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PARAMETRIC NUMERICAL STUDY OF THE SEISMIC RESPONSE OF CLASSICAL COLUMNS

Ioannis E. Kavvadias[1] and Lazaros K. Vasiliadis[1]

[1] Democritus University of Thrace, Dept. of Civil Engineering,
Institute of Structural Mechanics and Earthquake Engineering
Vas. Sofias 12, 67100 Xanthi, Greece
{ikavvadi, lvasilia}@civil.duth.gr

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Abstract. *This paper presents a numerical investigation of the seismic response of monolithic and multidrum columns. The effect of the column size and the effect of the input motion characteristics on the dynamic response of free standing columns are studied. Single columns and two columns coupled with an architrave subjected to a set of 20 ground motions are examined. The selection of the seismic excitations was made in order to provide a wide spectrum of structural damage due to statistical reasons. Further various prototype geometry sections are considered in order to include as key parameter the column size effect on the seismic behavior of these structural systems. Correlation study is performed to estimate the interrelationship between the most substantial ground motion parameters and the damage indices. Moreover the effect of the column geometry on the seismic response of classical column structural systems is studied based on the results of the linear regression analysis. Finally the relation between the maximum developed rotations and the residual displacements is examined. For the purposes of this study finite element models for the in space simulation of the members are adopted and results in term of relative rotations and relative residual displacements between the drums are presented.*

1 INTRODUCTION

The investigation of the seismic response of ancient structural systems such as ancient columns and colonnades has received increasing attention during the last decades. Different types of columns with numerous variations in their geometrical characteristics can be found in the Eastern Mediterranean region. Usually these are constructed of limestone or marble blocks (drums), which are placed on top of each other, without connecting mortar between them. These rigid-body assemblies display a very different dynamic response compared to modern structures, as their response is composed primarily of the rocking and the sliding among the individual drums of the structure. This behavior can be characterized as highly nonlinear due to the continuously changing of the geometry and boundary conditions of the structural system during a strong earthquake.

Early studies on the rocking response of a rigid block undergoing horizontal motion were presented by Housner [1]. Extensive investigation specifically on the response of single multidrum columns or of columns connected with each other at the top level by architraves has been presented by several researchers [2-7]. A numerical study of the seismic response of ancient columns conducted in two dimensions based on the distinct element method has been presented by Psycharis et al[2] while, Papantonopoulos et al [3] used a three dimension modeling in order to predict the experimental results of a scale multidrum column model[4]. Furthermore, Konstantinidis and Makris [6] examined the effect of wooden poles installed in ancient times, in the dynamic response of multidrum columns. Additionally Papaloizos and Komodromos [7] investigated the seismic response of ancient columns and colonnades with epistyles using a custom-made software based on the Discrete Element Method (DEM).

It is concluded that the dynamic behavior of free standing columns is very sensitive even to trivial changes in the ground motion characteristics or of the geometry of the model. Classical columns are, in general, earthquake resistant, as proven from the fact that many classical monuments have survived many strong earthquakes over the centuries. The predominant period of the excitation significantly affects the response, with low frequency pulses being much more dangerous while, the size of the column is another important parameter, with bigger structures being much more stable than smaller ones with the same slenderness.

In this paper, we present a numerical investigation of the seismic response of classical columns. The parameters we examined refer to the column geometry and the excitation characteristics. Regarding the numerical model, four prototype geometry sections are considered in order to examine the column size effect on the seismic behavior of these structural systems. Both monolithic and multidrum columns are simulated so as to provoke the beneficial drum dislocation. In addition two columns coupled with a varying geometry architrave is considered as to arise its influence on the dynamic response of colonnades. Regarding the excitations a set of 20 ground motions is used.

Correlation coefficients are evaluated to express the grade of interdependency between seismic parameters and the structural damage. Correlation between seismic parameters and structural damage has been studied mainly for RC buildings [8]. The ground motion parameters considered are the peak parameters (PGA, PGV and PGD) and the spectra parameters provided by the Fourier spectrum. Due to the fact that such structures do not possess natural modes in the classical sense and the periods of free vibrations are amplitude dependent the Fourier spectrum is used to find out the period and the amplitude of the main pulse of each ground motion record. The structural damages are represented in terms of relative rotation and relative residual displacements between the drums.

Moreover, linear regression analyses have been performed between the seismic parameter which has the strongest correlation with the overall structure damage, so as to compare the seismic response between the various models. Especially is examined the size and the slenderness influence, the construction technic (monolithic against multidrum) and the colonnade with epistyle against the single column response. Finally, is presented the interrelationship between the two damage indices which are the maximum developed relative rotation and the relative residual dislocation, in order to arise the dominant response responsible for the collapse of classical columns.

2 NUMERICAL MODEL

For the purpose of this study finite element models are adopted for the in space simulation of the members, in which the blocks are simulated as deformable elements and the ground as a rigid surface. Specifically Young's modulus (E=84.5 GPa), the poison ratio (ν=0.23) and the density of the marble (d=2750 kg/m3) are defined.

Of particular significance of the simulation are the appropriate modeling of the contact between the drums. A Mohr-Coulomb model is adopted to describe the mechanical behavior of the joints. For both normal and tangential direction of the contact element the stiffness is assumed as infinite. In the normal direction no tensile strength is considered while the shear strength is governed by the Coulomb friction coefficient. Typical values of the friction coefficients for marble blocks are μ=0.7.

Prototype geometry columns with two different heights and two different ratios of the heights over the columns diameter are studied. Table 1 presents the dimensions of the examined models. The selection of the dimension was made to be in accordance with the size and the slenderness of recorded ancient columns. Regarding the multidrum columns, a drum of 1m height is considered for every model. Concerning the effect of the architrave existence, two varying geometry architraves are examined. The values of the architrave height defined as a ratio over the columns diameter taking values h/2B =0.5, 1. The axial distance between the columns is L=3m and is spanned with a single block architrave. Figure 1 shows the dimensions specified in the models.

Model	2H (m)	H/B	Number of Drums
I	5	6	5
II	5	7	
III	8	6	8
IV	8	7	

Table 1: Examined models geometry

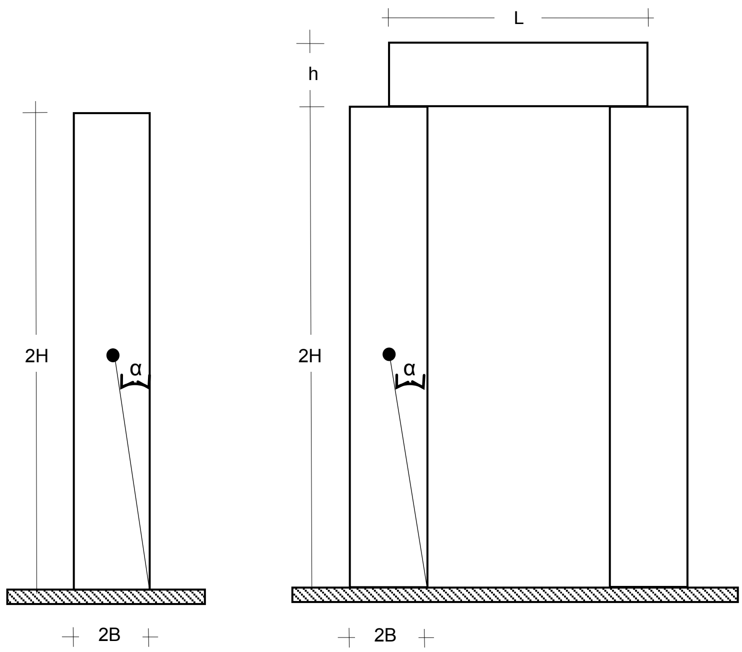

Figure 1: Columns and colonnades with epistyle geometry.

3 SELECTION OF GROUND MOTIONS

Our analyses used a set of 20 ground motions (Table 2) with different characteristics in order to investigate how the response of the columns is influenced by the characteristics of the seismic excitations. The events have been chosen from worldwide well-known sites with strong seismic activity. A further aspect which has been taken into consideration is the expected damage potential of the seismic excitation on the structure to be analyzed. Seismic excitations which provide a wide spectrum of structural damage, from negligible to severe, are taken into account due to statistical reasons. The selected ground motion are in the range of Mw=6.2-7.62. As the predominant period of the ground motion seems to be the main parameter which affects the stability of the column, the ground motion acceleration signal must be converted from a time domain to a frequency domain.

Due to the fact that the free standing columns do not possess natural modes in the classical sense, we do not use the response spectrum parameters. On the contrary, the period of the maximum Fourier amplitude spectrum is not dependent on the structural response and therefore is a more accurate method to find out the period of the main pulse which affects the seismic response of these structures. The term $\alpha_p \bullet T_p = v_p$ seems to be representative as it combines the amplitude with the period of the main pulse. Also the product $\alpha_p \bullet T_p^2 = L_p$ is examined which is a characteristic length scale of the main pulse [9, 10]. Several peaks are shown in the Fourier spectrum. The combination α_p - T_p selected is the one that maximizes the products $\alpha_p \bullet T_p$ and $a_p \bullet T_p^2$ which do not necessarily correspond to the maximum acceleration amplitude spot.

Earthquake	Record	M_w	PGA (g)	PGV (cm/s)	PGD (cm)	T_p (s)	α_p (g)	v_p (m/s)	L_p (m)
Bucharest 04/03/1977	Bucharest	7.50	0.20	73	126	1.71	0.31	5.31	9.06
Chi-Chi 20/09/1999	TCU52	7.62	0.34	159	184	2.28	0.48	10.64	24.2
Chi-Chi 20/09/1999	TCU88	7.62	0.52	35	29	0.10	0.24	0.23	0.02
Chuetsu 16/06/2007	Kariwa	6.80	0.36	103	54	2.34	1.03	23.7	55.6
Corinth 24/02/1981	Corinth	6.60	0.30	25	7	0.85	0.14	1.20	1.02
Duzce 12/11/1999	Lamont 531	7.14	0.16	13	8	0.39	0.15	0.59	0.22
Erzincan 19/03/1992	Erzincan	6.69	0.52	84	28	2.28	0.30	6.64	15.1
Friuli 06/05/1976	Tolmezo	6.50	0.31	31	5	0.67	0.23	1.50	1.01
Gazli 17/05/1976	Karakyr	6.80	0.72	71.6	23.7	0.52	0.32	1.65	0.87
Imperial Valley 19/05/1940	El Centro Array #9	6.95	0.31	30	13	0.85	0.26	2.16	1.84
Imperial Valley 15/02/1979	El Centro Array #7	6.53	0.33	48	25	1.20	0.17	1.98	2.39
Kalamata 13/09/1986	Kalamata	6.20	0.25	29	9	1.22	0.10	1.13	1.39
Kobe 16/01/1995	Nishi - Akashi	6.90	0.51	37	10	0.47	0.40	1.88	0.90
Landers 28/06/1992	Joshua Tree	7.28	0.28	43	14	1.51	0.31	4.62	7.02
Loma Prietta 18/10/1989	UCSG 16 LGPC	6.93	0.97	109	66	2.93	0.40	11.54	33.7
Northridge 17/01/1994	Jensen Filter Plant	6.69	1	68	25	2.05	0.27	5.38	11.0
Parkfield 28/06/1966	Cholame #2	6.20	0.48	75	22	1.37	0.19	2.61	3.56
San Fernando 09/02/1970	Paicoma Dam	6.61	0.32	16	2	0.34	0.15	0.52	0.18
Superstition Hill 24/11/1987	Mtn Camera	6.54	0.68	33	5	0.66	0.27	1.72	1.14
Tabas 16/09/1978	Dayhook	7.35	0.33	20	11	0.64	0.14	0.87	0.56

Table 2: Ground motion used in the analyses

4 RESULTS

Numerical analyses are performed in order to examine the correlation between the parameters of the earthquake excitations and the seismic response of the examined columns. Subsequently the effect of the structural system geometry is performed comparing the lines exported by the linear regression analyses. The overall structure damage index is presented in terms of maximum rotation and residual relative displacement. Both indices are introduced as a ratio over the critical overturning rotation and the critical relative displacement respectively. The critical overturning rotation (θcr) is equal to the slenderness (α) and take the value

$$\theta_{cr} = \alpha = \arctan(B/H) \quad (1)$$

Finally for the multidrum columns, the two indices are plotted in order to display the interrelationship of both and as a result to highlight the most crucial phenomenon between the rocking and the sliding response.

4.1 Correlation analysis

To estimate the degree of the correlation between the ground motion parameters and the damage indices, the linear rank correlation coefficients after Spearman is calculated. Table 3 presents the correlation coefficients regarding all the models (monolithic, multidrum, colonnade connected with architrave) of the 8m height column with dimensional ratio H/B=6 and h/H=1.

Excitation Parameters	Monolithic	Multidrum	Colonnade
PGA	0.353	0.396	0.515
PGV	0.852	0.903	0.929
PGD	0.768	0.746	0.792
T_p	0.845	0.843	0.775
α_p	0.752	0.748	0.847
v_p	0.930	0.912	0.917
L_p	0.876	0.860	0.821

Table 3: Correlation coefficients

Examining Spearman's rank correlation coefficient in Table 3, easily reconcilable is the maximum correlation of the maximum developed rotation with PGV and v_p. Significant values of correlation coefficient also have with T_p and L_p. The lower correlation occurred with PGA, PGD and α_p. It is obvious that the seismic parameters associated with the predominant period of the ground motion exhibit better correlation. It is known that the period of the excitation affects the response of the classical columns, with long period pulses being more dangerous. As expected the columns overturn when they are subjected to excitations with predominant period longer than $T_p > 2$s. Concerning the correlation coefficients from all 24 modes, v_p is the highest correlated seismic parameter whose coefficient ranges from 0.713 to 0.93.

4.2 Linear regression analysis

Linear regression analyses have been performed considering all of the results for each particular model, to notice the relations of maximum developed rotation to v_p, which is the highest correlated seismic parameter with that damage index. Furthermore by comparing the linear regression results between the models are extracted considerable results as regards the effects of the geometry alteretions. Comparative presentation of the performed linear regression analyses results are shown in Figures 2-7.

The response of the 8m height monolithic columns exhibit important stability when excited by ground motion with v_p < 4m/s. Comparing the two columns with same height but with different slenderness ratio H/B (Figure 2) is apparent that both columns overturn when exited by long period ground motions. Only for the Erzincan earthquake the bulkier column developed rotation 72% of columns slenderness without overturns in contrast with the less slender column. Comparing the maximum rotations, the main difference occurred for ground motion with low values of v_p where an increased value of rotation developed to the thinner column.

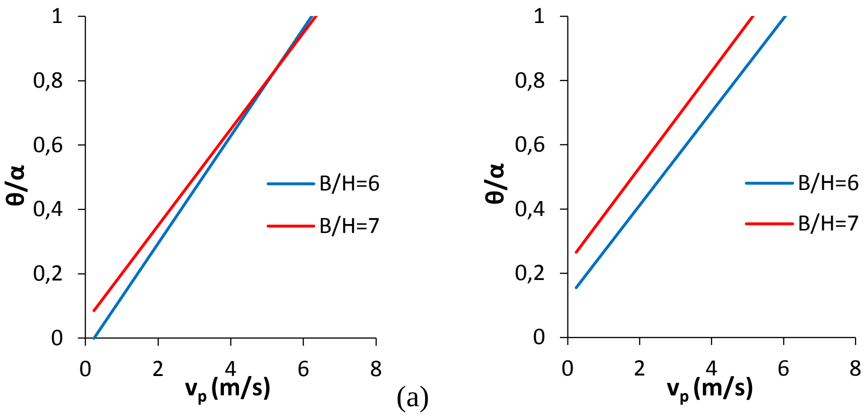

Figure 2: Maximum rotations (a) of the 8m height column, (b) of the 5m height column.

The 5m height columns seismic response demonstrates a significant rocking instability. As it can be observed in Figure the column with slenderness ratio H/B=7 is vulnerable when it is subjected to ground motions with low values of v_p. Overturn of the column occur even when excited by El Centro Array #7 which takes value v_p=1.98m/s. The bulkier column show smaller rotations in relation with the thinner one. Moreover, comparing the columns with the same slenderness ratio but with different actual size (Figure 3) the taller columns displays increased stability

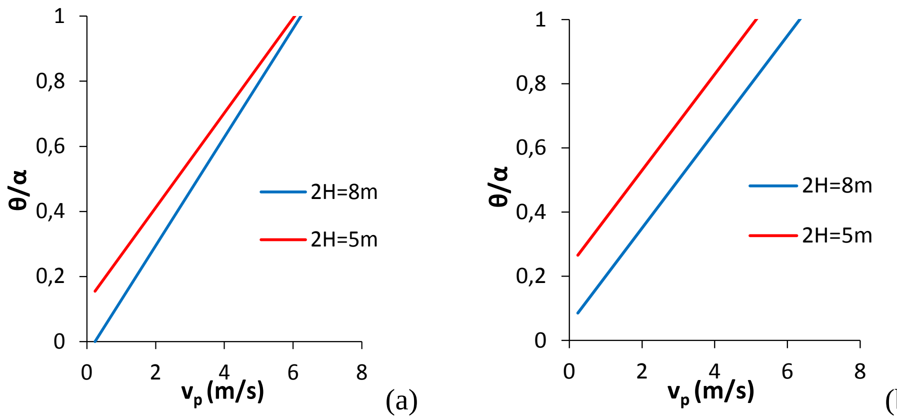

Figure 3: Maximum rotations of columns with slenderness ratio (a) B/H=6, (b) B/H=7.

The seismic response of a structural system composed of two columns linked with an architrave is also examined. Comparative presentations of the maximum developed rotations of the examined columns with and without architrave are shown in Figure 4. It can be observed that the 8m height colonnade request lower values of rotation in contrast with the single column. The epistyle geometry do not significantly affects the response of the structural system. Nevertheless, regarding the 5m height colonnade the geometry of the architrave seems to be of crucial importance.

The seismic response of the colonnade with an architrave with dimensional ratio h/2B=0.5 displays important similarities with the single column models. The maximum developed rotation is almost the same while overturn of the structural system occurs for the same excitations as to the single column. In the examine case when the architraves dimensional ratio is h/2B=0.5 the colonnade system exhibit reduction of the developed rotations. Moreover in contrast with the single columns response the colonnade systems do not overturn excited by the Gazli ground motion.

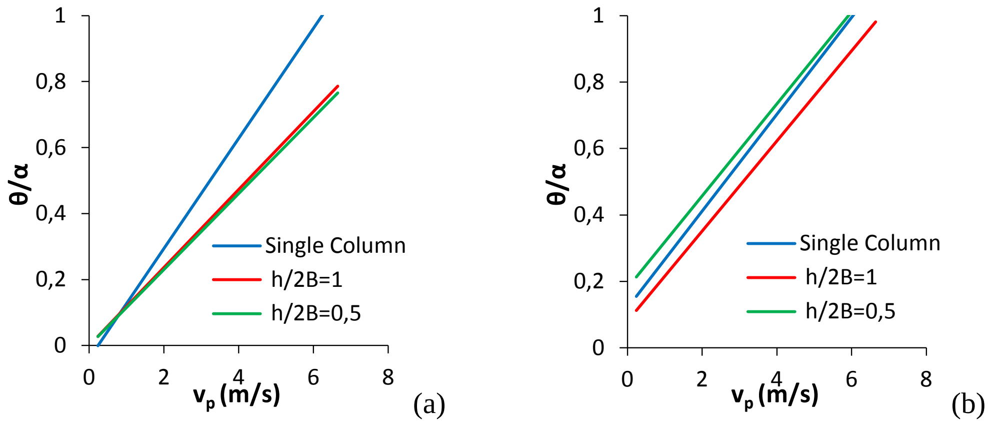

Figure 4: Developed rotations of colonnade systems with (a) 8m height column, (b) 5m height column.

Multidrum columns exhibit very complicated, highly nonlinear seismic response that depends on numerous parameters. Their response are very complex containing both sliding and rocking when they are subjected to low predominant period pulses. On the other hand rocking is the prevailing phenomena when they are subjected to high period pulses. Subjected to ground motion such as Erzincan (v_p=6.67m/s), Chi-Chi TCU52 (v_p=10.60m/s) or to the rest of the earthquakes with greater value of v_p, the columns overturn regardless of whether is monolithic or multidrum column. Comparing the monolithic with the multidrum columns the developed rotation on average does not present large alterations.

Figure 5 demonstrates the comparison of the developed rotations between the monolithic and multidrum 8m height columns. The requested rotations is slight reduced to the multidrum column with slenderness H/B=6. When excited by ground motion which overturn the monolithic column, the drums tend to rotate in a single group with similar to the monolithic column response. Regarding the more slender column did not overturn when it is subjected to long predominant period excitation such as Erzincan's and Northridge's. Nevertheless, it overturns partially when subjected to Gazli and Superstition Hills excitations.

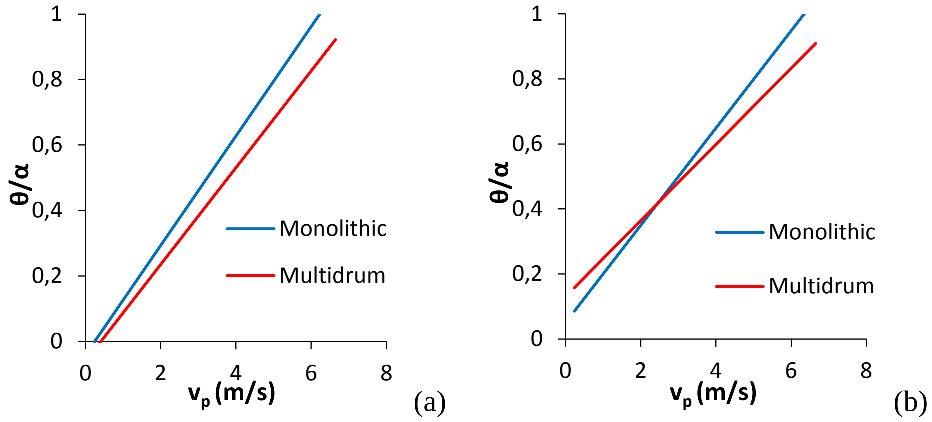

Figure 5: 8m height multidrum column developed rotations (a) for slenderness B/H=6, (b) for slenderness B/H=7.

It is apparent from the Figure 6 that regarding the 5m height column the developed rotations are smaller in the case of the multidrum columns when subjected to excitations with small values of v_p. This remark is common for both considered slenderness's. Subjected to ground motions which have higher values of v_p the demanded rotations of the multidrum models are bigger than those of the monolithic columns especially for the bulkier one. Particularly, subjected to the Landers excitation the monolithic column developed 78% of it slenderness in comparison with the multidrum column which overturn. Similar response occur also to the less slender column.

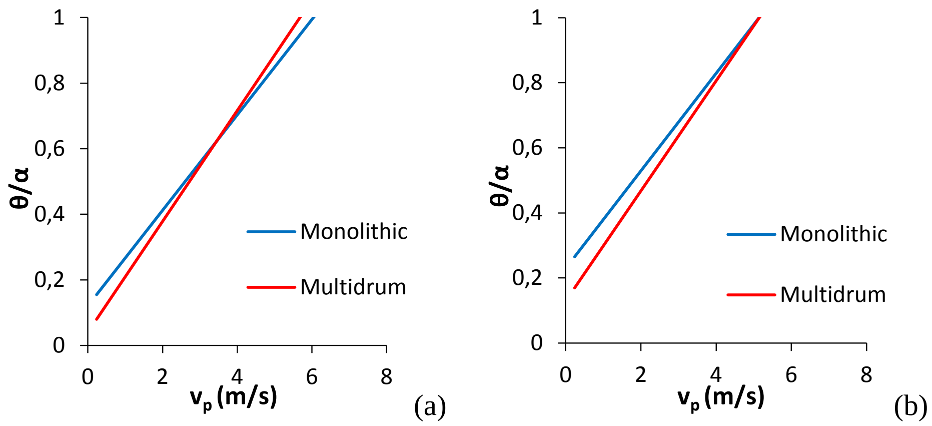

Figure 6: 5m height multidrum column developed rotations (a) for slenderness B/H=6, (b) for slenderness B/H=7.

The seismic response of two columns connected with architrave is studied also for multidrum columns. It is clear that the effect of the architrave to the dynamic response of the structural system is similar among the monolithic and the multidrum column. Regarding the 8m height column the colonnade exhibit significant stability when is excited to ground motion wictht demand large values of rotation. On the other hand the 5m height column models exhibits grate instability and therefore the effect of the architrave on the seismic response of the structural system minor.

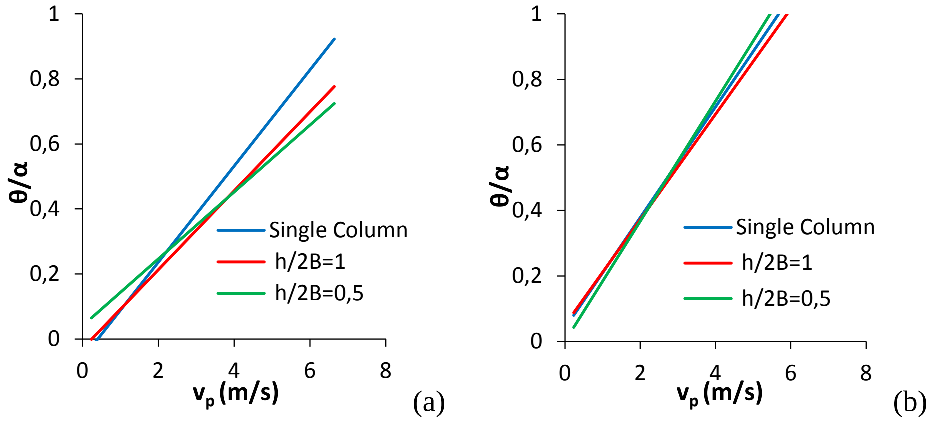

Figure 7: Colonnades developed rotation (a) for the 8m height column, (b) for the 5m height column.

4.3 Relationship between the residual displacement and the maximum rotation

Noticed from the correlation analysis regarding the multidrum column models, results in term of residual displacements did not interrelated with none of the examined seismic parameters. In addition even results in terms of maximum developed rotation did not correlate with the residual dislocation of the drums. The maximum relative dislocation is demonstrated between the drums in which is presented the maximum rotation and specifically they are induced during impacts when the rocking drums alternates pivot points.

Figure 8 displays the maximum relative rotation versus the relative residual displacement. It can be easily observed that rocking is the dominant response of multidrum columns excited by earthquake excitations and the prevailing phenomenon that occur ancient columns collapse. Even for rotation which reached the 65% of the columns slenderness the relative dislocation is restricted to 15%. This Figure data correspond to the 8m height with slenderness H/B=6 column and is representative of all the analyzed multidrum models

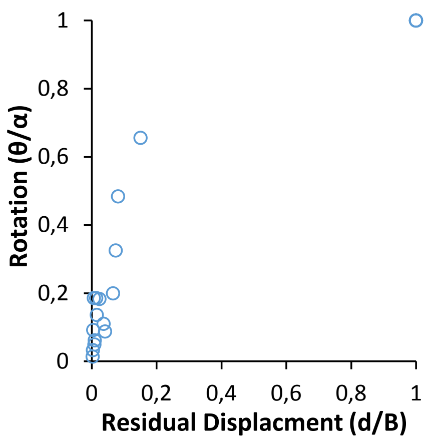

Figure 8: Relation between the developed maximum rotations and the residual relative displacements.

5 CONCLUSIONS

This paper presents an extensive numerical investigation on the seismic response of classical columns. Standalone monolithic and multidrum columns, as well as colonnades with epistyles subjected to a set of 20 excitations are analyzed. The effect of the ground motion characteristics and the effect of the structural system geometry on the dynamic response of these structures are studied.

The effect of the ground motion characteristics was examined through a correlation study between the main seismic excitation parameters and the damage occurred to the structure in terms of maximum rotations. The estimation of the interrelationship has been expressed by the linear Spearman rank correlation coefficient. The results have shown that the developed rotation exhibit strong interrelation with the product $\alpha_p \bullet T_p = v_p$, the values of α_p and T_p are extracted from the Fourier spectra. This product combines the amplitude with the period of the main pulse which is significantly affects the rocking response of these structures.

The effect of the geometry on the seismic response of these structural systems is based on the results of the linear regression analysis in terms of maximum developed rotations. The 5m height columns displays significant vulnerability even when they are subjected to excitations with limited values of v_p. In general the bulkier columns demonstrated increasing stability as they are requested smaller values of rotation. The 8m height colonnade regardless of the architrave geometry present restricted values of developed rotation in contrast to the single column model. However, regarding the 5m height colonnade the dynamic response do not appear great difference in comparison with the single column model.

Multidrum columns presented very complicated dynamic response and sensitive even to minor changes of the excitation characteristics. Subjected to ground motions with long predominant period their response are similar with the corresponding monolithic columns as the drums tend to rotate in a single group while when they are excited by short predominant period ground motions the relative developed rotations are restricted. The colonnade structural systems with multidrum columns present similar response with the multidrum columns.

Furthermore, comparing the maximum developed rotations with the residual relative displacements between the drums is obvious that rocking is the dominant response that occur ancient column collapse as the drum dislocations are minor even when notable rotations are developed.

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