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SEISMIC ANALYSIS OF FREE STANDING MUSEUM CONTENTS

Ioannis E. Kavvadias[1], Lazaros Vasiliadis[2], Anaxagoras Elenas[3], Konstantinos Koutsoupakis[4]

ABSTRACT

The seismic protection of cultural heritage artifacts has become a challenging objective the last decades. Artistic assets, which are placed on museums, are subjected to the floors' acceleration signal. The actual seismic action is affected by the seismic response of the host building. The contents are usually standing unanchored on the base, and as such, they demonstrate rocking behavior under ground motion excitation. In the present study the seismic response of rigid rocking blocks placed on the floors of a two storey reinforced concrete building is investigated. Base isolation is currently applied in contemporary museum buildings in order to reduce the ground motions' intensity. However, especially on existing museum buildings, base isolation can be implemented on the base of a specific cultural heritage object of great importance. These two different alternatives of base isolation implementation, mentioned above, are considered regarding the seismic mitigation technique of the free standing contents.

Keywords: Rocking Contents; Rocking Response; Seismic Isolation; RC Structures; Fragility Analysis

1. INTRODUCTION

The seismic response evaluation of building contents which present rocking behavior, has become a challenging task for the structural engineers. At museums, laboratories or nuclear power stations, the damage of their contents are of great importance. The contents are usually standing free unanchored at the floors. As such, their seismic performance is affected by the response of the host building and especially by the acceleration signal of the specific floor. The performance of both free standing contents and nonstructural components placed on building structures, subjected to ground motion acceleration has been examined the last years (Filiatrault and Sullivan 2014, DiSarno et al. 2015, Dar et al. 2016, Spyrakos et al. 2016, Petrone et al. 2017, Fragiadakis et al. 2017). In the present study a seismic fragility analysis of a free standing rocking rigid block, without considering sliding, with dimensions corresponding to a museum asset hosted in a RC frame building is performed.

The seismic protection of rocking rigid blocks using base isolation devices has been thoroughly examined (Vestroni and Di Cinto 2000, Calio and Marletta 2003, Roussis et al. 2008, Vassiliou and Makris 2012, Chrysostomou et al. 2015, Kavvadias et al. 2017). Moreover, for acceleration sensitive building contents, the application of floor isolation systems has been studied (Gidaris et al. 2016, Sorace and Terenzi 2014). In this scope, two alternatives of base isolation implementations are examined. In the first one the host building is considered isolated, while in the second one the rocking content.

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[1] PhD, Civil Engineer, Department of Civil Engineering, Democritus University of Thrace, Campus of Kimmeria, 67100 Xanthi, Greece, ikavvadi@civil.duth.gr

[2] Associate Professor, Department of Civil Engineering, Democritus University of Thrace, Campus of Kimmeria, 67100 Xanthi, Greece, lvasilia@civil.duth.gr

[3] Professor, Department of Civil Engineering, Democritus University of Thrace, Campus of Kimmeria, 67100 Xanthi, Greece, elenas@civil.duth.gr

[4] Civil Engineer, Department of Civil Engineering, Democritus University of Thrace, Campus of Kimmeria, 67100 Xanthi, Greece, konskout10@civil.duth.gr

2. NUMERICAL ANALYSIS

2.1 RC frame building

For the scope of that study a two storey building was considered. That choice is justified due to the fact that, museum buildings are in common low rise and stiffer than the conventional ones. The building was designed based on the EC2 and EC8. The building dimensions, as well as, the structural elements cross sections are depicted in Figure 1. The selected concrete quality is C25/30, while the reinforcing steel quality is B500C. Concentrated plasticity elements were used in order to simulate the structures nonlinear response. The dynamic analyses were performed without considering the simultaneous rocking response of the examined block as it mass is lesser than the 5% of the floors mass. Due to that fact, the seismic response of the rocking block does not affects the seismic response of the hosting structure. The nonlinear dynamic analyses are performed in the software SAP2000.

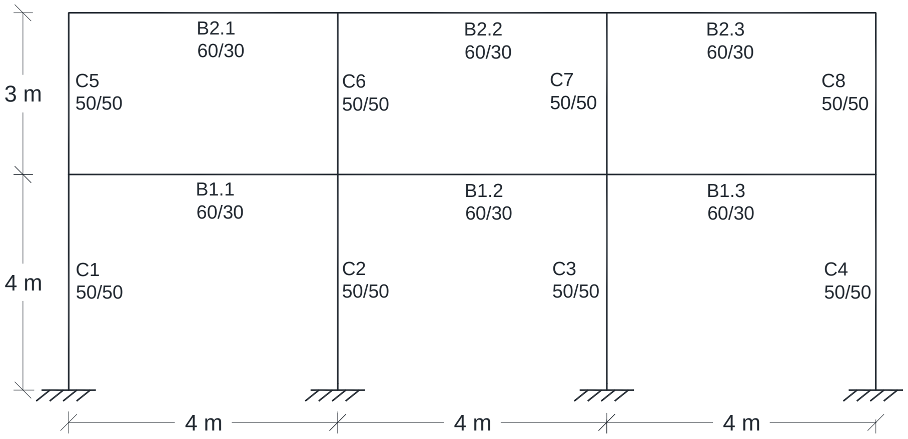

Figure 1. Frame Structure

2.2 Seismic Response of free standing rigid blocks

The unachord content of a building can be modeled as a rigid block (Figure 2). A rigid block standing free on a rigid base, with slenderness α, semi-diagonal R and frequency parameter p, oscillates about the centers of rotation O and O' when base acceleration exceeds $\ddot{u}/g \geq \tan(\alpha)$. The problem of a rigid rocking block motion under a seismic excitation, without considering sliding, can be described by the following equation (Yim et al. 1980):

$$\ddot{\theta} = -p^2 \cdot \left\{ \sin[\alpha \cdot sgn(\theta) - \theta] + \frac{\ddot{u}_g}{g} \cdot \cos[\alpha \cdot sgn(\theta) - \theta] \right\} \tag{1}$$

where sgn() is the sign function and $p = \sqrt{3g/4R}$ is the frequency parameter of the rigid block.

During the rocking motion, energy is lost only during impact (when the rotation changes sign at $\theta = 0$) which causes a reduction of the rotational velocity after it:

$$\dot{\theta}_{n+1}{}^2 = r \cdot \dot{\theta}_n{}^2 \tag{2}$$

where r is the restitution coefficient, $\dot{\theta}_n$ is the velocity before the impact and $\dot{\theta}_{n+1}$ is the velocity after the impact.

Considering that the angular momentum remains constant about point O exactly before the impact and right after it, the coefficient of restitution for a rigid rectangular block is given by the following equation (Housner 1963):

$$r = [1 - \frac{3}{2}(\sin\alpha)^2]^2 \tag{3}$$

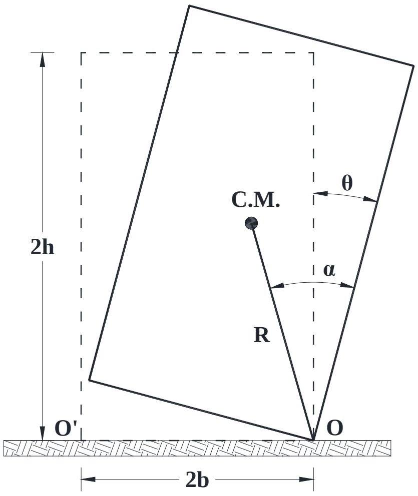

Figure 2. Rocking Block

The considering block has height 2h = 2.0 m and width 2b = 0.5 m, dimension that correspond to a semi - diagonal R = 1.03 m and slenderness α = 0.245 rad. The rocking block is examined as it is placed on the first floor of the examined structure. Thus, it is subjected to the floors acceleration signal. The floors acceleration signals are derived from the results of the nonlinear time history dynamic analyses of the RC structure.

2.3 Isolation Implementation

Friction pendulum systems (FPS) (Zayas et al. 1990) are studied as isolation devices. In Figure 3 the two isolated methods are pictured. In the first one, where the whole building is isolated, FPS devices with radius R_{eff} = 2.24 m and friction coefficient μ = 0.1 were considered. Regarding the rocking block isolation, FPS devices with radius R_{eff} = 2.24 m and friction coefficient μ = 0.03 are used. In both cases the isolation period is T_{is} = 2 s. When base isolation is implemented on the rocking block, the acceleration signal that subjects the rocking block is measured on the isolated base instead of the floor. In that case the floors acceleration is equal to the fixed based structure.

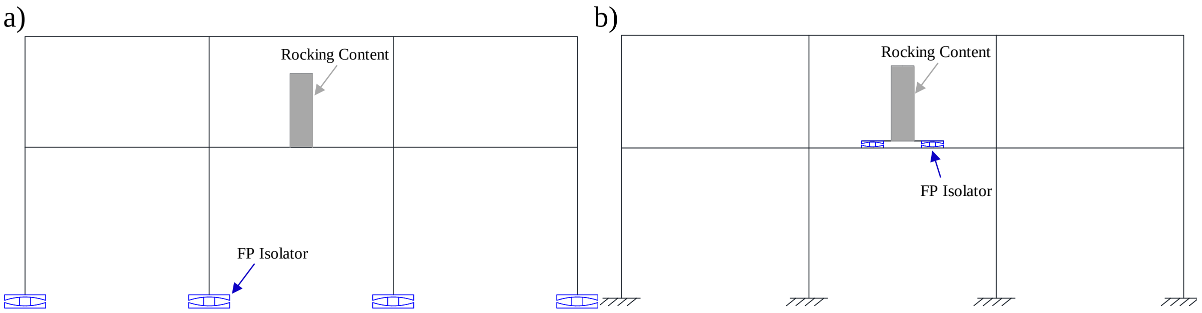

Figure 3. Base isolation arrangements

2.4 Ground Motion Records

A set of 35 natural ground motion record has been used for the dynamic analyses. The initiation of rocking on the fixed base structure due to all the seismic excitations are the main criteria of the specific records selection. Both near-fault and far-fault records are employed, in order to present a wide range of intensities and frequency contents A rigorous search on the PEER and the European strong motion database are carried out concluding to the used records. In Table 1 they are listed shorted by increasing values of PGV.

Table1. Ground Motion Records List

No	Earthquake	Station	Date	M_s	R (km)	PGV (cm/s)
1	Iwake	Ichinoseki Maikawa	14/7/2008	6.9	23.02	7.86
2	Duzce	Lamont 531	12/11/1999	7.1	8.03	11.96
3	Whittier	LA - Obregon Park	1/10/1987	5.3	13.62	14.31
4	San Fernando	Paicoma Dam	9/2/1970	6.6	1.81	15.64
5	Corinth	Corinth	24/2/1981	6.6	10.28	24.83
6	Tabas	Dayhook	16/9/1978	7.4	13.94	25.58
7	Kalamata	Kalamata	13/9/1986	6.2	10.00	29.40
8	Imperial Valley	El Centro Array #9	19/5/1940	7.0	6.09	29.69
9	Friuli	Tolmezo	6/5/1976	6.5	15.82	31.29
10	Taiwan SMART1(40)	Smart1 M02	15/111986	6.3	60.89	31.33
11	Chi-Chi	CHY035	20/9/1999	7.6	12.56	31.95
12	Athens	ATH4	7/9/1999	5.9	16.62	32.27
13	Superstition Hill	Mtn Camera	24/11/1987	6.5	5.61	32.50
14	Chuetsuoki	Nakanoshima Nagaoka	16/7/2007	6.8	19.89	32.82
15	Kobe	Nishi -Akashi	16/1/1995	6.9	7.08	36.56
16	Chi-Chi	TCU88	20/9/1999	7.6	18.16	36.59
17	Aigion	AIGA	25/6/1995	6.4	21.50	39.86
18	Landers	Joshua Tree	28/6/1992	7.3	11.03	43.05
19	Northridge	Paicoma Dam	17/1/1994	6.7	7.01	45.41
20	Imperial Valley	El Centro Array #8	15/2/1979	6.5	3.86	49.56
21	Imperial Valley	El Centro Array #7	15/2/1979	6.5	0.56	53.94
22	Northridge	Newhall – Fire Station	17/1/1994	6.7	5.43	59.23
23	Coalinga	Fault Zone 14	2/5/1983	6.4	29.48	63.29
24	Denali	TAPS Pump Station #10	3/11/2002	7.9	2.74	69.26
25	Bucharest	Bucharest	4/3/1977	7.5	115.0	73.46
26	Parkfield	Cholame #2	28/6/1966	6.2	17.64	73.70
27	Irpinia	Sturno	23/11/1980	6.9	10.84	75.07
28	Darfield	Papanui High School	4/9/2010	7.0	26.76	78.16
29	El Mayor Cucapah	Chihuahua	4/4/2010	7.2	19.47	79.99
30	Gazli	Karakyr	17/5/1976	6.8	5.46	80.37
31	Erzincan	Erzincan	19/3/1992	6.7	4.38	83.96
32	Loma Prietta	Los Gatos - Lexington Dam	17/11/1986	7.0	5.02	86.32
33	Kobe	Port Island	16/1/1995	6.9	3.31	89.42
34	Northridge	Jensen Filter Plant	17/1/1994	6.7	5.92	97.27
35	Chi-Chi	CHY101	20/9/1999	7.6	9.94	106.91

3. FRAGILITY ANALYSIS

In the present study the effect of the seismic protection alternatives are evaluated by generating fragility curves of the rocking block. To estimate the probability of overturning the problem should be considered as a categorical one, by grouping the data into non-collapse and collapse ones. So to estimate the parameters of the fragility function (mean μ and standard deviation β) that provides the probability of collapse, the maximum likelihood approach is adopted (Shinozuka et al. 2000). The maximum likelihood function L is defined as follows:

$$L = \prod_{j=1}^{m} \binom{n_j}{z_j} p_j^{\,z_j} \left(1 - p_j\right)^{n_j - z_j} \tag{4}$$

where the probability of z_j collapses out of n_j ground motions of a certain value of IM is given by the binomial distribution, p_j is the probability that a ground motion of a particular IM value, will cause the collapse of the structure, m is the number of IM levels and Π denotes a product over all IM levels.
Assuming lognormal cumulative distribution for the overturning probability, Equation 4 converts to the following:

$$L = \prod_{j=1}^{m} \binom{n_j}{z_j} \Phi\left(\frac{\ln x_j - \mu}{\beta}\right)^{z_j} \left(1 - \Phi\left(\frac{\ln x_j - \mu}{\beta}\right)\right)^{n_j - z_j} \tag{5}$$

The maximization of L gives the statistical moments $\hat{\mu}$ and $\hat{\beta}$.

$$\left\{\hat{\mu}, \hat{\beta}\right\} = \max_{\mu,\beta} \prod_{j=1}^{m} \binom{n_j}{z_j} \Phi\left(\frac{\ln x_j - \mu}{\beta}\right)^{z_j} \left(1 - \Phi\left(\frac{\ln x_j - \mu}{\beta}\right)\right)^{n_j - z_j} \tag{6}$$

The introduced engineering demand parameter (EDP) has to get a clear physical meaning. Being aware of this principle, for the examined free-standing structures, the most appropriate EDP that can be used has to be based on the rocking rotation as rocking is the dominant response of this structure. For this purpose, the absolute maximum developed rotation $|\theta_{max}|$ normalized to the critical overturning rotation (Equation 7), is considered.

$$EDP = \frac{\left|\theta_{\max}\right|}{\alpha} \tag{7}$$

For the rocking block contents of a structure the parameters of the floor acceleration signal could be used as EDPs. As intensity measures the PGA and PGV is used for the vulnerability analysis. The latter is a better damage indicator for rocking blocks of large size (Dimitrakopoulos and Paraskeva 2015, Kavvadias et al. 2017)

4. RESULTS

In order to estimate the efficiency of the base isolation alternatives, their affection on the floors seismic acceleration signal is studied. The two main excitation parameters presented above, are the Peake Floor Acceleration (PFA) and the Peak Floor Velocity (PFV). These two parameters are presented normalized to the PGA and the PGV of the initial record respectively.
Regarding the PFA (Figure 4) values, the statue isolation is the most efficient. By performing seismic isolation on the base of the building, the PFA seems to be in general lesser than the corresponding PGA values. Examining the fixed base structure, the PFA values are on average took larger valued than the PGA ones. When the structure behaves elastically, the increase of the PFA values exceeds even 150% of the PGA values, whereas when severe structural damage occurs, the PFA are reduced.

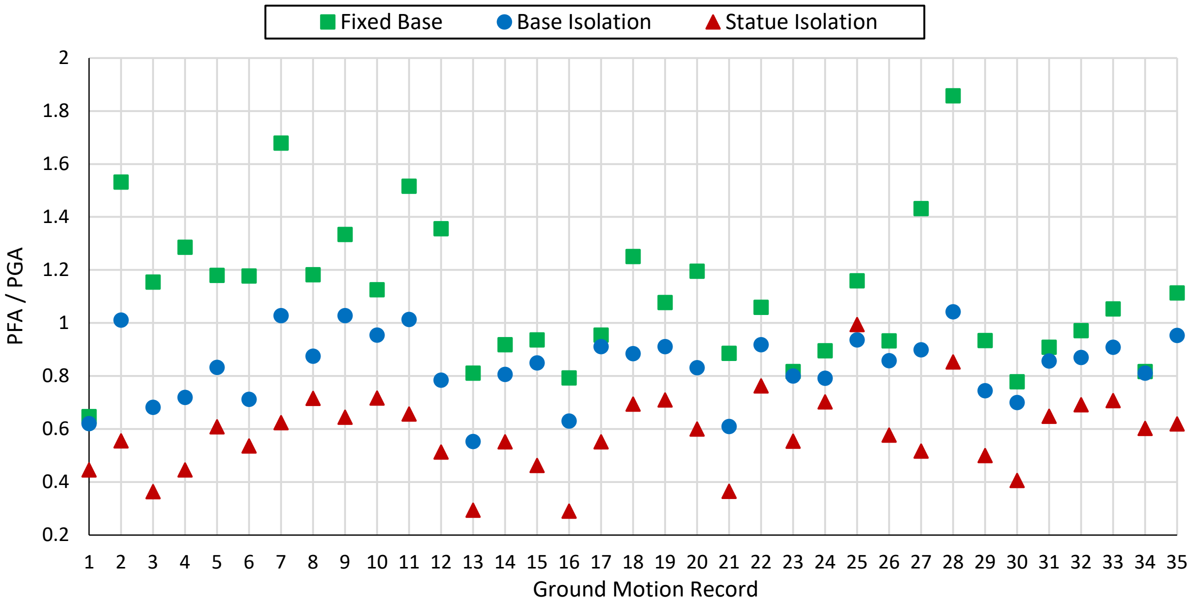

Figure 4. PFA/PGA values for all the ground motion records

Due to the fact that the peak acceleration is not an optimal IM regarding the prediction of rocking response, the PFV values are also presented (Figure 5). In the fixed base structure, the PFV values are increased under all the seismic excitations. Examining the base isolated structure the PFV values are in common slightly increased. Reduction of the floors velocities are presented only when base isolation is performed to the monument base.

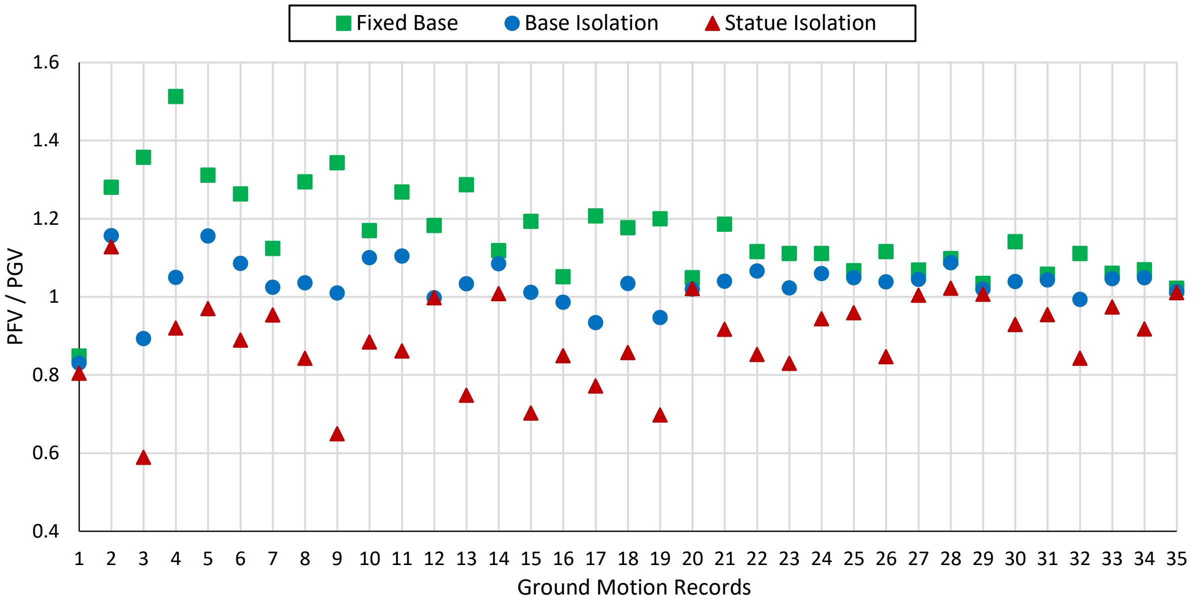

Figure 5. PFV/PGV values for all the ground motion records

In Figure 6 the rocking rotations, normalized over the blocks slenderness, in respect with PGA and PGV are presented. As expected, via base isolation the free standing block developed less rocking rotations. Specifically, when the structure is considered fixed base the block overturns under 9 seismic events, while it overturns under 5excitation when it is hosted on the base isolated structure. The most efficient solution regarding the protection of the rocking block seems to be the statue isolation in which the block overturns only under one excitation.

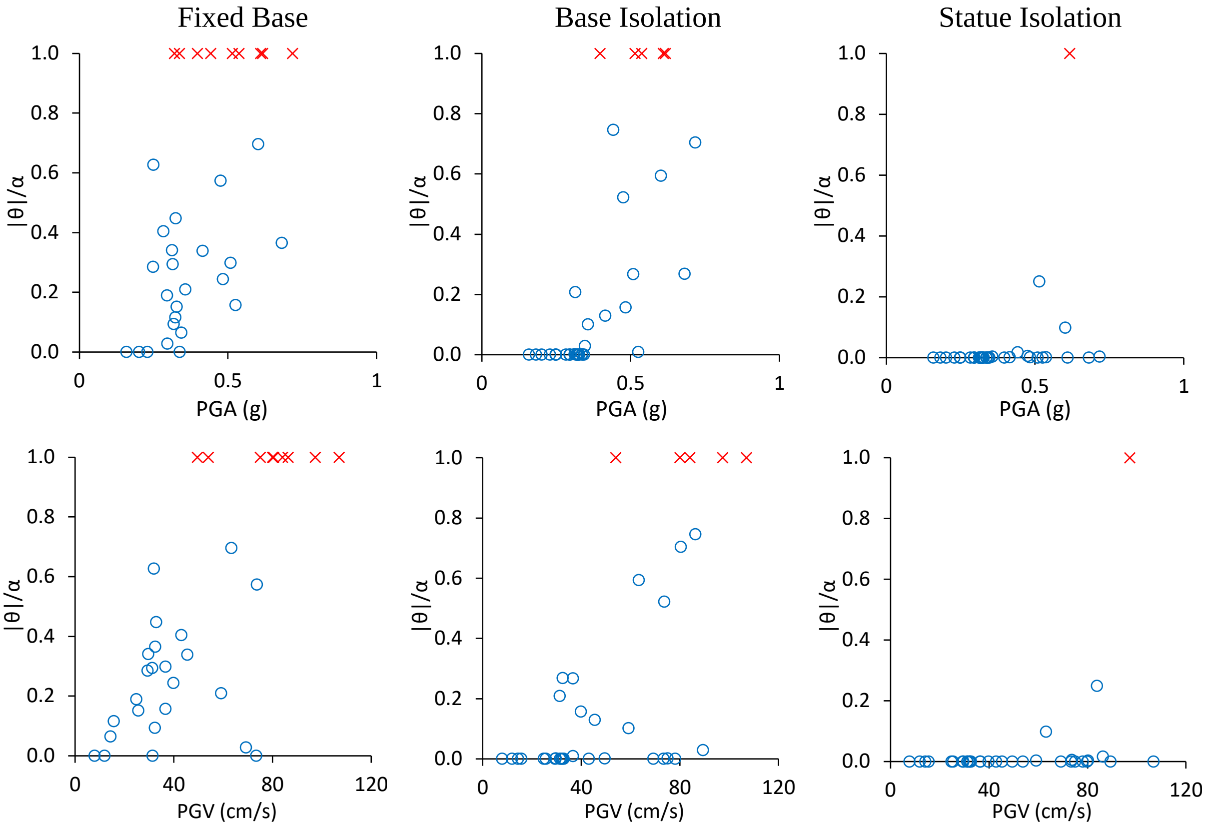

Figure 6. Developed Rocking Rotations

In Figure 7 the blocks overturn fragilities are displayed. The standard deviation values, using the PGA as an IM, are 0.47, 0.39 and 0.27 for the fixed base structure, the base isolated structure and the statue isolation case respectively. Using the PGV these values took the values of 0.37, 0.37 and 0.14. It can be remarked that the standard deviation values of the fragility curves in terms of PGV are much lower than those in terms of PGA. The median values of the fragility curves using the PGA are 54, 66 and 85 g, while using the PGV are 72, 92 and 107 cm/s respectively. By the fragility curves, the enhanced seismic response of the isolated block is obvious. It has to be noticed that base isolation via bearing has beneficial effect of the seismic response of small rocking blocks (Vassiliou and Makris 2012).

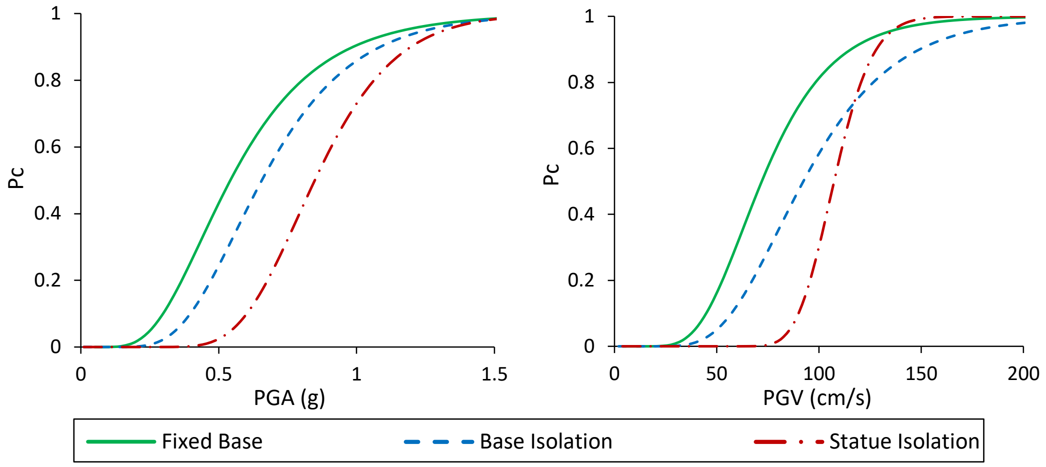

Figure 7. A figure in the text; first letter capitalized, and centrally aligned

5. CONCUSIONS

In the present study the seismic response of rocking building contents is examined. Specifically, the seismic performance of a museum rocking content hosted on a two storey RC building is studied. Moreover, two base isolation alternatives are investigated for the protection of the building contents. In the first the host building is considered base isolated, while in the second one only the rocking content at the level of the floor is isolated. The base isolation is performed using friction pendulum bearings. In both alternatives the examined, small in size, rocking block presents enhanced response compared with the fixed base structure. The results indicated that the floor isolation seems to be more beneficial for the seismic protection of the structures' free standing contents.

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