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NUMERICAL STUDY ON THE DYNAMIC RESPONSE OF CLASSICAL COLUMN STANDING FREE ON AN ISOLATED BASE

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Abstract. *A numerical study of the seismic response of base isolated free standing monolithic ancient column is presented in this paper. These rocking structural systems are analyzed standing free on an isolated base supported on friction pendulum (FP) bearings. Specifically, the implementation of multi-spherical friction bearings is examined. The rocking columns as well as the friction pendulum bearings were simulated using finite element method. Of particular importance is the detailed modeling of the isolators, which seismic behavior are validated. It is known that subjected to lower predominant period excitations, free standing rocking blocks exhibits increased stability. While, they are vulnerable to long period excitations. That opposes to the main characteristic of the base isolation technic which is to elongate the oscillation period. Thus, a thorough investigation of the influence of the FP bearings radius on the seismic response of free standing columns is caring out, to result in optimal design of the isolation devices in order to avoid rocking overturning.*

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1 INTRODUCTION

The seismic response of ancient structural systems receive an increased attention the last years. As they constitute cultural heritage assets and as such they are irreplaceable, their seismic protection is of utmost importance for the international community. Due to the fact that their form must remain intact, contemporary intervention methods should be preferred that traditional ones.

Monument structures such as Classical columns displays rocking seismic response as they standing free on the base, thus they are analyzed as rocking rigid blocks. Seismic response of rocking blocks present very complex behavior. In this way a plethora of researchers investigated the seismic response of rigid blocks and specifically ancient column in order to unveil the hidden aspects of their behavior. Seismic behavior of monolithic and multidrum columns have been thoroughly investigated both numerically and analytically [1-9]. Moreover, the influence of the epistyle mass on the rocking response of the colonnade has been examined by Makris and Vasiliou[10]. The influence of the IMs in the rocking response has been also examined [11, 12]

The seismic risk mitigation of museum artifact and ancient structural systems form a challenging task to researchers. The intervention method has to be not-intrusive to the form of the monument. Hence, the base isolation seem to be the only method that fulfill this restriction. The implementation of base isolation has been studied as a technique of protecting art objects and statues in museums [13-18]. The response of rocking blocks standing free on isolated base has been investigated extensively by Vassiliou and Makris [19]. They suggested that base isolation is not efficient when it is applied to large blocks or when it is subjected to high frequency excitations.

The isolation devices are divided into two general categories, the rubber and the friction bearings. Based on the friction pendulum bearings principles [20], more sophisticated systems have been proposed such as double pendulum bearings and triple pendulum bearings [21-24]. These isolation devices, among their beneficial performance in seismic mitigation, demonstrate adaptive seismic behavior, although they consist passive protection systems.

In the present study, the seismic response of an ancient column standing free on an isolated base is examined. Multi-spherical friction pendulum bearing are applied as isolation devices. A parametric investigation focusing on the effect of the friction pendulum radius on the seismic response of the rocking column is presented. Both, double pendulum friction bearing and a triple friction bearing are utilized. For the purpose of this study validated finite element models are adopted, for the simulation of both the rocking column as well as the friction pendulum bearings.

2 NUMERICAL MODELING

For the purpose of this study, finite element models are utilized for simulation of the examined structural systems. Despite the fact that the structural members being modeled as 3D members, planar analyses are performed. Explicit dynamic analyses were employed as it is computationally efficient for discontinuous events like impact problems, using the central difference algorithm.

The response of the rocking column is validated with results obtained from the numerical solution of the rocking motion equation [25]. The analyses results of the friction pendulum isolators models are also verified with those obtained by analyses in other commercial software which encapsulate link models appropriate for the simulation of friction pendulum bearing. The validation procedure is presented by Kavvadias et al. [26].

In the current study a column with 8m height and slenderness α=0.165rad is studied. The dimensions of the column are representative of a classical column. Specifically, the columns of the Temple of Olympic Zeus and the Temple of Apollo in Syracuse are 8 m high whereas, the Parthenon Pronaos columns have a slenderness of 0.16 rad.

Regarding the friction pendulum bearings, two double friction pendulum bearings (DFP), and one triple friction pendulum bearing (TFP) are considered. The double friction pendulum isolators have the same radius and coefficient of friction in both concave surfaces. Particularly, the friction coefficient in both isolators are consider equal to μ=0.1. Moreover, the radius of the bearing are selected as R=1.18 m and 0.65 m, which correspond to an isolation period T_{is}= 3 s and 2 s respectively. Concerning the triple friction pendulum bearing, the friction coefficients are μ=0.03 for the two inner surfaces and μ=0.1 for the two outer. Further, the radius are R=0.53 m and 2.05 m for the inner and the outer concave surfaces. According to these characteristics, the isolation period is equal to T_{is}= 2 s or 4.5 s, which is depending on the magnitude of the ground motion. In Figure 1 is depicted the examined rocking column, the friction pendulum bearings considered in the study and finally, the implementation of those.

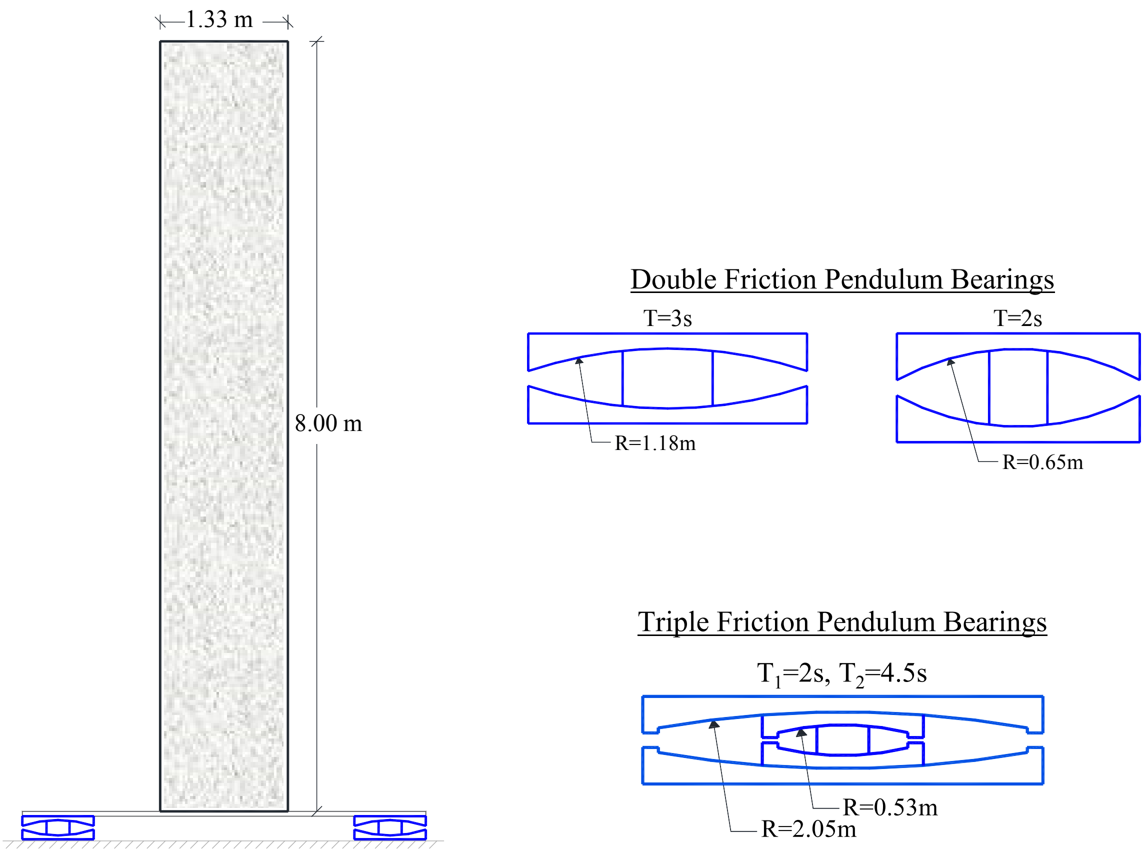

Figure 1. Examined column and friction pendulum bearings.

In order to investigate the performance of the isolation systems to mitigate the seismic risk of monumental rocking structures such as the examined column, a set of 35 ground motion records is used. Excitations with earthquake magnitudes (Ms) between 5.3 and 7.6, including both near-fault and far-fault records are employed, in order to present a wide range of intensities and frequency contents. Regarding their frequency content, the main period T_m [27] is ranged T_m = 0.10 - 1.68 s. In Table 1 the ground motion considered in this study are listed shorted by increasing values of T_m [28, 29].

Earthquake	Station	Date	M_s	R (km)	T_m (s)
Iwake	Ichinoseki Maikawa	14/7/2008	6.9	23.02	0.10
Chi-Chi	TCU88	20/9/1999	7.62	18.16	0.16
Whittier	LA - Obregon Park	1/10/1987	5.27	13.62	0.24
Athens	ATH4	7/9/1999	5.9	16.62	0.26
Tabas	Dayhook	16/9/1978	7.35	13.94	0.33
Superstition Hill	Mtn Camera	24/11/1987	6.54	5.61	0.33
Duzce	Lamont 531	12/11/1999	7.14	8.03	0.35
San Fernando	Paicoma Dam	9/2/1970	6.61	1.81	0.35
Gazli	Karakyr	17/5/1976	6.8	5.46	0.40
Northridge	Paicoma Dam	17/1/1994	6.69	7.01	0.46
Aigion	AIGA	25/6/1995	6.4	21.5	0.48
Kobe	Nishi -Akashi	16/1/1995	6.9	7.08	0.49
Friuli	Tolmezo	6/5/1976	6.5	15.82	0.50
Imperial Valley	El Centro Array #9	19/5/1940	6.95	6.09	0.53
Coalinga	Fault Zone 14	2/5/1983	6.36	29.48	0.55
Corinth	Corinth	24/2/1981	6.6	10.28	0.56
Kalamata	Kalamata	13/9/1986	6.2	10	0.58
Imperial Valley	El Centro Array #8	15/2/1979	6.53	3.86	0.60
Chi-Chi	CHY035	20/9/1999	7.62	12.56	0.72
El Mayor Cucapah	Chihuahua	4/4/2010	7.2	19.47	0.74
Landers	Joshua Tree	28/6/1992	7.28	11.03	0.78
Parkfield	Cholame #2	28/6/1966	6.2	17.64	0.83
Taiwan SMART1(40)	Smart1 M02	15/111986	6.32	60.89	0.83
Chuetsuoki	Nakanoshima Nagaoka	16/7/2007	6.8	19.89	0.86
Irpinia	Sturno	23/11/1980	6.9	10.84	0.87
Loma Prietta	Los Gatos - Lexington Dam	17/11/1986	6.93	5.02	0.89
Chi-Chi	CHY101	20/9/1999	7.62	9.94	0.89
Imperial Valley	El Centro Array #7	15/2/1979	6.53	0.56	0.96
Northridge	Jensen Filter Plant	17/1/1994	6.69	5.92	0.99
Darfield	Papanui High School	4/9/2010	7	26.76	1.19
Northridge	Newhall – Fire Station	17/1/1994	6.69	5.43	1.19
Denali	TAPS Pump Station #10	3/11/2002	7.9	2.74	1.31
Erzincan	Erzincan	19/3/1992	6.69	4.38	1.38
Kobe	Port Island	16/1/1995	6.9	3.31	1.47
Bucharest	Bucharest	4/3/1977	7.5	115	1.68

Table 1. Ground motion records sorted by increasing values of T_m.

3 RESULTS

3.1 Transmissibility of the isolation systems

The first results in order to evaluate the efficiency of the multi-spherical friction pendulum systems implementation, should be their affection in the ground motion excitation. The main feature of the base isolation technique is that it decrease the acceleration values of the seismic signal. However, due to the fact that it elongates the period of the excitation wave it could be harmful for implementation to rocking structures [19]. Moreover, it is known that the rocking response of slender blocks is affected mainly by the velocity characteristics of the excitation [11, 12].

Based on the above facts, the peak acceleration and the velocities that are transmitted from the isolator to the rocking classical column are depicted. In Figure 2 the peak acceleration of the initial excitations are compared with those developed on the isolated base for all the isolation cases. Among with these values, the marginal acceleration a_{min} [30] that initiates the rocking is depicted. The base isolation seems to be more effective for high frequency excitations as it reduces the acceleration to values even lower to the critical acceleration for the rocking block. As the frequency of the excitation tends lower, the accelerations did not reduces in such grade. It is obvious also that as the isolation period is increased, the accelerations are decreased. Comparing the different types of friction pendulum systems, the TFP bearings are notably more effective than the DFP ones, except of the case when it is subjected under the CHY101 (No 27) excitation. Initially it is marked an extremely high value of acceleration (a = 1.60 g) which is observed due to the fact that the displacement capacity of the isolator is reached. After redefining the displacement capacities of the TFP bearing, a favorable response is displayed.

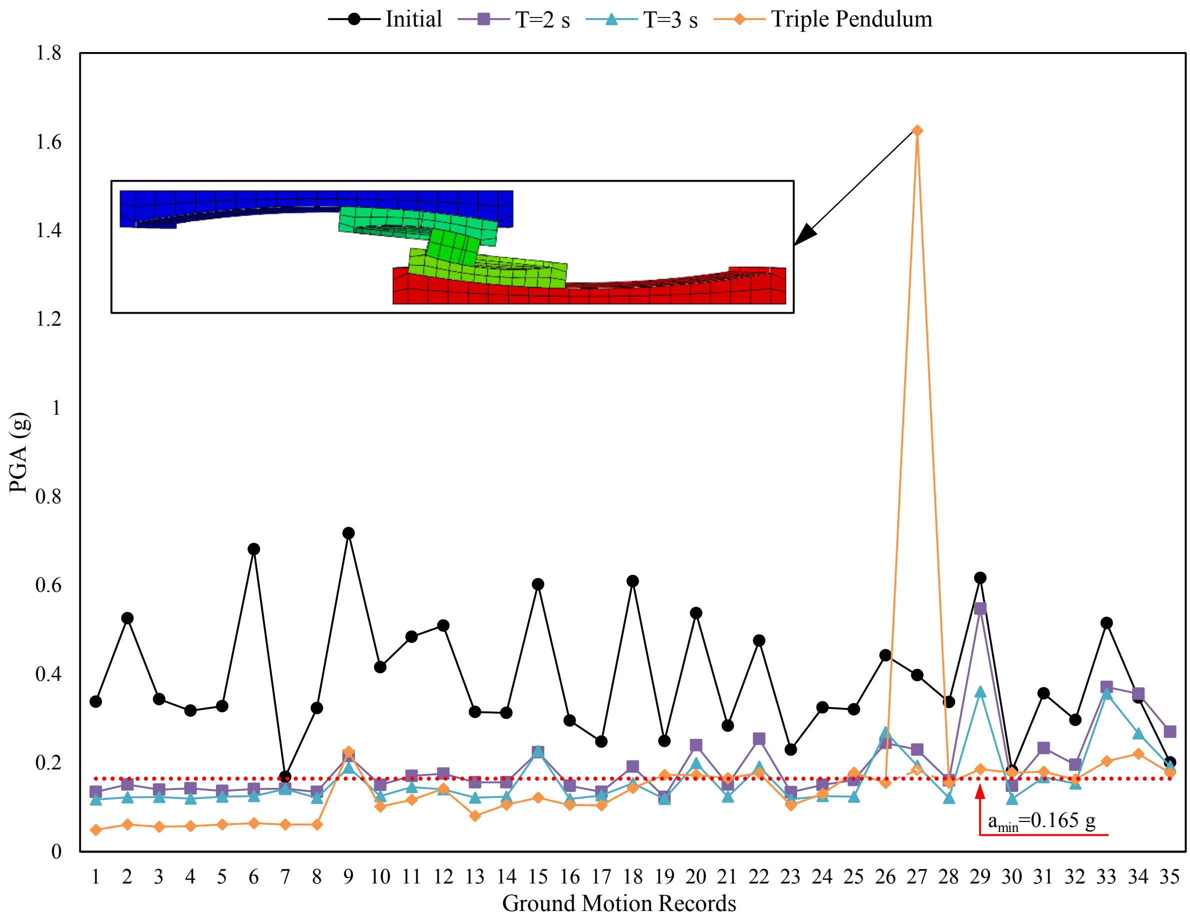

Figure 2. Peak acceleration values of the initial excitation and the signal at the isolated base.

The acceleration of the isolated base is reduced as expected. An important ground motion characteristic is the velocity of the base. Velocity is dependent of both the acceleration amplitude and the frequency content of the excitation. Due to the fact that the acceleration values are reduced due to the base isolation but simultaneously it period is elongated, it is difficult to estimate the expected results of the velocities. In Figure 3 the peak velocities of the fixed base as well as the velocities of the isolated bases are presented. It could be seen that the velocities are not altered as the acceleration values. On average, there is not a notable influence of the base isolation in the peak velocities of the transmitted signal. There is depicted both increasing and decreasing of the velocities values. The velocity of an excitation consist a ground motion parameter that affects importantly the rocking response.

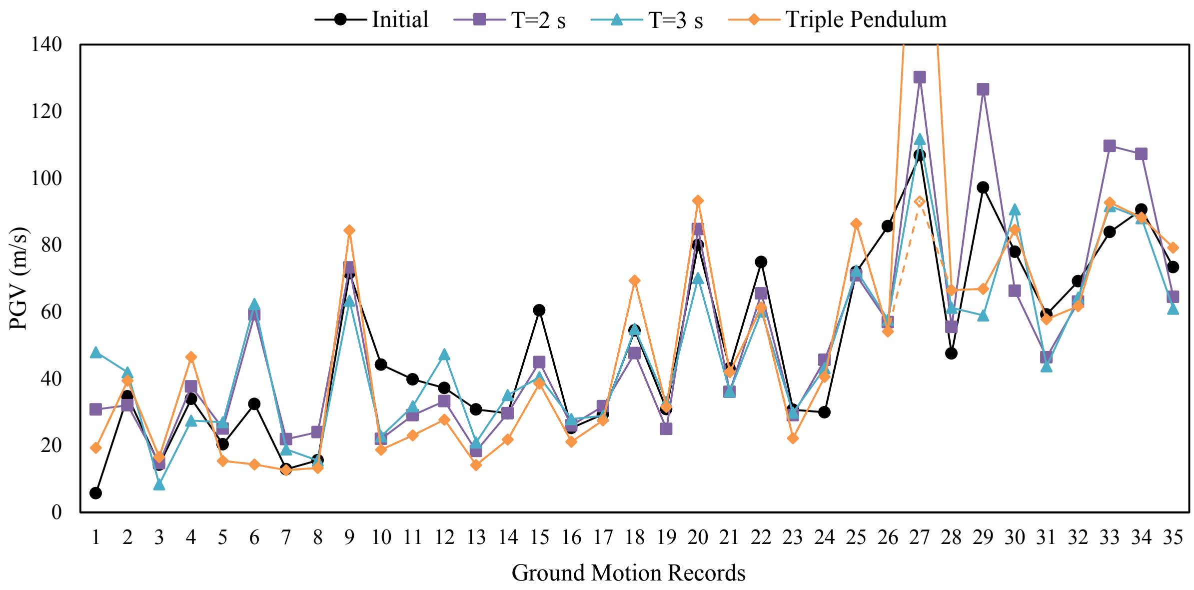

Figure 3. Peak velocity values of the initial excitation and the signal at the isolated base.

3.2 Seismic response of the rocking classical column

The velocity of an excitation consist a ground motion parameter that affects importantly the rocking response. Thus any increase of the velocity values combined with acceleration values that exceed the minimum acceleration that activates uplift should be devastating for the rocking blocks. In Figure 4 the maximum developed rocking rotations normalized to the slenderness of the block is pictured.

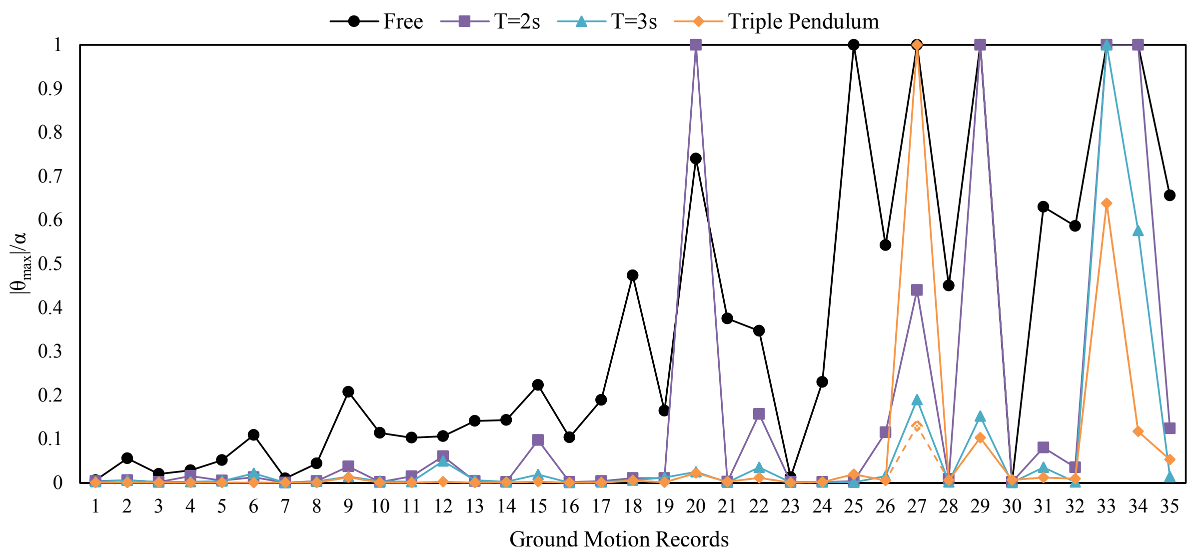

Figure 4. Peak normalized rotation values of the rocking block standing free on a fixed and isolated bases.

For the cases that the acceleration values (Figure 3) did not overcome the a_{min}, the developed rocking rotations are equal to zero. When rocking initiates, the velocity of the seismic excitation constitutes an accurate indicator of it destructiveness. That fact is confirmed by the developed rocking rotation in Figure 4. The rocking block standing free on an isolated base with period T_{is}=2 s, overturns when is subjected 4 ground motions. In these cases the acceleration values exceed the minimum acceleration that initiates rocking, while the velocities are increased compared with the initial signal. Standing on an isolated base with period T_{is}=3 s, it overturns only subjected under one seismic excitation. The implementation of DFP bearings to isolate free standing blocks has been thoroughly instigated by Vassiliou and Makris [19], showing their detrimental effect for large blocks or when it is subjected to high frequency pulses.

Examining the rocking block standing free on a rigid base which is isolated with the use of TFP bearings, interesting remarks are arose. The implementation of TFP result in the most reduced acceleration values of the high frequency content ground motions. Subjected to the excitation with the longer main period their performance are in general the best comparing with the DFP bearings. The most important fact is that the rocking block did not overturn under any ground motion excitation. Only when the displacement capacity of the TFP is restricted, collapse occurred.

4 CONCLUSIONS

In the present study base isolation technique is examined as a protection system of free standing ancient columns. These structural systems consist irreplaceable cultural heritage elements, and as though have to be preserved throughout the years. The effectiveness of three different isolation bearings in the seismic risk mitigation of a slender rocking column is investigated. Two double friction pendulum bearings (DFP) and one triple friction pendulum bearings (TFP) are considered.

For the ground motions set considered in this study the seismic isolation with the use of TFP appear to be beneficial for the seismic protection of the examined free standing column. Despite the fact that in general the seismic signal period is elongated due to the base isolation, when TFP bearing is implemented, the accelerations are reduced in such grade that lead to restricted rocking rotation. The results indicated that the usage of TFP bearings, with a carefully selection of it displacement capacity, can form an intervention solution that results in enhanced seismic performance of structures such as free standing classical columns.

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