The effect of earthquakes' vertical components on ancient multi-drum structures

Loizos Papaloizou
Department of Civil and Environmental Engineering, University of Cyprus

Petros Komodromos
Department of Civil and Environmental Engineering, University of Cyprus

SUMMARY:
This research work investigates the effect of the vertical component of earthquake excitations on the seismic behaviour of ancient monumental structures such as multi-drum classical columns. In particular, the Discrete Element Method (DEM) is utilized in the study of ancient columns under strong ground excitations including the vertical component of seismic excitations, by simulating the individual rock blocks as distinct bodies. A specialized software application has been developed, using a modern object-oriented programming language, in order to enable the effective simulation of multi-drum columns under these conditions. A number of parametric studies with different earthquakes is performed with and without the vertical component. The results show that the effect of the vertical acceleration of the ground motion significantly affects the response. Specifically, the vertical component seems to affect the contact forces between the rigid blocks and this alters the final response of the columns.

Keywords: DEM, Ancient Columns, Earthquake Engineering, Vertical component

1. INTRODUCTION

Strong earthquakes are common causes of destruction of ancient monuments, such as classical columns and colonnades. Ancient classical columns of great archaeological significance can be abundantly found in high seismicity areas in the Eastern Mediterranean (Figure 1). Multi-drum columns are constructed of stone blocks that are placed on top of each other, with or without connecting material between the individual blocks. The seismic behaviour of these structures exhibits complicated rocking and sliding phenomena between the individual blocks of the structure that very rarely appear in modern structures.

In ancient Greece the temples formed the most important class of buildings erected during that era and can be classified into three "Orders of Architecture", the Doric, Ionic and Corinthian order. An "order" in Greek architecture consists of the column, including the base and the capital, and the entablature (Figure 2). The entablature is divided into the architrave (lower part), the frieze (middle part) and the cornice (upper part). The differences among these three orders refer on the dimensions, proportions, mouldings and decorations of the various parts.

Today, the remains of most of these temples are often limited to series of columns with an entablature or only an architrave, and in some cases only standalone columns. The investigation of the seismic behaviour of such monuments is scientifically interesting, as it involves complicated rocking and sliding responses of the individual rock blocks. The understanding of the seismic behaviour of these structures contributes to the rational assessment of efforts for their structural rehabilitation and may also reveal some information about past earthquakes that had struck the respective region.

Figure 1. Multi-drum columns, Jerash, Jordan

Ancient monuments, compared to modern structures, have been exposed to large numbers of strong seismic events throughout the many centuries of their life spans. Those that survived have successfully withstood a natural seismic testing that lasted for several centuries. Thus, it is important to understand the mechanisms that enabled them to avoid structural collapse and destruction during strong earthquakes. Since analytical study of such multi-block structures under strong earthquake excitations is practically difficult, if not impossible for large numbers of blocks, while laboratory tests are very difficult and costly, numerical methods can be used to simulate their seismic response.

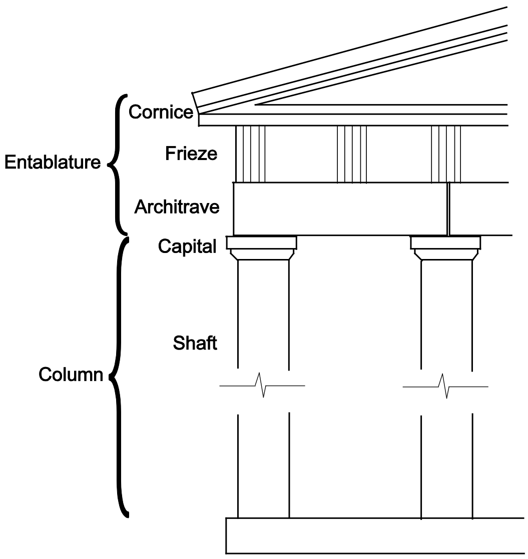

Figure 2. Architecture of a typical classical monument

A very extensive review of the literature on the usage of numerical methods for the analysis of monuments until 1993 was published by Beskos (1993). The dynamic behaviour of infinitely rigid bodies during horizontal excitations was studied by Housner (1963), while, later on, other researchers (Psycharis et al., 2003, Pompei et al., 1998, Makris & Zhang, 1998, Manos et al., 2001, Komodromos et al., 2008) investigated further, both analytically and experimentally, the required conditions to overturn rigid bodies. Such structures can be simulated utilizing the Discrete Element Methods (DEM), which have been specifically developed for systems with distinct bodies that can move freely in space and interact with each other with contact forces through an automatic and efficient recognition of contacts.

Research efforts to use the DEM in the simulation of ancient structures have already shown promising results, motivating further utilization of this method. Recent research work based on commercial DEM software applications (Psycharis et al., 2003, Papantonopoulos, 2002), demonstrated that the DEM can be reliably used for the analysis of such structures, although they reported a sensitivity of the response to small perturbations of the characteristics of the structure or the excitation. However, similar sensitivity has also been observed in experiments with classical columns (Mouzakis et al., 2002). Hence, it is important to perform large numbers of simulations with varying earthquake characteristics and design parameters to properly assess and interpret the simulation results. Yim, Chopra and Penzien (1980) through analytical study of rigid blocks under horizontal and vertical ground motion suggested that the vertical acceleration affects rocking motion significantly but not systematically.

Latest research studies in the fields of paleoseismology and archaeoseismology (Hinzen et al., 2010, Caputo et al., 2011) investigate the damage in ancient monument structures and propose various quantitative models to test the seismogenic hypothesis of observed damage. Papaloizou and Komodromos (2012) used the Discrete Element Method (DEM) as well as a modern object-oriented design and programming approach, in order to examine the simulation of multi-drum columns and colonnades under harmonic and earthquake excitations.

Stefanou et al. (2011) showed, by using stability analysis, that rocking is unconditionally unstable and that wobbling is the dominant motion for frustums. Furthermore, the authors suggest that the two dimensional analyses should fail to capture wobbling as the out-of-plane motion is ignored. Dimitri et al. (2011), studied the dynamic behavior of masonry columns and arches on buttresses with the discrete element method. Ambraseys and Psycharis (2012) studied the stability of columns and statues under earthquakes, by investigating various parameters that affect their response.

A custom-made DEM software has been specifically designed (Papaloizou and Komodromos, 2012) and implemented to enable efficient performance of large numbers of numerical simulations with varying parameters, modelling these structures with independent distinct bodies, as they are constructed in practice. Such simulations allow the assessment of the influence of different earthquake characteristics as well as the various mechanical and geometrical parameters of these structures on their seismic responses.

2. METHODOLOGY

For the analyses performed, a specialized software application (Papaloizou and Komodromos, 2011) is extended to take into account the vertical component of the excitation. For the development of the software application a modern object-oriented programming language is used. Additionally, the Discrete Element Method (DEM) is utilized in this study to include the vertical earthquake component.

Specifically, the interactions between two bodies in contact are created in DEM when contact is detected, kept as long as the bodies remain in contact and removed as soon as the bodies are detached from each other. No tension force is transmitted between the contact surfaces. In order to be able to consider potential sliding according to the Coulomb friction law, normal and tangential directions are considered during contact. The normal and tangential directions are based on a contact plane, which is defined at each simulation step. The bodies slide along the contact plane relatively to each other, whenever the tangential force exceeds the maximum allowable force in that direction.

The simulations take into account the individual rock blocks as distinct rigid bodies. At any simulation step, when two bodies come in contact, equivalent springs and dashpots are automatically created, in the normal and tangential directions, to estimate the contact forces that are applied to the bodies. The interactions between bodies may involve new contacts, renewed contacts, slippages and complete detachments from other bodies with which they were, until that time, in contact. The contact forces, which are applied at contact points during impact, are then taken into account, together with the gravity forces, in the formulation of the equations of motion. Finally, the equations of motion are numerically integrated using the Central Difference Method (CDM) in order to compute the displacements at the next time step.

3. NUMERICAL ANALYSES

Single multi-drum columns are examined with earthquake ground motions selected from regions, where these monuments are often built, such as the Greek region (Table 3.1). The response spectra of the horizontal earthquake ground motions are presented in Figure 3, whereas for the vertical components the response spectra are shown in Figure 4.

Table 3.1. List of earthquake records that have been used in the analyses

No.	Place	Date and Time	Earthquake Component	PGA *(m/sec^2)*
1	Athens, Greece	11:56:50, SEPTEMBER 7, 1999	KALLITHEA DISTRICT N46	2.602
			KALLITHEA DISTRICT VERT	1.449
2	Corinth, Greece	20:53:37, FEBRUARY 24, 1981	KORINTHOS- OTE BUILDING E-W	3.038
			KORINTHOS- OTE BUILDING VERT	1.139
3	Kalamata, Greece	17:24:31, SEPTEMBER 13, 1986	KALAMATA OTE- BUILDING N10W	2.671
			KALAMATA OTE- BUILDING VERT	1.966
4	Lefkada, Greece	15:52:12, NOVEMBER 4, 1973	LEFKADA OTE- BUILDING N-S	5.148
			LEFKADA OTE- BUILDING VERT	1.096
5	Thessaloniki Greece	20:03:21, JUNE 20, 1978	THESSALONIKI-CITY HOTEL E-W	1.431
			THESSALONIKI-CITY HOTEL VERT	1.200

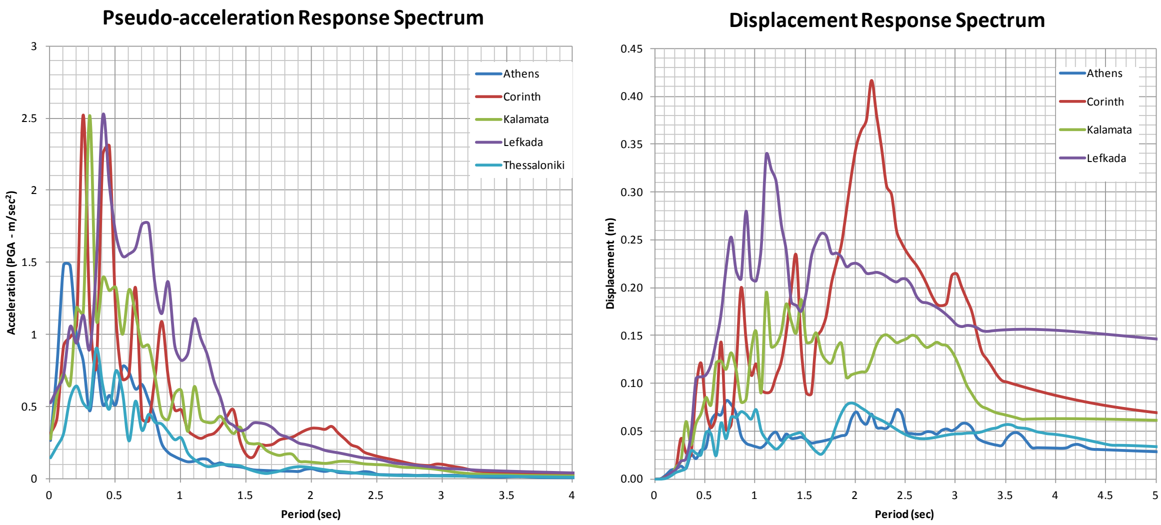

Figure 3. Response Spectra for horizontal components

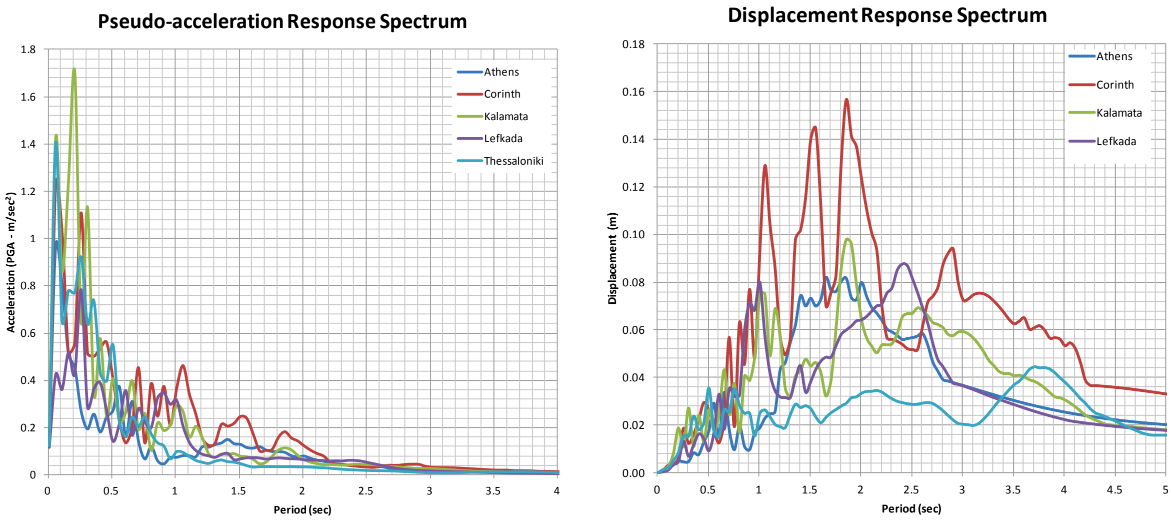

Figure 4. Response Spectra for vertical components

The columns analyzed (Figure 5) have a total width of *1 m,* a height of *6 m* and divided into four drums. The coefficient of friction that is used for the analyses is set to $\mu = 0.485$. A contact stiffness of the order of 10^8 N/m^2 and a damping coefficient of 10^3 $N\,s/m$ are used in the simulations. The time step Δt was selected to be of the order of 10^{-6}.

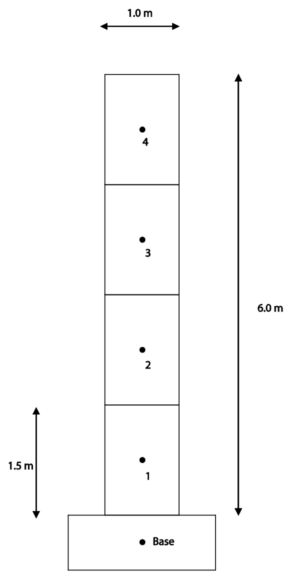

Figure 5. Dimensions of the analyzed column

3. ANALYSES RESULTS

A number of parametric studies is performed in order to investigate the effect of excitation characteristics as well as the influence of the vertical earthquake component on the behaviour and response of multi-drum columns under earthquake excitations. Specifically, a set of analyses is performed for each earthquake excitation (Table 3.1), with and without the vertical acceleration of the ground motion recording.

A comparison is made between the occurring of sliding and rocking of the drums, aiming at understanding how the vertical acceleration may influence the dominance of either of the two phenomena. In the parametric studies the sum of the overall sliding of the drums of a column is defined as “Total sliding” and measured in centimetres. “Total rocking”' is defined as the average absolute rotation of the drums measured in radians.

For each of the selected earthquakes, two analyses are computed, one including only the horizontal earthquake component and a separate analysis combining both the horizontal and vertical components simultaneously. The earthquake ground motions used were not scaled or modified. In all of the analyses performed no overturning or collapsing has been computed. Figure 6 shows snapshots of the response of the analyzed column for the horizontal acceleration of the Corinth earthquake. Figure 7 to Figure 11 show the “Total sliding” and “Total rocking” of the performed analyses at each time step, for the Athens, Corinth, Kalamata, Lefkada and Thessaloniki earthquake, respectively.

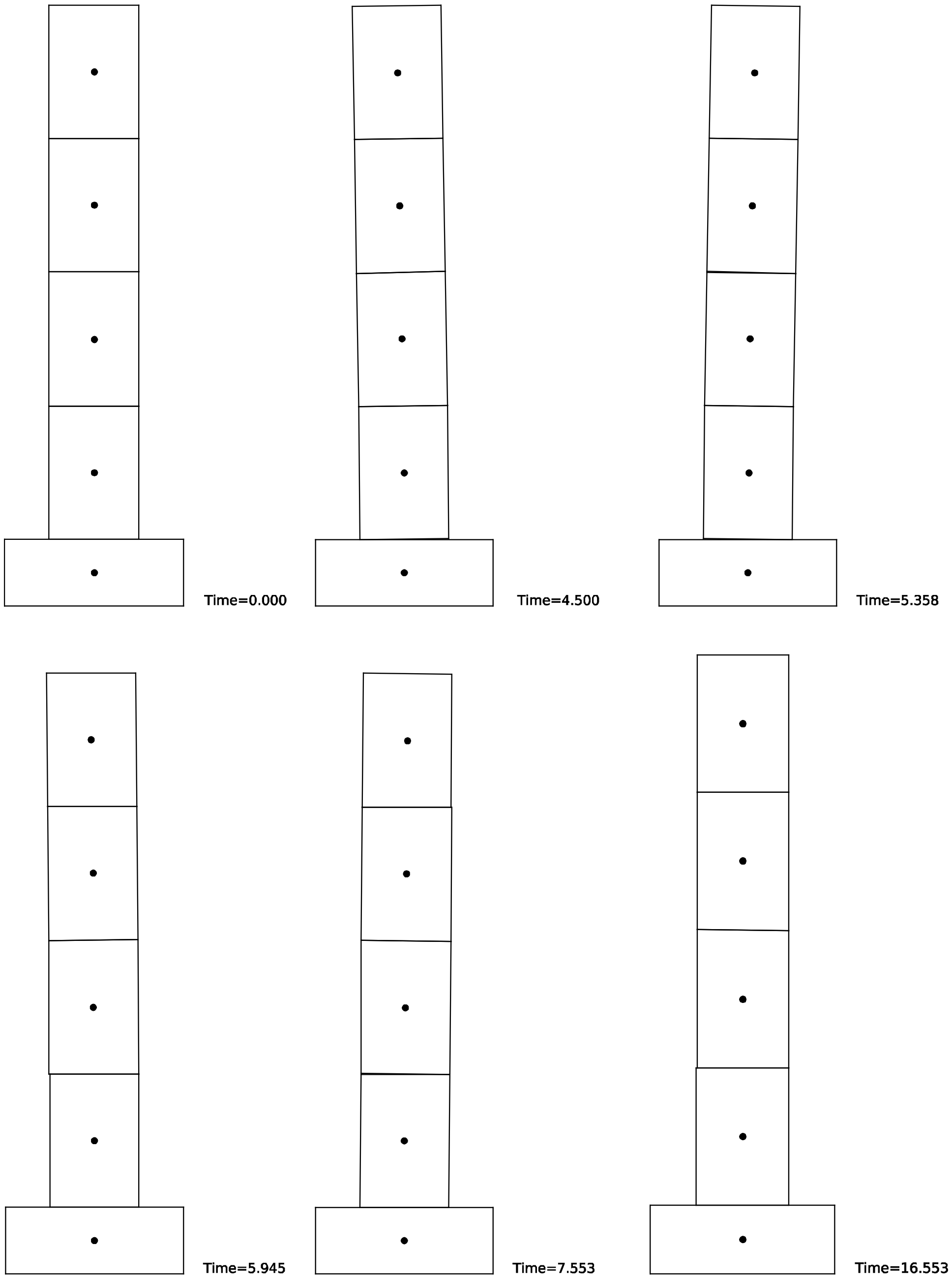

Figure 6. Response for the Corinth earthquake (horizontal component only)

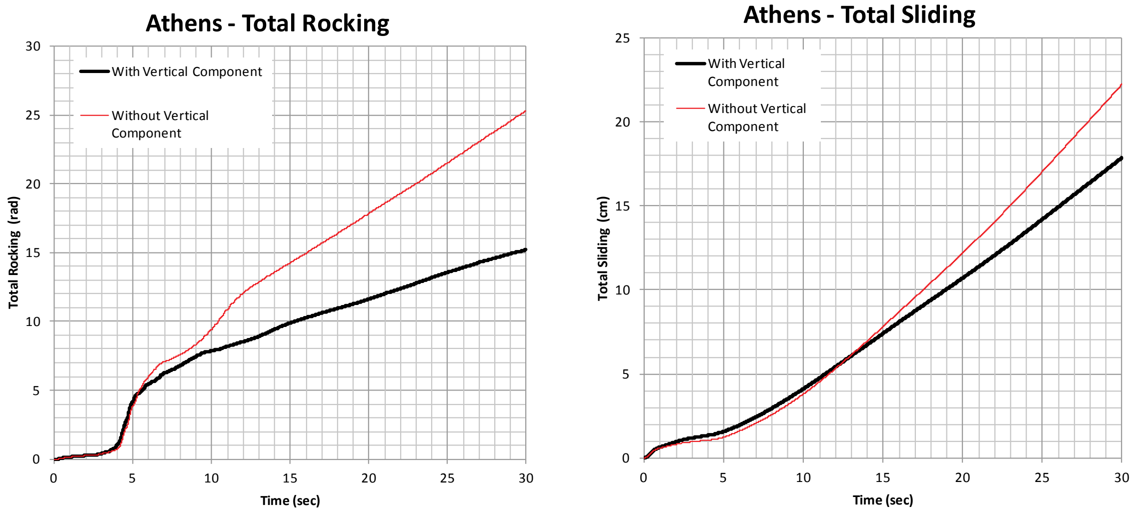

Figure 7. Total Rocking and Total Sliding for the Athens earthquake response

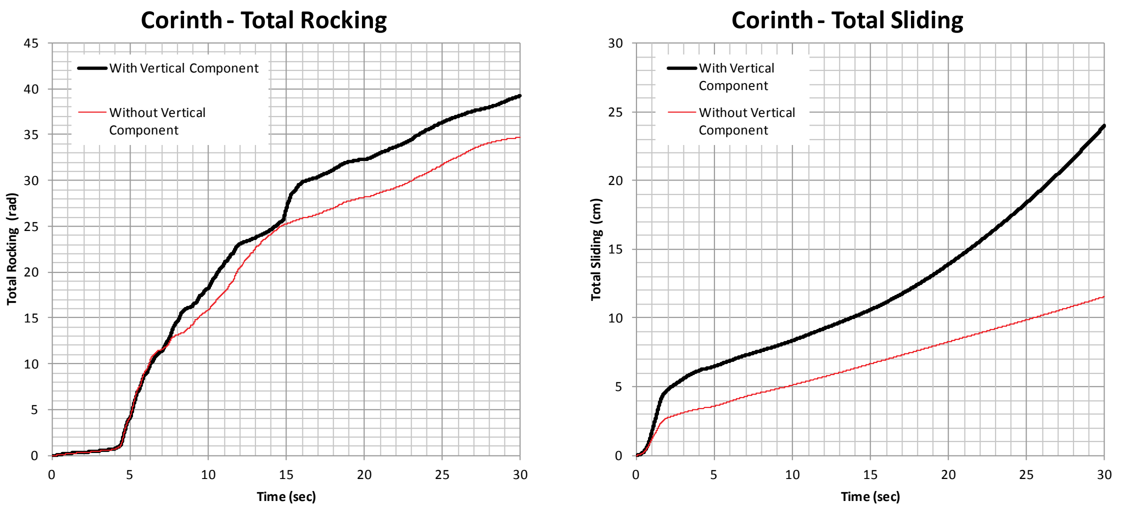

Figure 8. Total Rocking and Total Sliding for the Corinth earthquake response

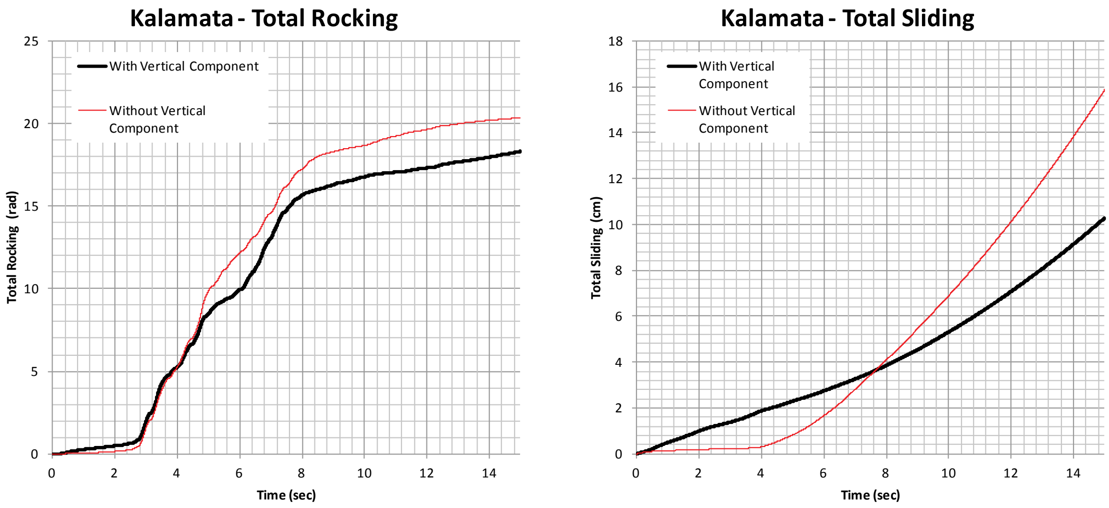

Figure 9. Total Rocking and Total Sliding for the Kalamata earthquake response

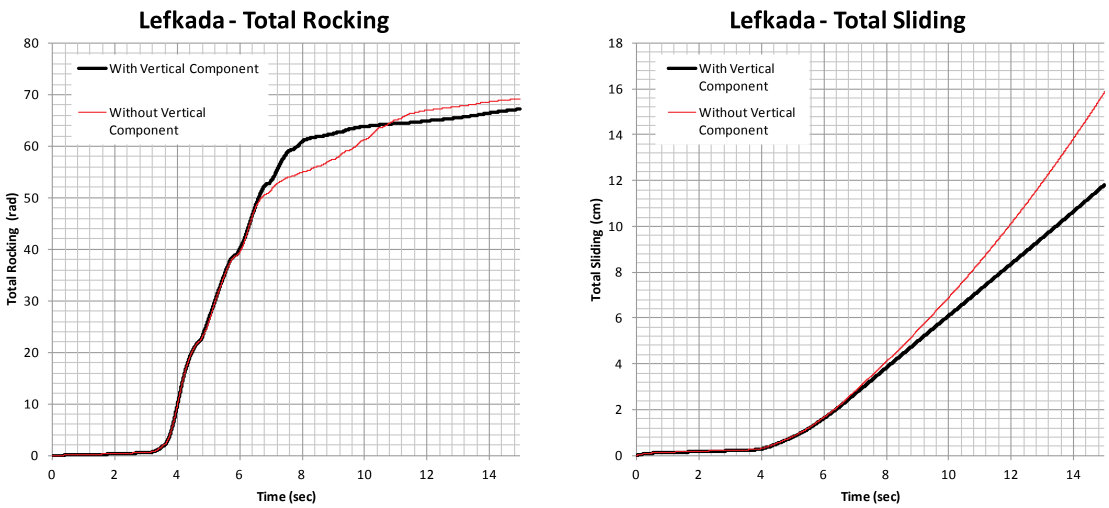

Figure 10. Total Rocking and Total Sliding for the Lefkada earthquake response

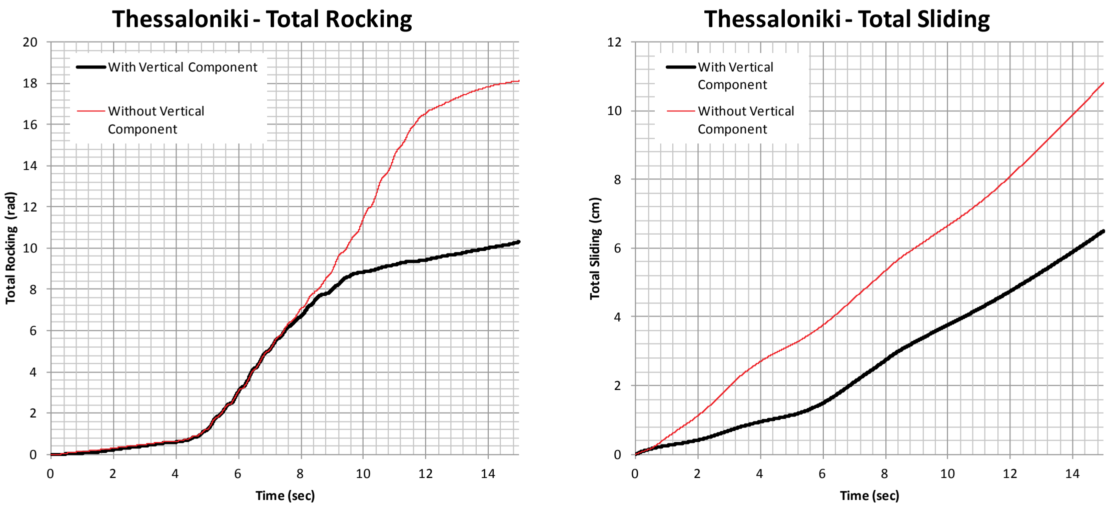

Figure 11. Total Rocking and Total Sliding for the Thessaloniki earthquake response

For the selected excitations and the specific multi-drum columns analyzed, the results (Figure 7 to Figure 11) show that the columns withstand the horizontal ground motions without overturning or collapsing. This is also observed for the analyses including both the vertical and horizontal acceleration. In addition, the vertical acceleration significantly affects the overall response of the column, where in most cases the “Total rocking” as well as the “Total sliding” is reduced, increasing in this way the stability of the column. This however is not the case for the Corinth earthquake, where the exact opposite occurs. This fact may comply with the fact that the Corinth earthquake components, both the vertical and the horizontal, have the largest displacements through a large range of periods in the displacement response spectra (Figure 3 and Figure 4).

5. CONCLUSIONS

The analysis results indicate that the frequency and the peak ground acceleration of seismic excitation, significantly affect the seismic response of multi-drum columns. Specifically, the columns exhibit an extremely non-linear response that is sensitive to both the horizontal as well as the vertical acceleration of the ground motion. The vertical acceleration significantly affects the response but the final effect does not seem to be systematic. The vertical component seems to affect the contact forces between the rigid blocks and this phenomenon alters the final response of the columns.

By examining the stability of multi-drum columns and colonnades for earthquakes that were selected from the Greek region, where these monuments are often built, the simulations show that these multi-drum structures have the capacity to successfully withstand strong earthquakes. Neither the horizontal acceleration of the earthquakes nor the combined action of both the horizontal and vertical accelerations, seem to endanger the specific structures that have been analyzed.

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REFERENCES

Ambraseys N. and Psycharis I.N, (2012) Earthquake Stability of Columns and Statues, Journal of Earthquake Engineering, **15:5**, 685-710

Beskos D. (1993), “Use of finite and boundary elements in the analysis of monuments and special structures”, Association of Civil Engineers of Greece, 217.

Caputo, R., Hinzen, K.-G., Liberatore, D., Schreiber, S., Helly, B., Tziafalias, A., (2011), “Quantitative archaeoseismological investigation of the Great Theatre of Larissa, Greece “Bulletin of Earthquake Engineering. **9 (2)**, 347-366.

Dimitri R., De Lorenzis L., Zavarise G., (2011) Numerical study on the dynamic behavior of masonry columns and arches on buttresses with the discrete element method, Engineering Structures, **33**, 3172–3188

Hinzen, K.-G., Fleischer, C., Reamer, S.K., Schreiber, S., Schütte, S., Yerli, B., (2010), “Quantitative methods in archaeoseismology” Quaternary International, **242**, 31-41

Housner G.W (1963), ‘The behavior of inverted pendulum structures during earthquakes”. Bulletin of seismological Society of America, **53**, 403-417.

Komodromos P., Papaloizou L., Polycarpou P., (2008) “Simulation of the response of ancient columns under harmonic and earthquake excitations”, Engineering Structures **30(8)**, 2154-2164.

Makris N. and Zhang J., (2001) “Rocking response of anchored blocks under pulse-type motions”, Engineering Mechanics **127**, 484-493.

Manos G.C., Demosthenous M., Kourtides V., Hatzigeorgiou A., (2001) “Dynamic and earthquake behavior of models of ancient columns and colonnades with or without energy absorbtions systems”, Proceedings of Second Greek National Conference on Earthquake Engineering and Seismology, **1**, 257-276.

Mouzakis H., Psycharis I., Papastamatiou D., Carydis P., Papantonopoulos C., and Zambas C., (2002). “Experimental investigation of the earthquake response of a model of a marble classical column”, Earthquake Engineering and Structural Dynamics **31**, 1681-1698.

Papaloizou, L., Komodromos, P., (2012) “Investigating the seismic response of ancient multi-drum colonnades with two rows of columns using an object-oriented designed software”, Advances in Engineering Software, **44 (1)** , 136-149.

Papantonopoulos C., Psycharis I., Papastamatiou D., Lemos J. and Mouzakis H., (2002). “Numerical prediction of the earthquake response of classical columns using the distinct element method”, Earthquake Engineering and Structural Dynamics **31**, 1699-1717.

Pompei A., Scalia A. and Sumbatyan M.A. (1998), “Dynamics of Rigid Block due to Horizontal Ground Motion”, Engineering Mechanics **124**, 713-717.

Psycharis I., Lemos J., Papastamatiou D., Zambas C. and Papantonopoulos C. (2003), “Numerical study of the seismic behaviour of a part of the Parthenon Pronaos”, Earthquake Engineering & Structural Dynamics **32**, 2063-2084.

Stefanou I., Vardoulakis I. and Mavraganis A. (2011), Dynamic motion of a conical frustum over a rough horizontal plane, InternationalJournalofNon-LinearMechanics, **46**, 114–124.

Stefanou I, Psycharis I., Georgopoulos I., (2011) Dynamic response of reinforced masonry columns in classical monuments, Construction and Building Materials, **25**, 4325-4337.

Yim C., Chopra A., Penzien J., (1980), Rocking response of rigid blocks to earthquakes, Earthquake engineering and structural dynamics, **8**, 565-587.