) and with A according to Mavroeidis and Papageorgiou (2003, 2004). Figure 1 depicts the ground displacement, $d_g(t)$, velocity $v_g(t)$ velocity and acceleration time history $a_g(t)$ given by the model of Mavroeidis and Papageorgiou (2003, 2004) for A= 0,5 m/s, T_p= 2s, v=0 and γ=1, γ=2, γ=3.

The Type A harmonic pulse is expressed by Makris and Black (2004):

$$\begin{aligned} a_g(t) &= \frac{\omega_p \cdot v_p}{2}\sin(\omega_p \cdot t), \qquad 0 \le t \le T_p \\ v_g(t) &= \frac{v_p}{2}\left(1-\cos(\omega_p \cdot t)\right), \qquad 0 \le t \le T_p \\ d_g(t) &= \frac{v_p}{2}\left(t-\frac{\sin(\omega_p \cdot t)}{\omega_p}\right), \qquad 0 \le t \le T_p \end{aligned} \tag{1}$$

The pulse suggested by Mavroeidis and Papageorgiou (2003, 2004) is given by:

$$\begin{aligned} v_g(t) &= \begin{cases} A\frac{1}{2}\cdot\left[1-\cos\left(\frac{2\pi\cdot f_p}{\gamma}\cdot t\right)\right]\cdot\cos[2\pi\cdot f_p\cdot t-\pi\cdot\gamma+v], & 0 \le t \le \frac{\gamma}{f_p}\ with\ \gamma > 1 \\ 0, otherwise \end{cases} \\ \alpha_g(t) &= \begin{cases} \frac{A\cdot\pi\cdot f_p}{\gamma}\cdot sin\left(\frac{2\pi\cdot f_p}{\gamma}\cdot t\right)\cdot\cos[2\pi\cdot f_p\cdot t-\pi\cdot\gamma+v], & 0 \le t \le \frac{\gamma}{f_p}\ with\ \gamma > 1 \\ 0, otherwise \end{cases} \end{aligned} \tag{2}$$

3. Structural model

In order to study the behavior of a base isolated building and to examine the response of both the isolation system and the superstructure, a model with at least two degrees-of-freedom (2-DOF) is suggested (Kelly, 1997). Therefore, the present study uses a 2-DOF isolated structure with a linear superstructure, a linear restoring force with stiffness k_b and both linear and non-linear isolation systems. The mass of the building superstructure and the mass of the base floor above the isolation system are demoted by m and m_b, respectively. In both cases, the system is characterized by the parameters: T_s, ξs, λ, T_b and additionally b_y ξ_b for the linear isolation system with viscous damping or by the yielding force Q and the yielding displacement u_y for the non-linear isolation system, defined as:

$$T_s = \frac{2\pi}{\omega_s} \tag{3}$$

$$and\ \omega_s = \sqrt{\frac{K_s}{m}} \tag{4}$$

$$2\xi_s\omega_s = \frac{c_s}{m} \tag{5}$$

$$and\ 2\xi_b\omega_b = \frac{c_b}{m+m_b} \tag{6}$$

$$\lambda = \frac{m}{m + m_b} \tag{7}$$

$$T_b = \frac{2\pi}{\omega_b} \tag{8}$$

$$and\ \omega_b = \sqrt{\frac{K_b}{m + m_b}} \tag{9}$$

The equations of motion for the 2-DOF shown in Figure 2 is given:

$$\begin{bmatrix} 1 & \lambda \\ 1 & 1 \end{bmatrix} \begin{bmatrix} \ddot{u_b}(t) \\ \ddot{u_s}(t) \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 2\xi_s\omega_s \end{bmatrix} \begin{bmatrix} \dot{u}_b(t) \\ \dot{u}_s(t) \end{bmatrix} + \begin{bmatrix} {\omega_b}^2 & 0 \\ 0 & {\omega_s}^2 \end{bmatrix} \begin{bmatrix} u_b(t) \\ u_s(t) \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} a(t) = -\begin{bmatrix} 1 \\ 1 \end{bmatrix} \ddot{u_g}(t) \tag{10}$$

where:
u_s = relative displacement of the superstructure
u_b = relative displacement of the isolation system

$$a(t) = \frac{P(t)}{m + m_b} \tag{11}$$

and P(t) is the dissipation force (given by:)

$$P(t) = c_b \cdot \dot{u}_b(t) \tag{12}$$

for viscous of damping or

$$P(t) = Q \cdot z(t) \tag{13}$$

for hysteretic damping, where the hysteretic dimensionless quantity z(t) is given in

$$u_y \cdot \dot{z} + \gamma \cdot \dot{u}_b(t) \cdot z \cdot |z|^{n-1} + \beta \cdot \dot{u}_b(t) \cdot |z|^n - \dot{u}_b(t) = 0 \tag{14}$$

The Equations (13) and (14) describe the Bouc-Wen model (Wen 1976) for elastoplastic behavior with smooth transition by setting $\beta = \gamma = 0.5$ and n = 20 (Wen 1976). The response of the 2-DOF structure is computed numerically in MATLAB using standard ordinary differential equation solvers (MATLAB 2005). In this study it is assumed that ξ_s=2%.

4. Dimensional Analysis of a 2-Dof Model with Linear Isolation System

In this paper the dimensional analysis (Langhaar 1951, Barenblatt 1996) used also by Makris and Black (2004) for a linear, rigid-plastic, elastoplastic and bilinear SDOF oscillator is employed in order to investigate the response of a 2-DOF isolated model. By using the harmonic pulses expressed by Equation (1), adequately described by the parameters T_p (or ω_p) and v_p (or a_p), one may specify the minimum number of parameters that describe the problem. Therefore, the maximum relative displacement of the superstructure, u_s, the maximum relative displacement of the isolation system, u_b, and the maximum structural acceleration, a_s, as well, will be functions of the following seven variables:

$$u_{s,max}, u_{b,max}, a_{s,max} = f(m, m_b, K_s, K_b, \xi_b, \omega_p, v_p) \tag{15}$$

It is noted that the function f is different for $u_{s,max}$, $u_{b,max}$, $a_{s,max}$ but the variables are the same.

The variables appearing in Equation (15), $u_{s,max}$, m_i, K_i, ω_p, v_p involve all three reference quantities, that is, the mass [M], length [L] and time [T]. According to Buckingham's Π-theorem (Langhaar 1951, Barenblatt 1996), the number of independent dimensionless Π-terms for the 2-DOF model with a linear isolation system will be 8 (variables)-3(reference dimensions) = 5. The Π-terms are:

$$\Pi_1 = \frac{u_{s,max} \cdot \omega_p}{v_p}, \frac{u_{b,max} \cdot \omega_p}{v_p}, \frac{a_{s,max}}{\omega_p \cdot v_p} \tag{16}$$

$$\Pi_1 = \Phi(\Pi_2, \Pi_3, \Pi_4, \Pi_5) \tag{17}$$

$$\Pi_2 = \frac{\omega_b}{\omega_p}\left(= \frac{T_p}{T_b}\right) \tag{18}$$

$$\Pi_3 = \lambda = \frac{m}{m + m_b} \tag{19}$$

$$\Pi_4 = \frac{K_b}{K_s} \tag{20}$$

$$\Pi_5 = \xi_b \tag{21}$$

At this point, it is worth mentioning that the Π-terms that describe the response of 2-DOF include the Π-terms used by Makris and Black (2004) for the response of the linear SDOF but additional dimensionless parameters Π_3 and Π_4.

As mentioned before, for the mathematical model proposed by Mavroeidis and Papageorgiou (2003) there exist two additional parameters v and γ which will be set as Π_6 = v and Π_7 =γ. In the next graphs use will be made of this model. Makris and Black (2004) showed that for the harmonic pulses the self-similar solutions of the SDOF oscillator scale better with the peak pulse acceleration ap rather than with the peak pulse velocity, indicating that peak pulse acceleration is a superior intensity measure of the pulse excitation. In this paper however, the peak velocity pulse ($A=v_p$) for normalization will be used, as it was originally presented in (Mavroeidis *et al*. 2004).

Figure 3 shows the variation of the normalized response (u_b,u_s,a_s) of the base-isolated 2-DOF structure with viscous damping as a function of $\Pi_2=T_p/T_b$ for various values of v and γ, as was initially done for the SDOF (Mavroeidis *et al*. 2004). This figure shows that the parameter v has a significant effect only on the normalized u_b and u_s when γ approaches the value of 1 and then only for small values of the term Π_2 (<0.7). In the other cases v has an insignificant effect and this influence diminishes as γ increases. In addition, the increase of γ, which means more half-cycles in the pulse, results in an increase of the peak normalized response characteristics of the 2-DOF attributed to resonance, a fact that is in agreement with the respective observations made for the SDOF (Mavroeidis *et al*. 2004, Chopra 2007). Finally, it is observed that as γ

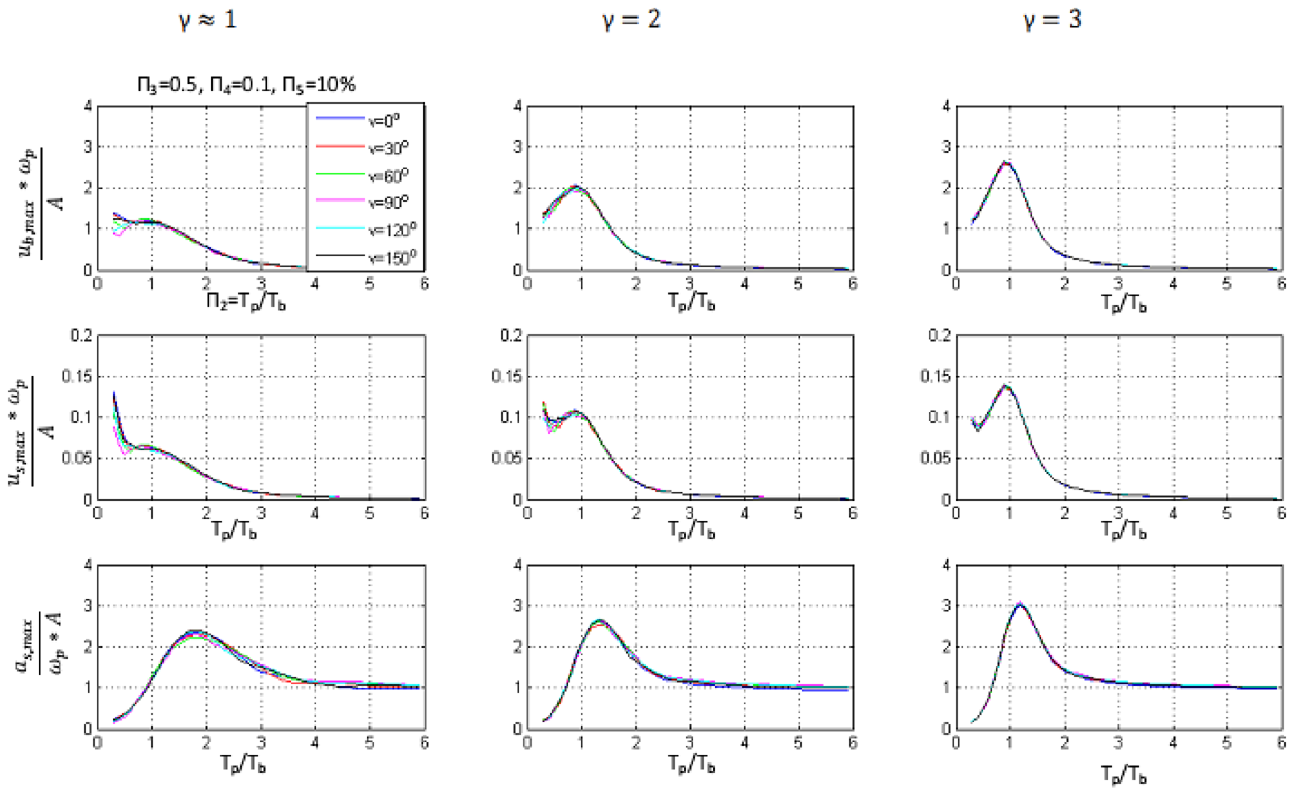

Fig. 3 Variation of the normalized response (ub, us, as) of the base-isolated 2-DOF structure with viscous damping as a function of $\Pi 2$=Tp/Tb for various values of v and γ

increases the peak value of the normalized acceleration, as occurs for smaller values of Π_2. For example for $\gamma \approx 1$ the peak value of normalized displacement as is achieved for $\Pi_2 \approx 1.8$s, but for $\gamma = 3$ the peak value of the normalized as corresponds to $\Pi_2 \approx 1.15$s. It is worth mentioning that the graphs of the normalized u_b and as of the 2-DOF plotted against T_p/T_b look similar to the ones of the linear SDOF plotted against T_p/T_s in the paper of Mavroeidis and Papageorgiou (2004).

Figure 4 illustrates the influence of the dimensionless terms Π_3, Π_4, Π_5 on the normalized response (u_b,u_s,a_s) of the base-isolated 2-DOF structure with viscous damping presented as function of Π_2 for $\gamma \approx 1$ and v=0. In particular, it is shown that the dimensionless term Π_3 does not influence the normalized displacement of the isolation system (u_b) and the total acceleration of the superstructure (a_s), but to a small degree it influences the normalized displacement of the superstructure (u_s) for values of Π_2 <2.5 by reducing the normalized (u_s) when Π_3 decreases . Similarly, the dimensionless term Π_4 has a minor effect on the normalized response characteristics (u_b, a_s), but a great effect on (us). For example, for Π_2=1an increase of Π_4 from 0.1 to 0.2 results in a 50% reduction of the normalized us. As for the dimensionless term Π_5, it seems to have a more complex role since an increase of Π_5 always decreases the normalized (u_b), but it can both increase or decrease the normalized response characteristics (u_s,a_s) depending on the value of Π_2. Specifically, in the case of $\gamma \approx 1$ for approximately 0.8<Π_2 <4, the normalized response characteristics (u_s,a_s) seem to decrease as Π_5 increases but for approximately Π_2=<0.7 the opposite happens.

From Figure 4 it can be concluded that the dimensionless parameters that play a key role on the dynamic behavior of the base-isolated 2-DOF structure with viscous damping under idealized near-fault pulses are the terms Π_2 and Π_5, while the normalized (u_s) is also greatly affected by Π_4 and much less by Π_3. In all these cases, however, the influence is significant only for values of Π_2 <3. These observations were made using the idealized pulse with $\gamma \approx 1$ but we have verified them also for greater values of γ (= 2 and 3) which, however, will not be presented here because of limited space.

In Figure 5 the influence of the dimensionless term Π_5 on the normalized response (u_b,u_s,a_s) of the base-isolated 2-DOF structure with viscous damping presented as function of Π_2 for v=0 and γ=1, 2, 3 is examined in detail. It is shown that the influence of the dimensionless term Π_5 on the normalized response (u_b,u_s,a_s) of the 2-DOF is greater as γ increases, a remark similar to the one for the SDOF (Jacobsen and Ayre 1958, Mavroeidis *et al.* 2004, Chopra 2007). For example, an increase of Π_5 from 5% to 30% leads to 40% reduction of the peak normalized as for $\gamma \approx 1$ and 53% reduction for γ=3. In addition, it seems that the effect of the dimensionless term Π_5 is similar for the different values of γ=1, 2, 3, since for all three cases there exists a range of values of Π_2 where an increase of Π_5 will decrease the normalized response characteristics (u_s,a_s) and another range of values of Π_2 where Π_5 will have the opposite effect on (u_s,a_s). This behavior implies the existence of an optimum value of the dimensionless term Π_5, namely, the viscous damping ξ_b, depending on the value of Π_2, that will minimize the normalized response

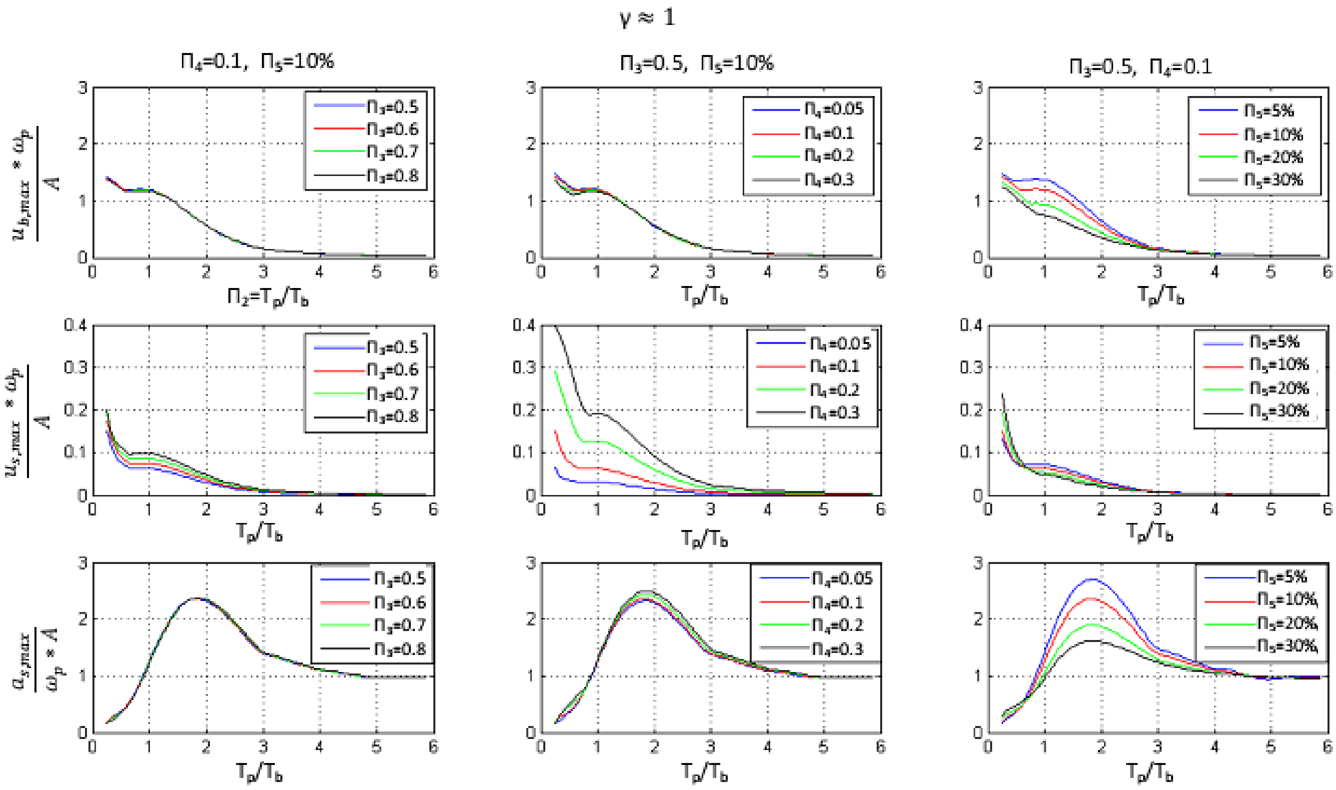

Fig. 4 Influence of the dimensionless terms Π3, Π4, Π5 on the normalized response (ub, us, as) of the base-isolated 2-DOF structure with viscous damping presented as functions of Π2=Tp/Tb for γ=1 and v=0

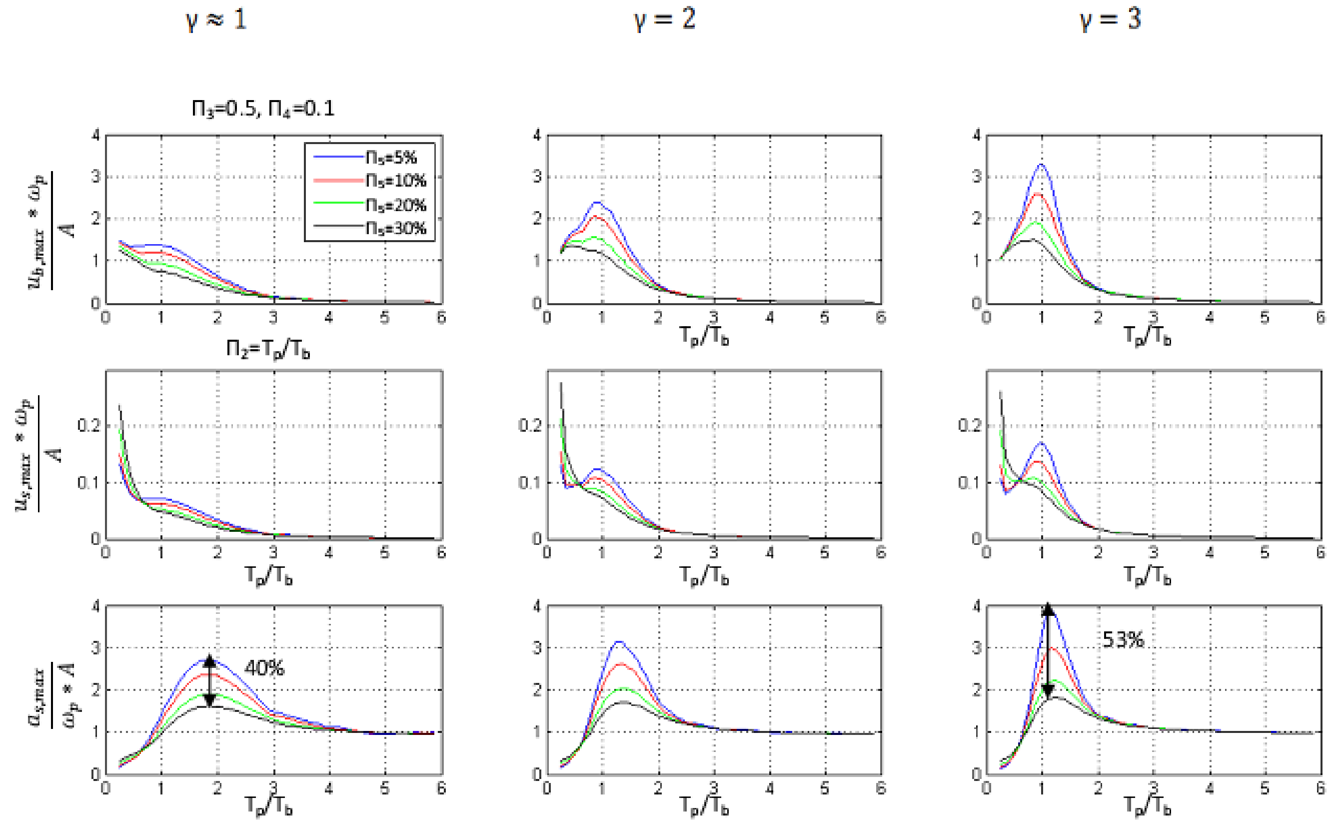

Fig. 5 Influence of the dimensionless terms Π5=ξb on the normalized response (ub, us, as) of the base-isolated 2-DOF structure with viscous damping presented as functions of Π2=Tp/Tb for v=0 and γ=1,2,3.

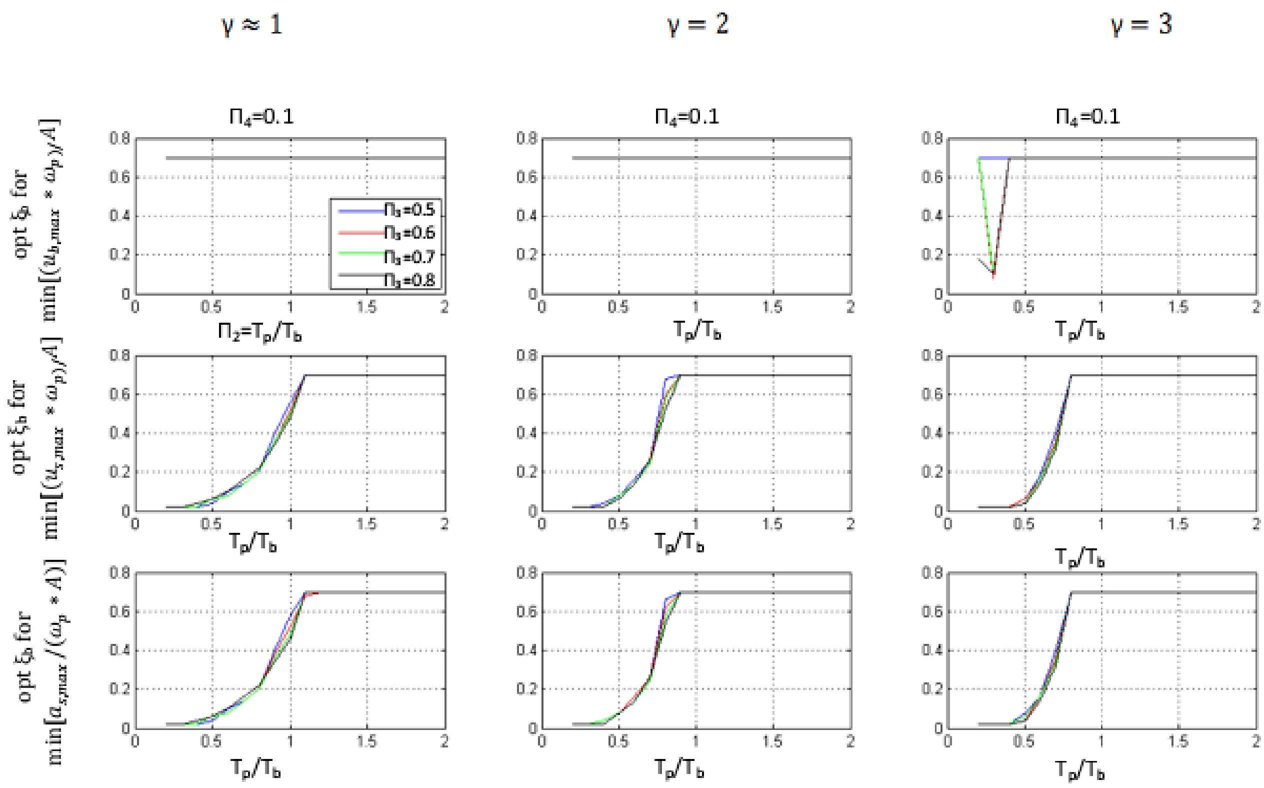

Fig. 6 Variation of optimum ξb as a function of Π2=Tp/Tb for Π4=0.1, v=0, γ=1,2,3 and various values of Π3

characteristics of the 2-DOF. The existence of the optimum ξ_b has also been observed by other researchers (Jangid and Kelly 2001, Alhan and Gavin 2004). In this study the influence of the dimensionless Π-terms on the optimum ξ_b is further investigated.

Based on the aforementioned remarks, it is considered very useful to plot the variation of the optimum ξ_b as a function of Π_2 for γ=1, 2, 3 and also examine how the other parameters of the system, Π_3 and Π_4 influence the value of optimum ξ_b. This is depicted in Figures 6 and 7. In these figures a minimum value of Π_5, minξb=1% and a maximum value max ξb=70% is considered for each value of Π2 in the range of 0.25 and 2 (which is of most practical interest), and all the damping values between minξ_b and maxξ_b are applied in order to find the optimum ξ_b for each one of the normalized response (u_b,u_s,a_s) separately, of the base-isolated 2-DOF. Thus, Figure 6 illustrates that the optimum ξ_b for minimizing the normalized (u_b) is always the maxξ_b (except some few small values of Π_2 <0.4 for γ=3) such a trend is in agreement with the previous conclusions, that is, the normalized (u_b) decreases as the damping ξ_b increases. On the other hand, the optimum ξ_b for minimizing the normalized (u_s and a_s) is different from the maxξ_b for a certain range of values of Π_2. For instance, in the case of the pulse with γ≈1, for approximately 1.1< Π_2<2 the optimum ξ_b is equal to the maxξ_b (=70% in these study), while ξ_b for Π_2<0.4 is equal to the minξ_b (=1%). For 0.4< Π_2<1.1 the optimum ξ_b is somewhere between the minξ_b and the maxξ_b, increasing monotonically from the minξ_b to the maxξ_b as the normalized frequency Π_2 increases from 0.4 to 1.1. Moreover, as γ increases, the range of values of Π_2 where the optimum ξ_b is somewhere between the minξ_b and the maxξ_b is reduced; thus, being approximately 0.4< Π_2<1.1 for γ≈1 and 0.4<Π_2<0.8 for γ=3. In addition, the increase of γ also leads to an increase of the value of optimum ξ_b. For example, for Π_2=0.75 in the case of γ≈1 and γ=3 the optimum ξ_b is approximately 18% and 52%, respectively. Thus, for a certain value of Π_2 a value of ξ_b may be optimum for reducing (u_s,a_s), when for example γ≈1, but it is not the optimum for a different γ, a fact that makes even more complex the selection of a suitable viscous damping for the isolation system in a building near a fault. Also, from Figure 6 and 7, respectively, it can be concluded that the dimensionless parameter Π_3 has an immaterial effect on the optimum ξ_b, but the dimensionless parameter Π_4 has a greater effect than Π_3 in the range of values of Π_2 where the optimum ξ_b is between the minξ_b and the maxξ_b. In all cases it is obvious that the optimum ξ_b and the variation of the optimum ξ_b, as a function of the normalized frequency Π_2, is the same for the normalized displacement and the acceleration of the superstructure (u_s and a_s). These examples have demonstrated that the optimum ξ_b is highly dependent on Π_2 and, also, on the number of half-cycles γ in a certain range of the Π_2 variation.

5. Dimensional Analysis of a 2-Dof Model with Non-Linear Isolation System

It is known that when damping emanates from non-linear mechanisms, such as friction or yielding, the response

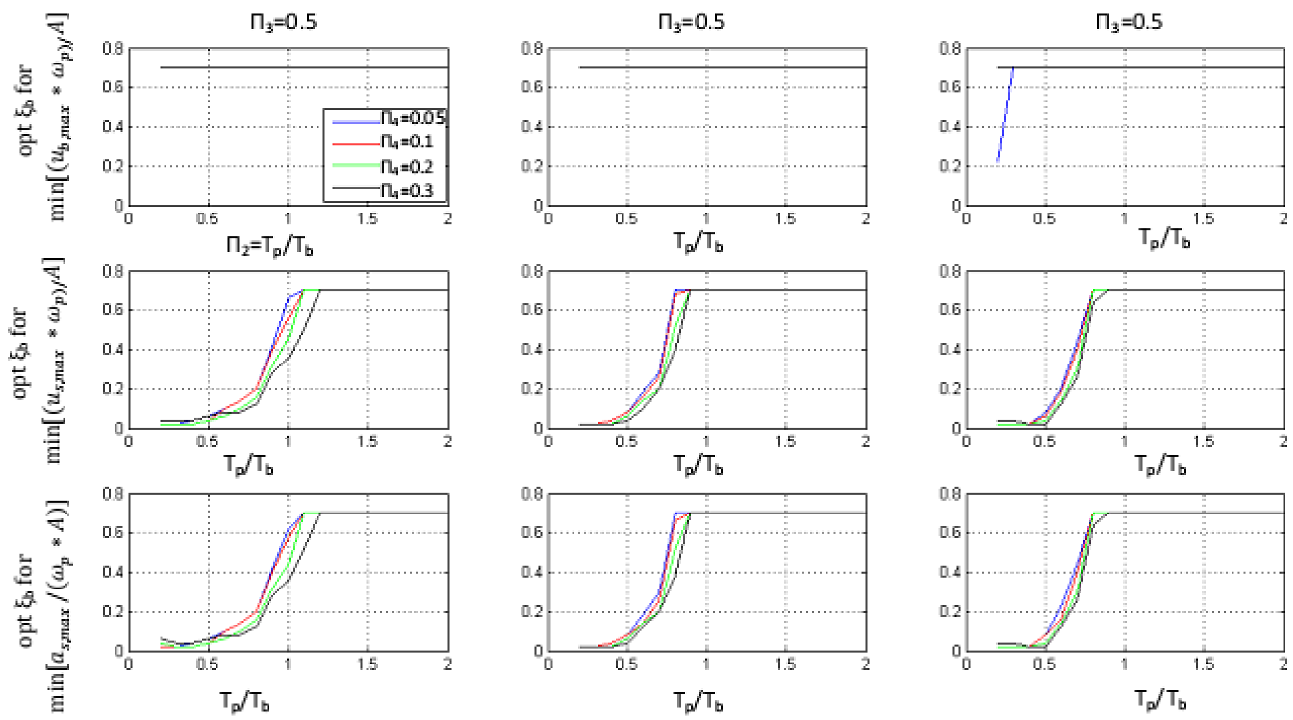

Fig. 7 Variation of optimum ξb as a function of Π2=Tp/Tb for Π3=0.5, v=0, γ=1,2,3 and various values of Π4

depends on the amplitude of the excitation (Alhan and Gavin 2004) which implies that different normalized response curves of the base-isolated 2DOF structure would be obtained for different values of the peak ground velocity A of the pulse. Therefore, it would not be easy to deduct general conclusions for a nonlinear isolation system. Nevertheless, Makris and Black (2004), showed that the use of dimensionless Π-terms defined from dimensional analysis have the great advantage to provide self-similar solutions independent of the peak ground velocity A (or acceleration) of the pulse, even in the case of non-linear damping. Therefore, using dimensional analysis, as presented for the linear isolation system, it is found that the dimensionless Π-terms that describe the 2DOF with the bilinear isolation system (where we set ξ_b=0) for the simple harmonic pulses are:

$$\Pi'_1 = \frac{u_{s,max} \cdot \omega_p}{v_p}, \frac{u_{b,max} \cdot \omega_p}{v_p}, \frac{a_{s,max}}{\omega_p \cdot v_p} \tag{22}$$

$$\Pi'_1 = \Phi(\Pi_2, \Pi_3, \Pi_4, \Pi_5) \tag{23}$$

$$\Pi'_5 = \frac{Q}{(m + m_b) \cdot \omega_p \cdot V_p} \tag{24}$$

$$\Pi_6 = \frac{u_y \cdot \omega_p}{v_p} \tag{25}$$

It should be mentioned that for the case of the mathematical model of Mavroeidis and Papageorgiou (2003), the dimensionless terms Π7 = v and Π8 = γ should be added. Notice that in Equations (22), (23) and (24) prime has been used to differentiate the Πi(i=1,5) terms from the ones expressed by Equations (16), (17) and (21).

Figure 8 shows the variation of the normalized response (u_b,u_s,a_s) of the base-isolated 2-DOF structure with nonlinear damping as a function of Π_2 for various values of v and γ. Also, Figure 10 demonstrates that the parameter v has a minor effect on the normalized response (u_b,u_s,a_s) of the base-isolated 2-DOF structure for small values of the dimensionless term Π'_5(=0.1), except for some small values of the dimensionless term Π_2<0.7, where the normalized (u_b) is affected by the variation of v. However, for larger values of Π'_5(=0.5) the parameter v seems to have a greater influence on the normalized response characteristics (u_b,a_s). This influence is diminished as the parameter γ increases. In addition, it is observed that for small values of the dimensionless term Π'_5=0,1 as γ increases, there appear larger peak normalized response characteristics (u_b,u_s,a_s), as in the case of the linear isolation system. It should be noted this is not the case for larger value of Π'_5=0.5, which implies that, as the dimensionless term Π'_5 increases, the effect of γ diminishes.

Figure 9 demonstrates the influence of the dimensionless terms Π_3, Π_4, Π'_5, Π_6 on the normalized response (u_b, u_s, a_s) of the base-isolated 2-DOF structure with nonlinear damping presented as functions of Π_2 for γ≈1 and v=0. In particular, it is shown that for both small and large values of the dimensionless term Π'_5(=0.1 and 0.5, respectively) the dimensionless term Π_3 does not influence the normalized displacement of the isolation system (u_b) and the total acceleration of the superstructure (a_s), but it affects the normalized displacement of the superstructure (u_s) to a small degree and only for values of Π_2 <2.5, by reducing the normalized (u_s) when Π_3 decreases. Similarly, the second column of the same figure shows the negligible effect of the dimensionless term Π_4 on

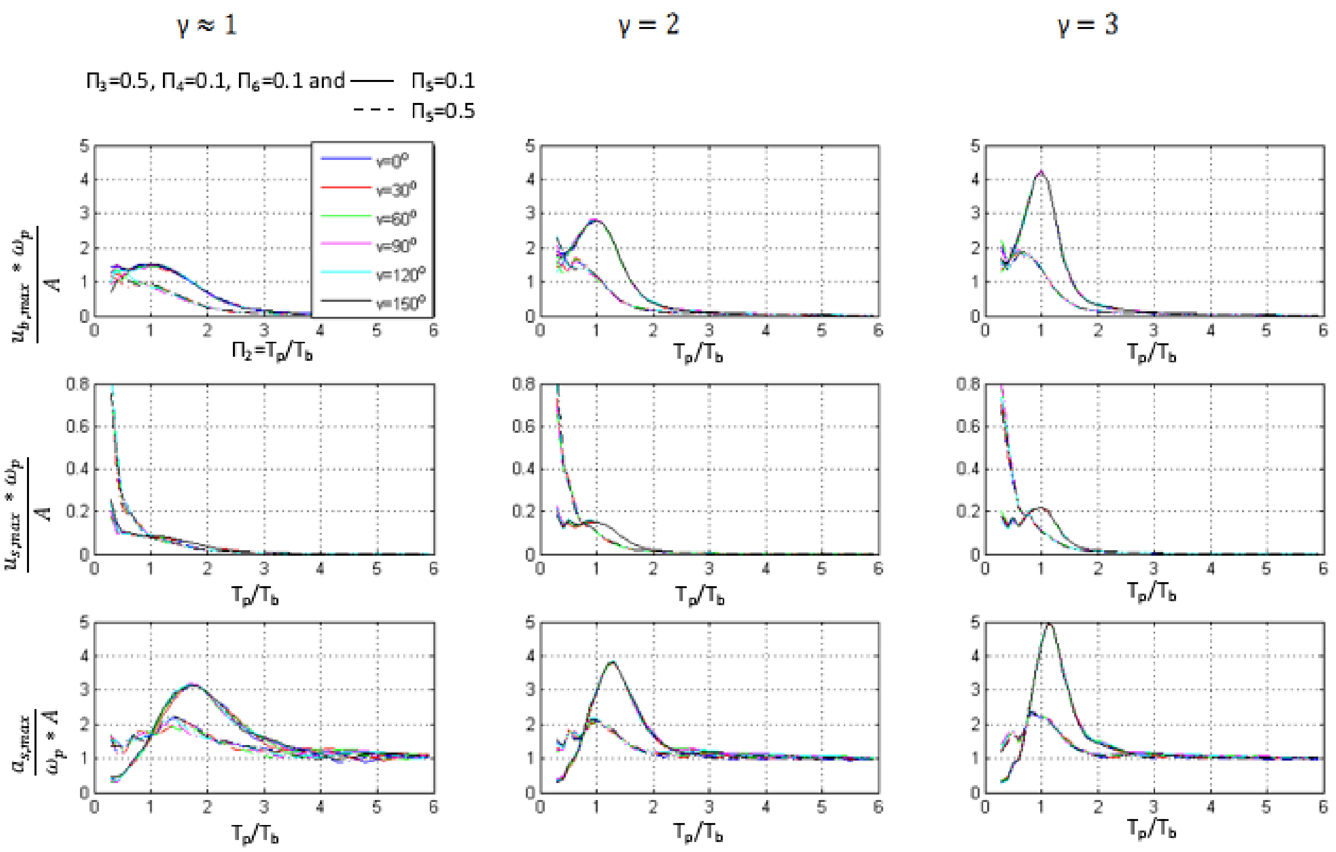

Fig. 8 Variation on the normalized response (ub, us, as) of the base-isolated 2-DOF structure with non-linear damping as a function of Π2=Tp/Tb for various values of v and γ

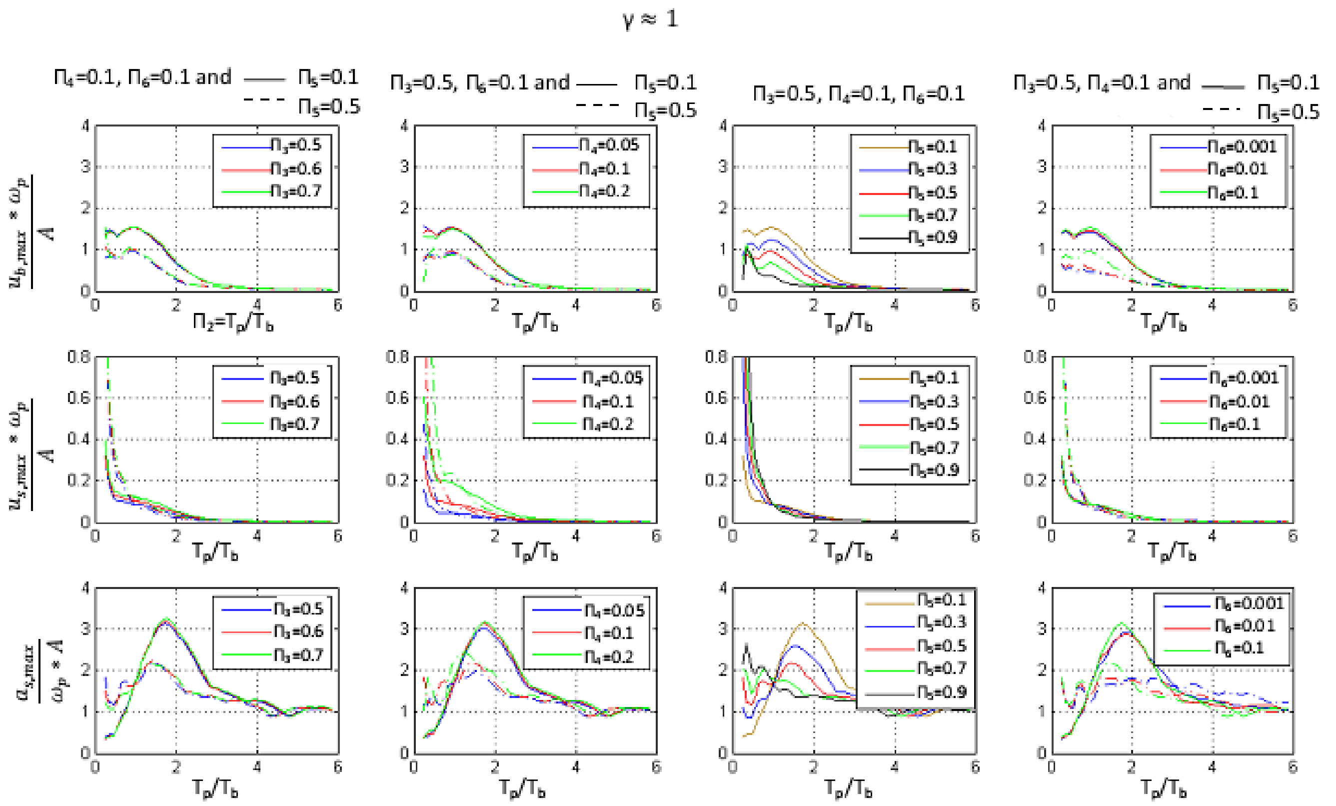

Fig. 9 Influence of the dimensionless terms Π3, Π4, Π'5, Π6 on the normalized response (ub, us, as) of the base-isolated 2-DOF structure with non-linear damping presented as functions of Π2=Tp/Tb for γ=1 and v=0

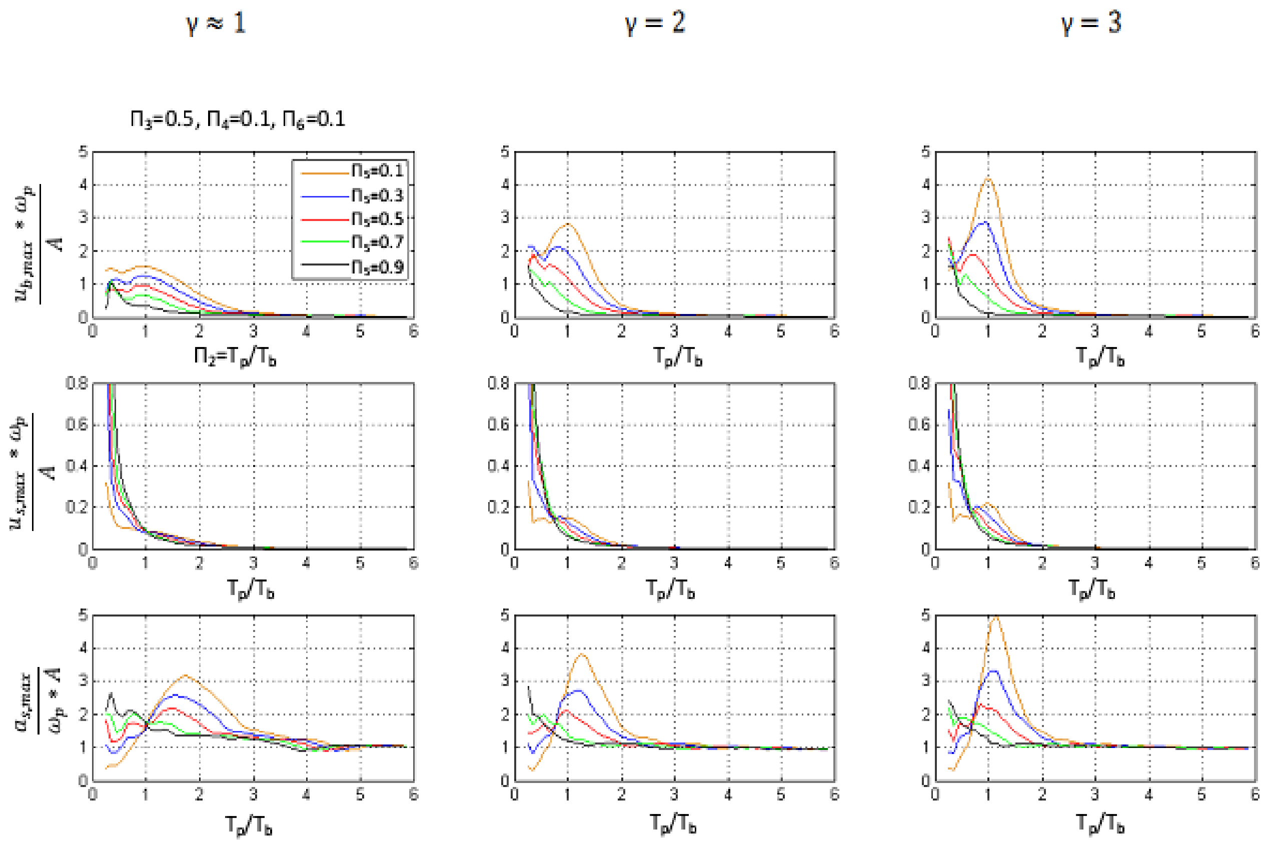

Fig. 10 Influence of the dimensionless terms Π'5 on the normalized response (ub, us, as) of the base-isolated 2-DOF structure with non-linear damping presented as functions of Π2=Tp/Tb for characteristic values of Π3, Π4, Π6 and v=0, γ=1,2,3

the normalized response characteristics u_b and a_s for small values of the dimensionless term $\Pi'_5 \leq 0{,}1$ and again only for values of $\Pi_2<2.5$. However, for $\Pi'_5=0.5$ one can observe that Π_4 has a noticeable influence on the normalized superstructure acceleration as for Π_2 2.5 which implies that the greater the value of Π'_5 is, the greater the

influence of Π_4 on as. Irrespective of the value of Π_5, though, for values of $\Pi_2<2.5$ the dimensionless term Π_4 has a decisive effect on the normalized u_s b_y causing a significant increase of (u_s) when it increases. As for the dimensionless term Π'_5 it seems to be the dominant factor in influencing the normalized response of the 2-DOF. It is quite interesting the fact that the dimensionless term Π_5 can either increase or decrease the normalized response (u_s, a_s) depending on the value of Π_2.

It is interesting to note that there exists a range of values of the dimensionless term Π_2 around the value of $\Pi_2=0.5$ where an increase in the normalized strength Π'_5 for certain values of Π'_5, increases the normalized isolation displacement u_b, a bahavior that could be regarded as 'counterintuitive'. In the third column of Figure 10 particularly, in the range of $\Pi'_2=0.5$ greater values of u_b are observed for $\Pi'_5=0.7$ and 0.9 than those for $\Pi'_5=0.5$. Finally, the fourth column of Figure 10 illustrates the insignificant effect of the normalized yielding displacement Π_6 of the nonlinear isolation system on the normalized maximum response of the 2-DOF (u_b,u_s,a_s) for small values of $\Pi_5 \leq 0.1$. This observation shows that the conclusion made by Makris and Black (2004) using a bilinear SDOF that 'under a strong earthquake an isolated bridge will exhibit the same maximum displacement, regardless if it is supported on lead-rubber bearings or friction pendulum bearings that exhibit the same strength and offer the same isolation period', can be also extended to a base-isolated building when $\Pi'_5 \leq 0.1$. For $\Pi'_5=0.5$. Although the effect of Π_6 on us is still insignificant, its effect on u_b and as becomes noticeable. In particular, it is worth noting that for Π_2 2 the normalized response (u_b, a_s) increases as Π_6 increases but for Π_2 2 the opposite occurs. This trend reveals that for large values of Π'_5 the dimensionless term Π_6 can increase or decrease the normalized response (u_b,a_s) depending on the value of Π_2.

From Figure 9 it can be concluded that the dimensionless parameters that primarily affect the dynamic behavior of the base-isolated 2-DOF structure with nonlinear damping under idealized near-fault pulses are the terms Π_2 and Π'_5 while the normalized (u_s) is also greatly affected by Π_4 and less by Π_3. However, as Π'_5 increases, Π_6 also begins also to have a noticeable effect on u_b and a_s. Even though these observations were made using the idealized pulse with $\gamma \approx 1$ the authors have verified them also for greater values of γ (= 2 and 3).

Figure 10 presents the influence of the dimensionless term on the normalized response (u_b,u_s,a_s) for the different

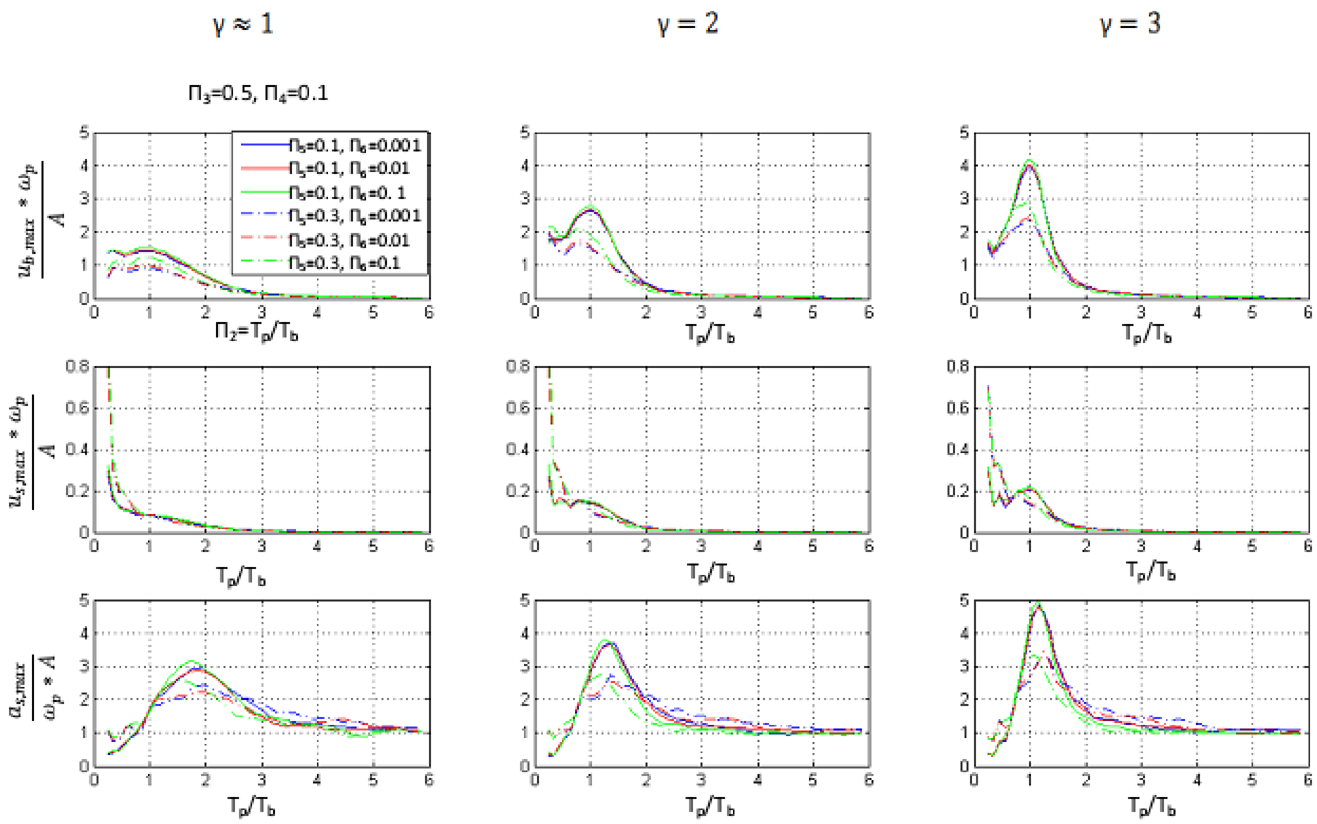

Fig. 11 Influence of the dimensionless terms Π6 on the normalized response (ub, us, as) of the base-isolated 2-DOF structure with non-linear damping presented as functions of Π2=Tp/Tb for characteristic values of Π3, Π4, Π'5 and v=0, γ=1,2,3

number of half-cycles of the idealized pulses (γ=1, 2, 3). The significant role of Π'_5 is verified, irrespective of the number of half-cycles. For all values of γ there exists a range of values of Π_2, where an increase of Π'_5 will increase the normalized response (u_s,a_s) and another range of values of Π_2 where Π'_5 will have the opposite effect on (u_s,a_s). Figure 10 also reveals the existence of an optimum value of the normalized strength Π'_5, depending on the value of Π_2, that will minimize the normalized response characteristics of the 2-DOF. The last conclusion is in agreement with the findings of other researchers that used recorded ground motions and the dimensionless term (Alhan and Gavin 2004, Jangid 2007) or other parameterization for the nonlinear isolation system (Jangid 2005) in their studies.

In Figure 11 the influence of the dimensionless term on the normalized response (u_b,u_s,a_s) for different numbers of half-cycles of the idealized pulses (γ=1, 2, 3) is presented. The role of Π_6 described previously is verified here, irrespective of the number of half-cycles. In addition, this figure clearly shows that the range of values of Π_2 , where an increase of Π_6 results in the increase of u_b and a_s, becomes smaller as γ increases, thus, being approximately $\Pi_2<1.8$ for $\gamma\approx1$ and $\Pi_2<1.2$ for γ=3. This means that there exists an optimum value of Π_6 depending again on the value of $\Pi_2=T_p/T_b$ that can minimize the normalized response of the 2-DOF, especially in the case of large values of Π_5.

Use of Figures 10 and 11 can help one choose the appropriate combination of values of Π'_5 and Π_6. Therefore, the appropriate yield strength and yield displacement of the isolation system that will most effectively minimize the response of the 2-DOF under an idealized near-fault pulse characterized by ω_p and A.

6. Comparison of the Fixed SDOF Model with the Isolated 2-Dof Model

The last part of this study examines that response of a fixed base building (SDOF) as well as the same building that is base isolated with linear or non-linear damping, both subjected to idealized pulses. As it is known, the dimensionless parameter T_p/T_s plays a key role on the dynamic behavior of the SDOF (Mavroeidis *et al.* 2004), and respectively, the dimensionless parameter T_p/T_b plays a key role on the dynamic behavior of the isolated 2-DOF. However, using the parameter T_p/T_s allows plotting the response of both structures on the same graph. Thus, Figure 12 presents the normalized response characteristics (u_s,a_s) of the fixed SDOF and the isolated 2-DOF as a function of the dimensionless parameter T_p/T_s ,where Ts is the period of the fixed SDOF. Inspection of this figure shows the vulnerability of the isolated building compared to the fixed one, as first revealed by other researchers, e.g., 7, 8. In particular, it is observed that, depending on the value of the parameter T_p/T_s and the values of the dimensionless terms Π_3, Π_4, Π_5, Π_6 that define the characteristics of the isolation

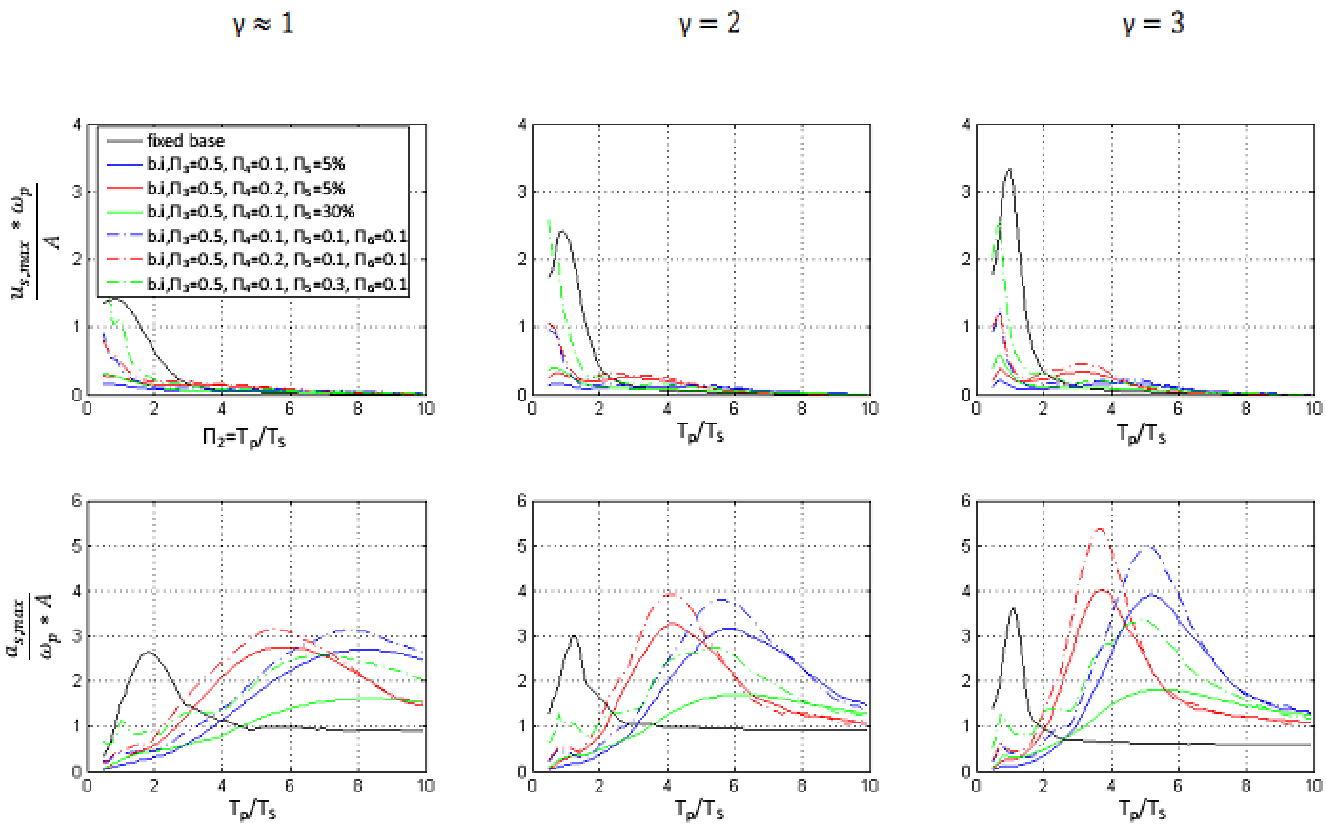

Fig. 12 Comparison of the response of (i) the fixed base structure; (ii) the base isolated structure with viscous damping and (iii) the base isolated structure with nonlinear damping

system, for the same superstructure and idealized pulse, base isolation can have a beneficial or a detrimental effect on the response of the structure. For instance, for γ=2, and T_p/T_s<2 the isolation system reduces significantly the normalized acceleration a_s, but for T_p/T_s>3 the opposite occurs and, even for highly damped systems with 30% viscous damping, the normalized acceleration of the structure as is amplified compared to the fixed structure. In addition, it is noted the fact that even the normalized displacement of the isolated superstructure u_s for certain values of T_p/T_s and for certain values of the characteristics of the isolation system can be greater than the respective one of the fixed-base building. This is clearly seen, for example for γ=3, where for T_p/T_s>2.5 the 2-DOF with viscous damping Π_5=5% and the one with nonlinear damping with Π'_5=0.1 and Π_6=0.1 that give greater normalized displacement u_s than the fixed base SDOF.

7. Conclusions

In this study the dynamic behavior of a 2-DOF base-isolated structure under idealized near-fault pulses is investigated. Both the linear and non-linear behavior of the isolation system is considered and the suitable dimensionless parameters of the isolation system are defined. Using the dimensional analysis in conjunction with closed form mathematical idealized pulses, self-similar curves are plotted on dimensionless graphs and various conclusions are drawn:

Respectively to the case of SDOF (Mavroeidis *et al.* 2004), it is also observed that for the base-isolated 2-DOF structure the parameter v has a minor effect on the peak normalized response of the structure for both the linear and the non-linear system, except for the case where γ approaches unity and then only for small values of the term Π_2<0.7. The effect of v diminishes as the parameter γ increases. In addition, an increase of γ results in larger peak normalized response for both the linear and non-linear isolation systems with small normalized yield strength $\Pi'_5\leq$0.1; however, the effect of γ diminishes as increases.

For the linear isolation system, it is revealed that: (a) the dimensionless parameters that play a significant role on the dynamic behavior of the base-isolated 2-DOF structure under idealized near-fault pulses are the pulse-to- base isolation period ratio Π_2 and the viscous damping Π_5, while (b) the peak normalized relative displacement of the superstructure is also greatly affected by the isolation-to-structure stiffness ratio Π_4 and much less by the mass ratio Π_3. However, the influence of Π_4 and $\Pi_5=\xi_b$ on the superstructure displacement is significant only for $\Pi_2=T_p/T_b$ <3. Regarding the peak normalized isolation displacement and superstructure acceleration; they are both insensitive to the stiffness and mass ratios. Furthermore, it is shown that the viscous damping ξ_b can have either a beneficial or a detrimental effect on the peak normalized displacement u_s and the acceleration a_s of the superstructure, depending on the value of Π_2. In addition, the existence of an optimum value of the viscous damping ξ_b that was first revealed by

Jangid and Kelly (2001) is verified. It is also shown that the optimum ξ_b is highly dependent on both the period ratio Π_2 and the number of half-cycles γ which implies that for a certain value of Π_2 a value of ξ_b may be optimum.

For the nonlinear isolation system, the dimensionless parameters that play a major role on the dynamic behavior of the base-isolated 2-DOF structure under idealized near-fault pulses are: (a) the pulse-to-base isolation period ratio Π_2 and (b) the normalized yield strength Π'_5, while the normalized superstructure relative displacement is also primarily affected by the stiffness ratio Π_4 and much less by the mass ratio Π_3. The normalized yield displacement Π_6 has a very small effect on the response of the 2-DOF for small values of $\Pi_5 \leq 0.1$, and only for greater values of Π_5 the term Π_6 begins to have a noticeable effect on the peak normalized isolation displacement and on the superstructure acceleration. This effect can be either detrimental or beneficial to the normalized isolation displacement and superstructure acceleration, depending on the value of Π_2. Respectively, to the effect of damping on linear isolation systems, on non-linear systems the increase of the normalized strength Π_5 can also either increase or decrease the normalized superstructure displacement and acceleration depending on the value of Π_2, a fact that implies the existence of an optimum normalized strength Π_5 for each value of Π_2. In addition, for the isolated 2-DOF, there exists a range of values of the dimensionless term Π_2 around the value of Π_2=0.5 and a certain range of values of the normalized strength Π_5, where an increase in the normalized strength Π_5 increases the normalized isolation displacement u_b. Knowing the influence of the normalized yield strength and yield displacement Π_5 and Π_6 on a response of the base-isolated building, as a function of the normalized period Π_2 and the number of half-cycles γ, can help one to choose the optimum combination of values of Π_5 and Π_6 for specific values of T_p/T_b and γ, as well as the appropriate yield strength and yield displacement of the isolation system that will most effectively minimize the response characteristics of the 2-DOF under a certain velocity pulse.

Finally, a comparison of the responses between a linear fixed-base SDOF and an isolated 2-DOF with both linear and non-linear damping has shown that, under certain values of the superstructure and isolation system characteristics, the use of an isolation system can amplify both the normalized acceleration as and the displacement of the superstructure u_s. This fact points out the need for careful design of base-isolated buildings that can be potentially subjected to strong velocity pulses.

In this study a simple 2-DOF model has been used for the base-isolated building. The simpler case of a non isolated 2-dof system as well as more complex and detailed models accounting for torsional response, for example models with more stories that could also account for more physical phenomena should be developed and studied to thoroughly investigate the response of real structural systems. Definitely, more research is required in this field.

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CC

Nomenclature

The following symbols and abbreviations are used in this paper:

Greek Letters

γ Number characterizing the shape of the pulse

λ Dimensionless parameter defined in eq. 19

ξ_b Damping parameter defined in eq. 6

ξ_s Damping parameter defined in eq. 5

π Archimedes' constant

ω_b Circular frequency defiend in eq. 9

ω_s	Circular frequency defiend in eq. 4

Latin Letters

A	Velocity pulse amplitude
a	Function of time defined in eq. 11
a_g	Ground acceleration
c_s	Damping parameter defined in eq. 5
DOF	Degree of freedom
d_g	Ground displacement
K_b	Lateral stiffness of isolators
K_s	Lateral stiffness of superstructure
m	Mass of superstructure
m_b	Mass of foundation
SDOF	Single degree of freedom
T_b	Period defined in eq.8
T_s	Period defined in eq.3
$\mathrm{u_b}$	relative displacement of the isolation system
$\mathrm{u_s}$	relative displacement of the superstructure
$\mathrm{v_g}$	Ground velocity
$\mathrm{v_p}$	Velocity amplitude