Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2021) 4824-4833

ECCOMAS Proceedia

COMPDYN 2021
8th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Streamed from Athens, Greece, 28 - 30 June 2021

SEISMIC PERFORMANCE OF DOUBLE FRICTION PENDULUM BEARINGS UNDER HORIZONTAL AND VERTICAL EXCITATION

Ioannis E. Kavvadias[1]

[1] Department of Civil Engineering, Democritus University of Thrace
Campus of Kimmeria, Xanthi 67100, Greece
e-mail: ikavvadi@civil.duth.gr

Abstract

In this study the effect of ground motion characteristics on the response of an isolated base using double friction pendulum bearings (DFPBs) is presented. Planar nonlinear time history analyses are performed considering one horizontal and the corresponding vertical component of natural ground motion records. Both far-fault and near-fault ground motion records are considered. In order to focus on the effect of the ground motion intensity measures on the DFPBs response, without taking into account the effect of any other structural characteristics, an analysis model comprised of two DFPBs coupled with a rigid beam is assumed. For this reason, a finite element modeling that can capture the kinematic behavior of the isolation bearing parts is adopted. In order to investigate the effect of the vertical seismic component on the response of the isolated base results in terms of peak developed displacements are presented. Moreover, the performance of ground motion intensity measures for use in probabilistic seismic demand models for isolated base under horizontal and vertical seismic component is assessed.

Keywords: Seismic Isolation, Double Friction Pendulum Bearings, Vertical Ground Motion, Optimal Intensity Measures.

ISSN:2623-3347 © 2021 The Authors. Published by Eccomas Proceedia.
Peer-review under responsibility of the organizing committee of COMPDYN 2021.
doi: 10.7712/120121.8830.18986

1 INTRODUCTION

Base isolation consist a seismic protection technique which may applied in both new and existing structures [1]. Two main categories of base isolation devices are in use, the rubber bearings and the friction pendulum ones. The single friction pendulum (SFP) bearings have been studied since 1990 [2-4]. Subsequently, bearings composed by multiple concave spherical surfaces, such as double friction pendulums (DFPs), have been also examined [5].

Isolation devices are principally described by low lateral stiffness. Due to this fact, the superstructure is decoupled from the ground by implementing isolators at a certain level. Thus, the seismic demands of the superstructure are significantly reduced, while large displacements are introduced at the isolators [1]. However, under near-fault ground motions, which are characterized by large amplitude, low frequency, and pulse type of excitation, the performance of the base isolation tends to be reduced [6].

Another feature of near-fault ground motions is the intense vertical component [7, 8]. The detrimental effect of the strong vertical excitation is examined in reinforced concrete buildings, bridges and isolated structures [9-16]. The performance of friction pendulum bearings is strongly affected by the axial load variation during the sliding phase [17, 18]. As such, the effect of vertical ground motions on the response of seismically isolated structures should be studied using more sophisticated models. Given that, in order to assess the seismic response under a probabilistic framework, and set the probabilistic seismic demand model (PSDM), the uncertainties introduced by the ground motions should be examined [19-21]. By this, the efficiency of several intensity measures (IMs) in predicting the seismic response of base isolated structures, under horizontal and vertical ground motions, is investigated.

In the present study the effect of seismic excitation characteristics on the response of an isolated base, formed using DFP bearings, is assessed. Specifically, 21 IMs are examined in order to conclude to the most optimal one upon which the PSDM should be conditioned. Near-fault, as well as far-fault natural ground motion records are considered. Moreover, both horizontal and vertical seismic excitation are assumed, in order to highlight the contribution of the vertical component on the seismic response, examining also the variation of the performance of the IMs in estimating the response of the isolated base.

2 OPTIMAL INTENSITY MEASURES

In recent years, probabilistic analysis has become widely used for structural engineering purposes and PSDMs have been developed aiming to predict the response of a structure under earthquakes of certain intensities. The most common tool for this assessment is to develop fragility curves of structures. Specifically, fragility expresses the probability (P) that the capacity (C) of a specifically measured engineering demand parameter (EDP) of a structure will exceed a certain level of demand (D), for a specific ground motion IM, as defined by the following equation [22]:

$$P\left(D > C \middle| IM\right) = \Phi\left(\frac{\ln(S_d / S_c)}{\sqrt{\beta_{D|IM}{}^2}}\right) \tag{1}$$

where Φ is the standard normal cumulative distribution function, S_c is the median value of the capacity which is estimated through the adopted limit states and $\beta_{D|IM}$ is the dispersion or logarithmic standard deviation for the demand conditioned the IM.

The median seismic demand S_d is related to an examined IM with the following expression:

$$S_d = a\left(IM\right)^b \tag{2}$$

where a and b are the linear regression coefficients for the logarithmic expression of the assumed scale law.

The linear regression analysis is performed between the engineering demand parameter calculated via the time history analyses and the corresponding IM values. The dispersion of the median demand is reported by the logarithmic standard deviation of the linear regression analysis (Eq. (3)). This parameter constitutes the demand uncertainty introduced in the probabilistic model.

$$\beta_{D|IM} \cong \sqrt{\frac{\sum (\ln(d_i) - \ln(a(IM)^b))^2}{N-2}} \tag{3}$$

where N is the total number of the data.

The appropriate selection of an IM plays an important role in the accuracy of a probabilistic seismic demand analysis (PSDA) for structures. As such, the choice must be made based on criteria, presented in the literature, which help to distinguish the accuracy of the seismic assessment. An optimal IM is defined by primary factors such as efficiency, practicality, proficiency and sufficiency [22-25].

Efficient IMs are the ones that eliminate the dispersion of the results about the median, which means a decrease in the uncertainties introduced to the PSDM, resulting in superior fragility curves during the vulnerability assessment. A distinguished IM according to its efficiency is represented by a lower logarithmic standard deviation $\beta_{D|IM}$ (Eq. (3)). Moreover, the coefficient of determination of the linear regression analysis (Rr^2) could represent a parameter that denotes the performance of an IM regarding its appropriateness in predicting the structural damage [26]. Practicality refers to whether or not there is any direct correlation between an IM and the demand placed on the structure and is measured by the regression parameter b in the PSDM Proficiency is a composite measure that assesses the effect of both efficiency and practicality as follows [25]:

$$\zeta = \frac{\beta_{D|IM}}{b} \tag{4}$$

3 EXAMINED GROUND MOTION RECORDS AND IMS

In order to examine the effect of the ground motion characteristics on the response of the isolated base a cloud analysis is performed using the natural ground motions proposed by FEMA P695 [27] are considered. The specific data set is comprised of both far-filed and near-field ground motion records. The hole set consists 50 pairs of ground motions. However, due to the fact that vertical excitations records are not provided for 4 seismic events (i.e. RSN725, RSN496, RSN723, RSN1048), 46 pairs of ground motions are used. From those, 21 pairs are far-filed records, while 25 are near-fault ones.

In order to designate the earthquake intensity measures (IMs) that affect the seismic response, a large number of seismic parameters is considered in the present study. Specifically, 20 IMs, of the horizontal seismic excitation, are taken into account which can be classified into amplitude, energy, spectral, and frequency parameters [28]. Amplitude parameters include peak ground acceleration (PGA), peak ground velocity (PGV), and peak ground displacement (PGD). The root mean square of acceleration (A_{RMS}), of velocity (V_{RMS}), and of displacement (D_{RMS}), the characteristic intensity [29] (I_C), the Arias intensity [30] (I_A), the cumulative absolute velocity (CAV), the specific energy density (SED), the strong motion duration [31] (t_D), the index proposed by Fajfar-Vidic-Fischinger [32] (I_{FVF}) and the characteristic length scale [33, 34] (L_m), fall into the class of energy ground motion parameters. Regarding the spectrum intensity measures, the acceleration spectrum intensity [35] (ASI), the velocity spectrum intensity [35] (VSI), the Housner spectral intensity [36] (SI_H), and the spectral acceleration ($Sa(T_t)$) that correspond to the fundamental vibration period of the superstructure (T_t) are considered. The mean period [37] (T_m), the ratio PGV/PGA, and the period (T_{pred}) corresponding to the peak acceleration of the elastic response spectrum are assumed as frequency parameters.

4 EXAMINED MODEL

Scope of this study is to examine the effect of the ground motion IMs on the response of a seismic isolated base using DFPBs, under horizontal and vertical excitation. As such, the DFPBs are simulated with a full three dimensional continuum modelling using the finite elements method. The analytical presentation of the adopted modelling approach, as well as it validation has been presented by Kavvadias et al. [38]. The detailed model of the bearing's geometry allows a complete description of it kinematic behavior, accounting the restoring forces, the variation of axial forces among the contact surfaces as a consequence of vertical acceleration or overturning moments, and uplift [39]. In order not to count the effect of any structural feature on the dynamic response, a simplified analysis model is examined. The analysis model consists of two identical isolation bearings connected with a rigid and massless beam. The gravity loads W are considered at the top of the isolators, while the ground motion excitation is applied at the base in terms of seismic acceleration. The schematic of the model, as well as the DFPB properties are presented in Figure 1.

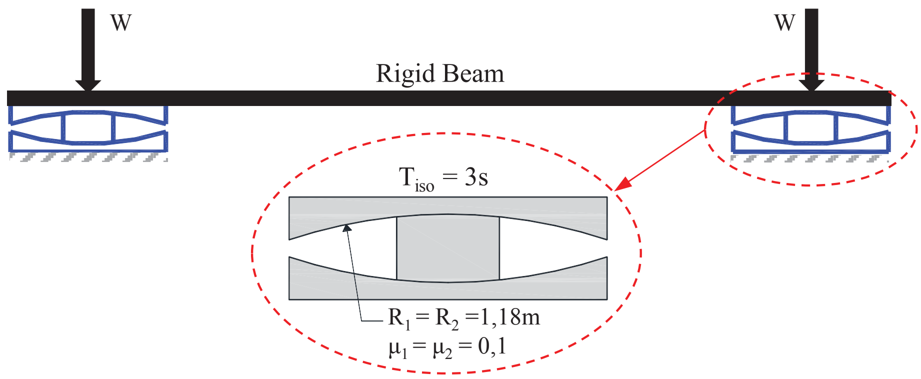

Figure 1: Schematic of the examined numerical model.

5 RESULTS

Planar nonlinear time history analyses are performed using each horizontal component individually. Additionally, in order to examine the effect of the vertical ground motion, time history analyses are conducted assuming also the vertical excitation along with each horizontal one. The data are classified also according to the seismic record type to far-fault and near-fault. In order to evaluate the seismic response of the isolated structural system, the maximum bearing displacement (MBD) is considered as EDP.

In Figure 2 two representative force-displacements loops of the DFPBs are presented. It is obvious that vertical excitation causes an intense variation of the shear forces which can be justified by the variation of the axial forces due to the vertical acceleration. However, in both loops can be observed that the maximum developed displacements do not present a noticeable variation.

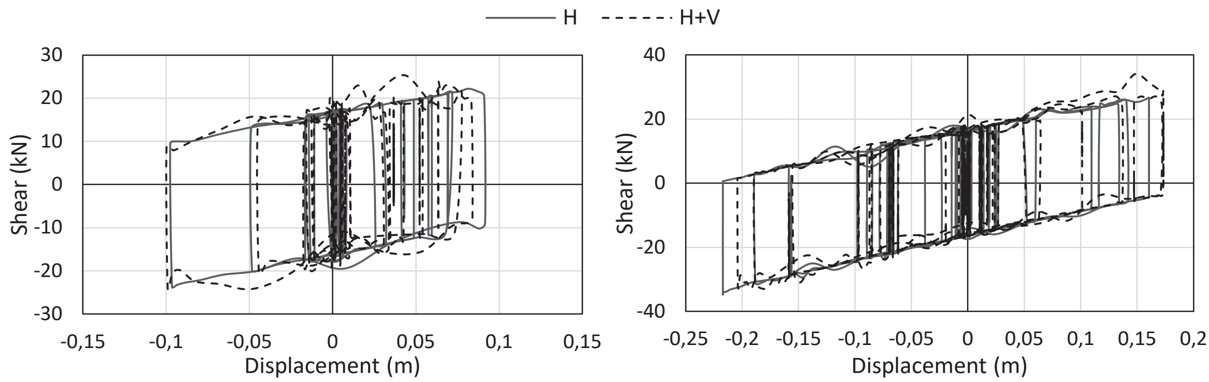

Figure 2: Force-Displacement hysteretic loops of the DFPBs.

In Figure 3 the MBDs for each analysis type is presented. Figure 3(a) depicted the results under far-field seismic records, while in Figure 3(b) the results under the near-fault records are illustrated. It can be observed that the maximum seismic demands are higher under near-fault records. However, regardless the ground motion record type, the maximum response seems not to be affected by the vertical excitation, as the maximum displacements considering only the horizontal component (MBD^{H}) are fairly equal to the displacements assuming also the vertical component of the ground motion (MBD^{H+V}). Although the detailed FEA modelling of the DFPBs, the effect of the vertical ground motion component on the MBD is negligible.

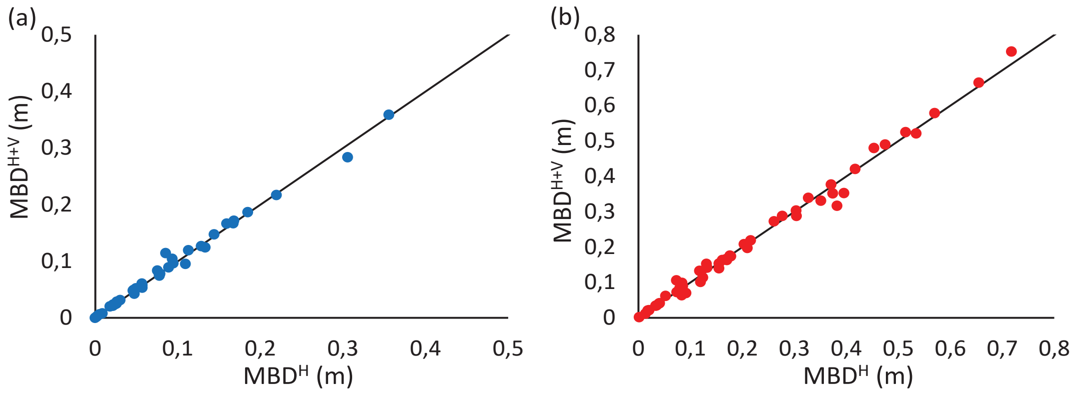

Figure 3: Comparison of the MBDs considering horizontal and horizontal along with vertical seismic excitation under (a) far-fault and (b) near-fault ground motion records.

As indicated above, the identification of an optimal IM in estimating the seismic demands, is based on criteria such as efficiency, practicality and proficiency. In Figure 4 the values of the coefficient of determination (R_r^2), the standard deviation ($\beta_{D|IM}$), the slope of the linear regression (b) and the proficiency value (ζ) are presented. The IMs criteria values are presented comparatively regarding the ground motion record type and the consideration of the vertical ground motion on the analysis.

It is obvious that the presence of the vertical component do not affect the performance of the horizontal seismic excitation IMs. Therefore, there is no need to examine the effect of the characteristics of the vertical acceleration signal on the seismic demands, as it should be negligible.

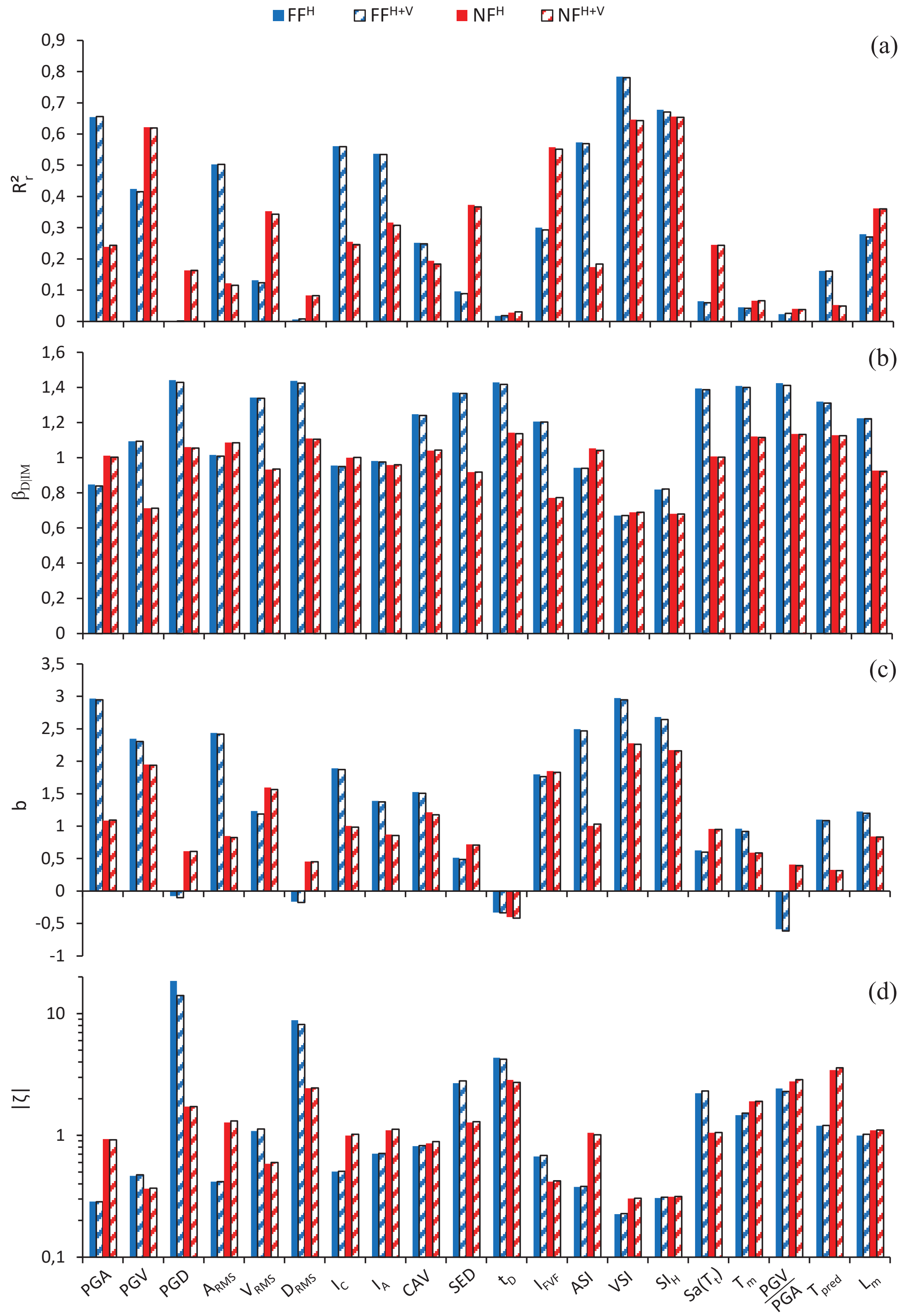

Figure 4: Values of (a) coefficient of determination R_r^2, (b) standard deviation $\beta_{D|IM}$, (c) slope of the linear regression b and (d) proficiency value ζ.

In general the most optimal IMs are the parameters VSI and SI_H. These two velocity based spectral parameters present at the same time the higher values of R_r^2 and b, and the lower values of $\beta_{D|IM}$ and ζ. As such these parameters rank as the most optimal ones regardless the assessment criteria. The performance level of the two aforementioned most optimal IMs are almost identical regardless the ground motion record type. Under far-fault excitations, acceleration based parameters such as PGA and ASI demonstrate high enough performance in predicting the seismic response with low uncertainties. Moreover, they present high level of practicality. That can be justified due to the fact that the acceleration level defines the initiation of sliding, given that a vast majority of the far-fault ground motions barely initiates the isolator's sliding. On the other hand, under near-fault excitations these parameters present poor performance. Furthermore, velocity based parameters such as PGV and I_{FVF} performs quite well in case of near-fault records. Finally, ground motion parameters such as PGD, t_D and frequency based ones are found to be the less optimal IMs to generate PSDMs for seismic isolated structures.

6 CONCLUSIONS

In the present study the effect of the ground motion intensity measures on the seismic response of a base isolated with double friction pendulum bearings is investigated. Moreover, the effect of the vertical ground motions is examined. Thus a finite element analysis modelling is adopted that can capture in high accuracy the kinematic response of the bearings. The main concluding remarks can be summarized as follows:

1. Vertical ground motion component may affect the shear forces of the bearings due to the variation of the axial forces, however does not significantly affect the developed maximum displacements.
2. Near-fault seismic records result to higher seismic demands.
3. The characteristics of the vertical excitations does not affect, in a systematic way, the developed maximum displacements of the isolation bearing. Therefore, the performance of the horizontal seismic component IMs presents identical performance regardless the consideration of the vertical seismic component.
4. The velocity spectrum intensity (VSI) and the Housner's spectral intensity (SI_H) are identified as the most optimal IMs for use in probabilistic seismic demand models for the examined structural system under both far-fault and near-fault ground motion records.
5. Under far-fault records, peak ground acceleration (PGA) and tacceleration spectrum intensity (ASI) follows, while under near-fault records peak ground velocity (PGV) and the intensity proposed by Fajfar-Vidic-Fischinger (I_{FVF}) present also a high performance.

REFERENCES

[1] F. Naeim, J.M. Kelly, Design of seismic isolated structures. Wiley, New York, USA, 1999.

[2] V. Zayas, S.S. Low, S.A. Mahin. A simple pendulum technique for achieving seismic isolation. *Earthquake Spectra*, **6**, 317–333, 1990

[3] M. Constantinou, A. Mokha, A. Reinhorn, Teflon bearings in base isolation I: testing. *Journal of Structural Engineering*, **116**, 438-454, 1990

[4] M. Constantinou, A. Mokha, A. Reinhorn, Teflon bearings in base isolation II: modeling. *Journal of Structural Engineering*, **116**, 455-474, 1990

[5] D.M. Fenz, M.C. Constantinou, Behavior of the double concave Friction Pendulum bearing. *Earthquake Engineering and Structural Dynamics*, **35**, 1403–1424, 2006.

[6] R.S. Jangid, J.M. Kelly, Base isolation for near-fault motions. *Earthquake Engineering and Structural Dynamics*, **30**, 691–707, 2001.

[7] Y. Bozorgnia, M. Niazi, Distance scaling of vertical and horizontal response spectra of the Loma Prieta earthquake. *Earthquake Engineering and Structural Dynamics*, **22**, 695–707, 1993.

[8] Y. Bozorgnia, M. Niazi, K.W. Campbell, Characteristics of free-field vertical ground motion during the Northridge earthquake. *Earthquake Spectra*, **11(4)**, 515–525, 1995.

[9] A.J. Papazoglou, A.S.Elnashai, Analytical and field evidence of the damaging effect of vertical earthquake ground motion. *Earthquake Engineering and Structural Dynamics*, **25**, 1109–1137, 1996.

[10] Y. Bozorgnia, S.A. Mahin, A.G. Brady, Vertical response of twelve structures recorded during the Northridge earthquake. *Earthquake Spectra*, **14(3)**, 411–432, 1998.

[11] L. Di Sarno, A.S. Elnashai, G. Manfredi, Assessment of RC Columns Subjected to Horizontal and Vertical Ground Motions Recorded During the 2009 L'Aquila (Italy). *Engineering Structures*, **33**, 1514–1535, 2011.

[12] C.C. Harrington, A.B. Liel, Collapse assessment of moment frame buildings, considering vertical ground shaking. *Earthquake Engineering and Structural Dynamics*, **45(15)**, 2475–2493, 2016.

[13] S.K. Kunnath, E. Erduran, Y.H. Chai, M. Yashinsky, Effect of near-fault vertical ground motions on seismic response of highway overcrossings. *Journal of Bridge Engineering*, **13**, 282–290, 2008.

[14] F.Mazza, A.Vulcano, Effects of Near-Fault Ground Motions on the Nonlinear Dynamic Response of Base-Isolated RC Framed Buildings. *Earthquake Engineering and Structural Dynamics*, **41**, 211–232, 2012.

[15] L. Landi, G. Grazi, P.P. Diotallevi, Comparison of Different Models for Friction Pendulum Isolators in Structures Subjected to Horizontal and Vertical Ground Motions. *Soil Dynamics and Earthquake Engineering*, **81**, 75–83, 2016.

[16] F.Mazza, M. Mazza, Nonlinear Seismic Analysis of Irregular RC Framed Buildings Base-Isolated with Friction Pendulum System under Near-Fault Excitations. *Soil Dynamics and Earthquake Engineering*, **90**, 299–312, 2016.

[17] G.M. Calvi, P. Ceresa, C. Casarotti, D. Bolognini, F. Auricchio, Effects of axial force variation in the seismic response of bridges isolated with friction pendulum systems. *Journal of Earthquake Engineering*, **8(1)**, 187–224, 2004.

[18] P.C. Roussis, M.C. Constantinou, Uplift-restraining friction pendulum seismic isolation system. *Earthquake Engineering and Structural Dynamics*, **35**, 577–593, 2006.

[19] F. Mazza, R. Labernarda, Structural and non-structural intensity measures for the assessment of base-isolated structures subjected to pulse-like near-fault earthquakes. *Soil Dynamics and Earthquake Engineering*, **96**, 115-127, 2017.

[20] F. Mollaioli, A. Lucchini, Y. Cheng, G.Monti, Intensity measures for the seismic response prediction of base-isolated buildings. *Bulletin of Earthquake Engineering*, **11**, 1841–1866, 2013.

[21] H. Ebrahimian, F. Jalayer, A. Lucchini, F. Mollaioli, G. Manfredi, Preliminary ranking of alternative scalar and vector intensity measures of ground shaking. *Bulletin of Earthquake Engineering*, **13**, 2805–2840, 2015.

[22] P. Giovenale, A.C. Cornell, L. Esteva, Comparing the adequacy of alternative ground motion intensity measures for the estimation of structural responses. *Earthquake Engineering and Structural Dynamics,* **33**, 951–979, 2004.

[23] N. Luco, C.Cornell, Structure-specific scalar intensity measures for near-source and ordinary earthquake motions. *Earthquake Spectra*, **23**, 357–392, 2007.

[24] K.R. Mackie, B. Stojadinovi¢, *Fragility basis for California highway overpass bridge seismic decision making.* PEER report, Berkeley, CA, University of California, 2005.

[25] J.E. Padgett, B.G. Nielson, R. DesRoches, Selection of optimal intensity measures in probabilistic seismic demand models of highway bridge portfolios. *Earthquake Engineering and Structural Dynamics,* **37**, 711–725, 2008.

[26] A. Elenas, Correlation between seismic acceleration parameters and overall structural damage indices of buildings. *Soil Dynamics and Earthquake Engineering*, 2000, **20(1)**, 93–100, 2000.

[27] FEMA P695, *Quantification of building seismic performance factors*. Federal Emergency Management Agency, Washington, DC, 2009.

[28] S.L. Kramer, *Geotechnical earthquake engineering*. Prentice-Hall, Upper Saddle River, NJ, 1996.

[29] A.H.S. Ang, Reliability bases for seismic safety assessment and design. Fourth U.S. National *Conference on Earthquake Engineering*, Earthquake Engineering Research Institute, Palm Springs, California, USA, 1990.

[30] A. Arias, *A measure of earthquake intensity.* MIT Press, Cambridge, Massachusetts, 1970.

[31] M.D. Trifunac, A.G. Brady, A study on the duration of strong earthquake ground motion. *Bulletin of the Seismological Society of America*, **65**, 581–626, 1975.

[32] P. Fajfar, T. Vidic, M. Fischinger, A measure of earthquake motion capacity to damage medium-period structures. *Soil Dynamics and Earthquake Engineering*, **9**, 236–242, 1990.

[33] N. Makris, C.J. Black, Dimensional analysis of rigid-plastic and elastoplastic structures under pulse-type excitations. *Journal of Engineering Mechanics,* **130(9)**, 1006–1018, 2004.

[34] E.G. Dimitrakopoulos, A.J. Kappos, N. Makris, Dimensional analysis of yielding and pounding structures for records without distinct pulses. *Soil Dynamics and Earthquake Engineering,* **29(7)**, 1170–1180, 2009.

[35] J. Von Thun, L. Roehm, G. Scott, J. Wilson, Earthquake ground motions for design and analysis of dams. *Earthquake Engineering and Soil Dynamics II–Recent Advances in Ground-Motion Evaluation, Geotechnical Special Publication*, **20**, 463–481, 1988.

[36] G.W. Housner, Spectrum intensities of strong-motion earthquakes. *Symposium on Earthquakes and Blast Effects on Structures*, Los Angeles, California, USA, 1952.

[37] E.M. Rathje, N.A. Abrahamson, J.D. Bray, Simplified frequency content estimates of earthquake ground motions. *Journal of Geotechnical and Geoenvironmental Engineering,* **124(2),** 150–159, 1998.

[38] I.E. Kavvadias, H.F. Bibo, and L.K. Vasiliadis, Finite element modeling of single and multi-spherical Friction Pendulum Bearings. *6th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN 2017)*, Crete, Greece, June, 2017.

[39] P.C. Tsopelas, P.C. Roussis, M.C. Constantinou, Nonlinear dynamic analysis of multi-base seismically isolated structures with uplift potential I: formulation. *Earthquake Engineering and Engineering Vibration*, **8**, 421-431, 2009.