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THE EFFECT OF MULTIPLE EARTHQUAKE EXCITATIONS IN SEQUENCE ON ANCIENT MULTI-DRUM STRUCTURES

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Abstract. *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. Multi-drum columns are constructed of stone blocks that are placed on top of each other, often 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.*

The investigation of the dynamic response of such monumental structures, combined with the research fields of paleoseismology and archaeoseismology, may reveal certain information from past strong earthquakes that have struck the respective regions. Studying multi-drum structures under different earthquake excitations can provide some insights in defining the frequency content and magnitude of past destructive earthquakes. Furthermore, the understanding of the seismic behaviour of these structures can contribute to the rational assessment for their structural rehabilitation. Multi-drum classical columns 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.

This research work investigates how multiple earthquake excitations in sequence affect the overall seismic behaviour of multi-drum columns. Specifically, various strong motion excitations are selected from a specific region where these monuments are built, and used in series for the computation of the collective final deformation of multi-drum columns. In order to calculate this cumulative deformation for the series of motions, the individual deformation of the column for each excitation is computed and then used as initial conditions for the next earthquake. For this procedure, the Discrete Element Method (DEM) is utilized by simulating the individual rock blocks as distinct bodies. A specialized software application is developed, using a modern object-oriented programming language, in order to enable the effective and efficient simulation of multi-drum columns under these conditions.

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, often without any 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 are very rare in modern structures.

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 or parts of 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 the characteristics of past earthquakes that had struck the respective regions.

Figure 1: Multi-drum columns, Jerash, Jordan.

Ancient monuments, compared to modern structures, have been exposed to great numbers of severe seismic events throughout the many centuries of their life spans. Those that survived have successfully withstood a natural seismic testing that lasted for thousands of years. Thus, it is important to understand the mechanisms that allowed them to avoid structural collapse and destruction during very 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.

A very extensive review of the literature on the usage of numerical methods for the analysis of monuments until 1993 was published by Beskos [1]. The dynamic behaviour of infinitely rigid bodies during horizontal excitations was studied by Housner [2], while, later on, other researchers [3-7] 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 exhibited promising results, motivating further exploitation of this method. Recent research work based on commercial general-purpose DEM software applications [3,8], demonstrated that the DEM can be reliably used for the analysis of such structures, although a sensitivity of the response to small perturbations of the characteristics of the structure or the excitation has been reported. However, similar sensitivity has also been observed in experiments with classical columns [9]. 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 [10], 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 [11,12] investigate the damage in ancient monument structures and propose various quantitative models to test the seismogenic hypothesis of observed damage. Papaloizou and Komodromos [13] 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. [14,15] showed, by using stability analysis, that rocking is unconditionally unstable and that wobbling is the dominant motion for frustums. Furthermore, the authors suggested that the two dimensional analyses should fail to capture wobbling as the out-of-plane motion is ignored. Dimitri et al. [16], studied the dynamic behaviour of masonry columns and arches on buttresses with the discrete element method. Ambraseys and Psycharis [17] studied the stability of columns and statues under earthquakes, by investigating various parameters that affect their response. Efraimiadou et al. [18] examined the effect of multiple earthquakes on the collision between adjacent reinforced concrete buildings.

In this research project, a custom-made DEM software has been specifically designed [13] and implemented to enable efficient and effective performance of large numbers of numerical simulations with varying parameters, modelling these structures with independent distinct bodies, as they are actually constructed in practice. Such numerical 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, [13]) is appropriately extended to take into account the vertical component of the excitation. For the extension of the software application modern object-oriented design and programming is used, in combination with the Discrete Element Method (DEM), in order to include the vertical earthquake component.

Specifically, the interactions between two bodies in contact are created in DEM whenever a 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 can be 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 generated, in the normal and tangential directions, to estimate the contact forces that should be applied to the bodies in contact. 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, which are numerically integrated using the Central Difference Method (CDM) in order to compute the displacements at the next time step.

3 NUMERICAL ANALYSES

Two different types of single standing multi-drum columns are analyzed with the same overall dimensions but with different numbers of drums. Each set of columns analyzed (Figure 2) has a total width of *1 m* and a total height of *6 m*, divided into two and four drums, respectively. 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 is selected to be of the order of 10^{-6}.

The columns are examined with horizontal earthquake ground motions selected from regions, where these monuments are often built, such as the Greek region (Table 1). The earthquakes selected have a similar Peak Ground Acceleration (PGA) but significantly different frequency content. Furthermore, the earthquakes have been selected so that they do not overturn the columns analyzed. The response spectra of the horizontal earthquake ground motions are presented in Figure 3, whereas the motion characteristics are shown in Figure 4.

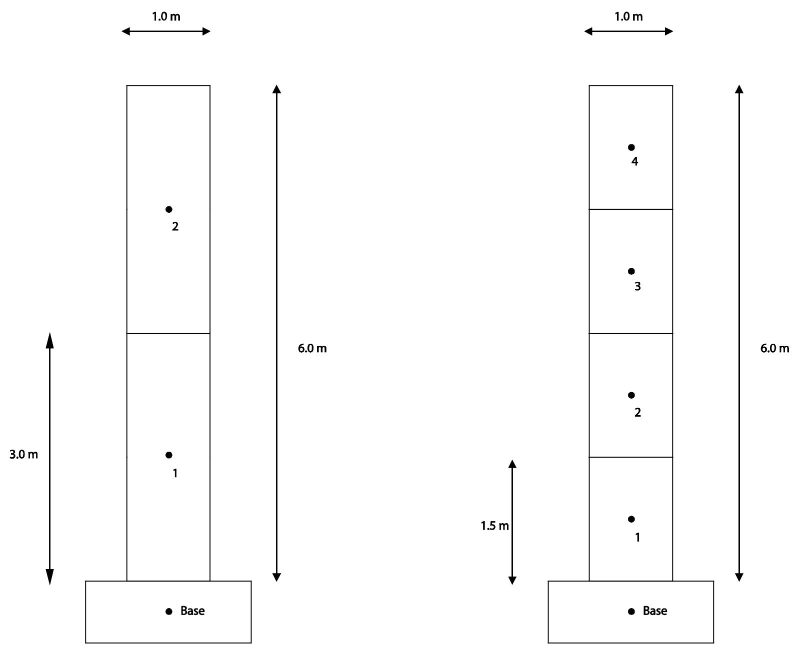


Figure 2: Dimensions of the analyzed columns.

No.	Place	Date and Time	Earthquake Component	PGA *(m/sec²)*
1	Athens, Greece	11:56:50, SEPTEMBER 7, 1999	KALLITHEA DISTRICT N46	2.602
2	Kalamata, Greece	17:24:31, SEPTEMBER 13, 1986	KALAMATA OTE-BUILDING N10W	2.671

Table 1: List of earthquake records that are used in the analyses.

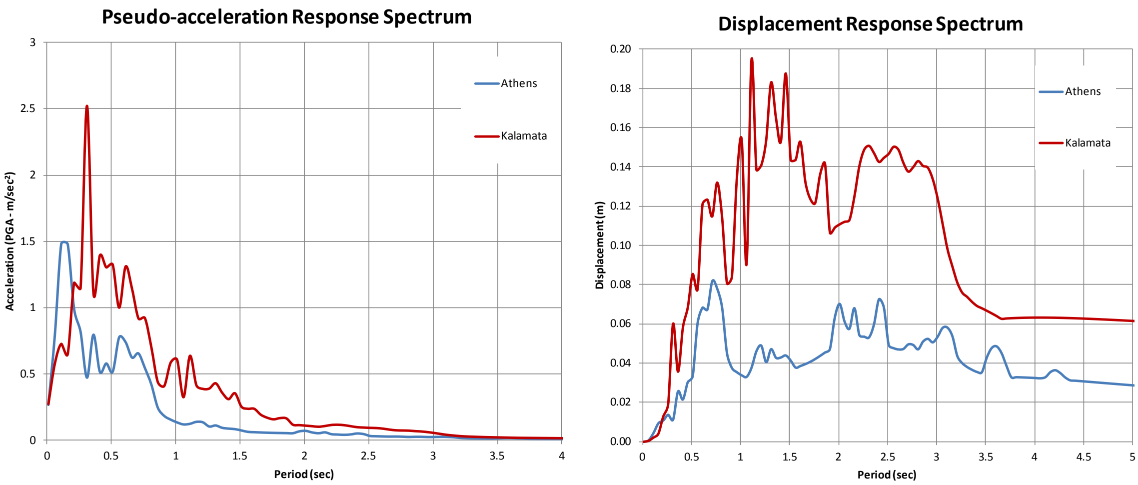
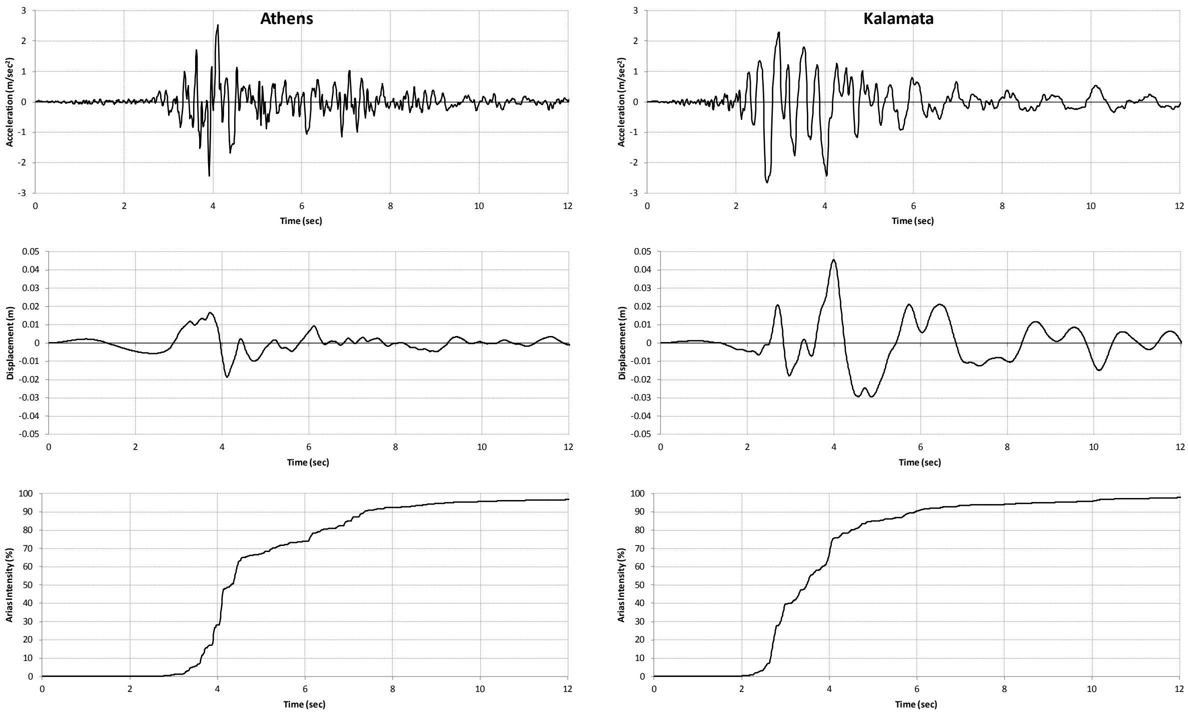


Figure 3: Response Spectra for horizontal components.



(a) (b)

Figure 4: Acceleration, Displacement and Arias Intensity for the Athens (a) and Kalamata (b) earthquake.

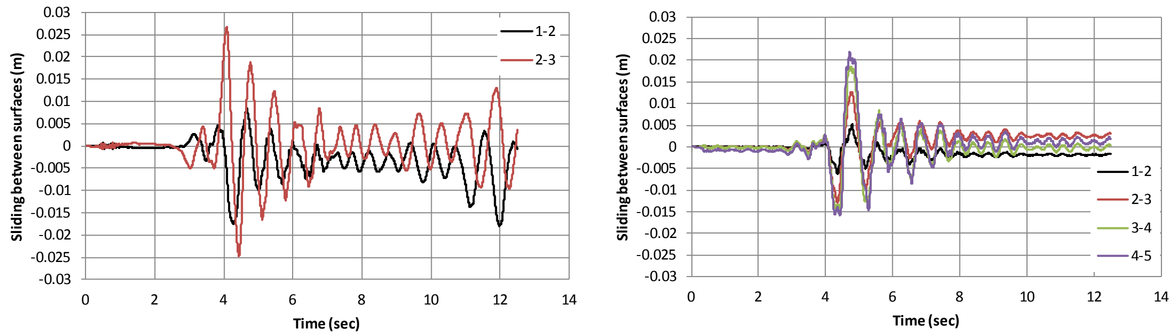
4 ANALYSES RESULTS

A number of parametric studies is performed in order to investigate the collective response of multi-drum columns under a series of strong motion excitations. The two columns previously described (Figure 2) are initially analyzed under the aforementioned Athens and Kalamata earthquake excitations.

The strong motion excitations are then applied repeatedly in series, for the computation of the collective final deformation of the columns. In order to calculate this cumulative deformation for the series of motions, the individual deformation of the column for each excitation is computed and then used as initial conditions for the simulation under the following earthquake excitation.

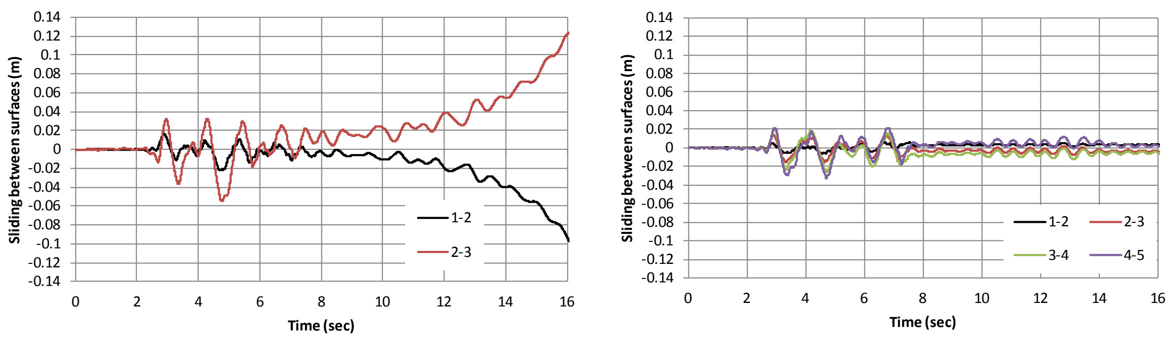
4.1 Single earthquake analyses

Figure 5 and Figure 6 show the horizontal sliding between surfaces for a two-drum column and a four-drum column under the Athens and Kalamata earthquakes, respectively. The results demonstrate that for both excitations a four-drum column seems to be more stable than a two-drum column. Furthermore, the horizontal sliding between the surfaces of the drums is larger for the Kalamata earthquake than for the Athens earthquake.



(a) (b)

Figure 5: Horizontal sliding between surfaces for a two-drum column (a) and a four-drum column (b) under the Athens earthquake.



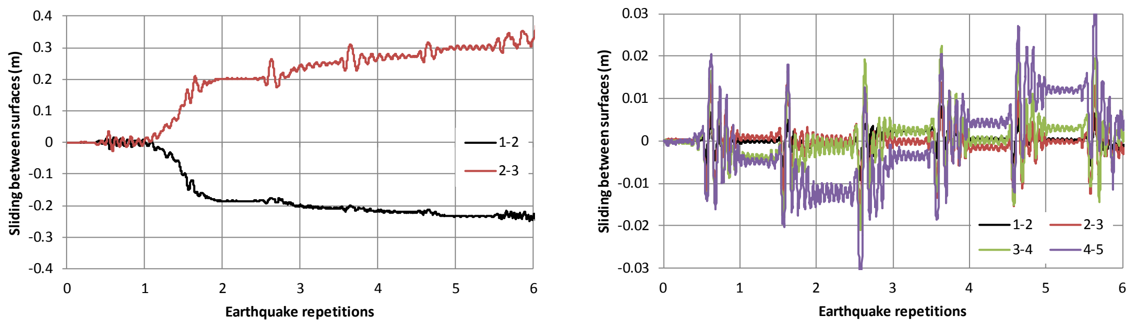
(a) (b)

Figure 6: Horizontal sliding between surfaces for a two-drum column (a) and a four-drum column (b) under the Kalamata earthquake.

4.2 Analyses under earthquakes in series

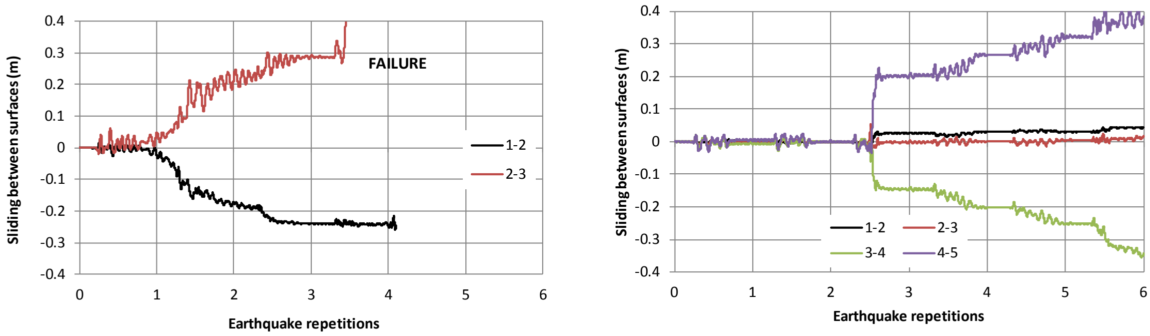
Figure 7 and Figure 8 show the horizontal sliding between surfaces for a two-drum column and a four-drum column under a series of repetitions of the Athens and Kalamata earthquake, respectively. The results show that for both series of excitations a four-drum column seems to be more stable than a two-drum column. In addition, the horizontal sliding between the surfaces of the drums is larger for the Kalamata earthquake, which has almost the same PGA with the Athens earthquake but different frequency content.

The analyses indicate that the cumulative deformation of the columns increases with each recurrence of the earthquake, with a failure occurring for the two-drum column under the Kalamata earthquake series (Figure 8a). Figure 9 shows snapshots of the deformations of a two-drum column under a repeated series of the Kalamata earthquake as well as the horizontal sliding between the drum surfaces. These snapshots show that the cumulative sliding increases on every recurrence of the earthquake, causing the top drum of the column to overturn before the 4th repetition.



(a) (b)

Figure 7: Horizontal sliding between surfaces for a two-drum column (a) and a four-drum column (b) under a series of repetitions of the Athens earthquake.



(a) (b)

Figure 8: Horizontal sliding between surfaces for a two-drum column (a) and a four-drum column (b) under a series of repetitions of the Kalamata earthquake.

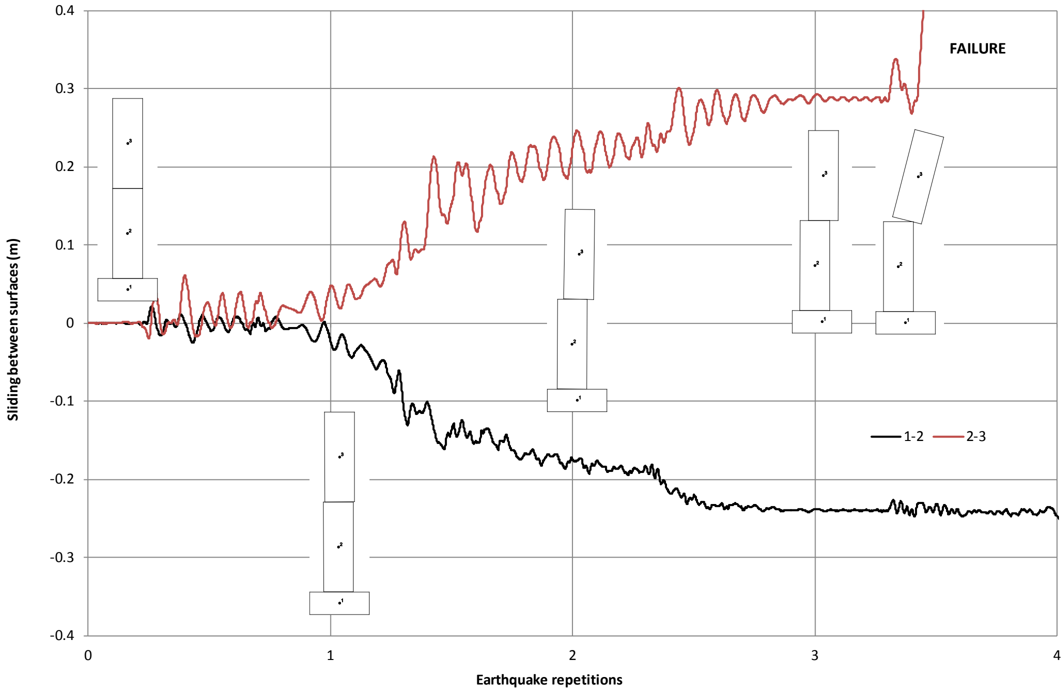


Figure 9: Horizontal sliding between surfaces and snapshots of the deformation for the two-drum column under a series of repetitions of the Kalamata earthquake.

5 CONCLUSIONS

The analysis results indicate that the frequency of seismic excitation, significantly affects the seismic response of multi-drum columns. Specifically, the horizontal sliding between the drums is larger for the Kalamata earthquake, which has lower frequency content than the Athens earthquake. Furthermore, under both excitations the four-drum columns seem to be more stable than the two-drum columns with the same overall dimensions.

By examining the stability of multi-drum columns for earthquakes that have been 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 a single strong earthquake motion. However, the simulations results concerning a number of the same excitations applied in series indicate that the cumulative sliding increases on every recurrence of the earthquake, causing in some cases, instability to the multi-drum columns.

REFERENCES

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

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

[3] 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.

[4] Pompei A., Scalia A. and Sumbatyan M.A. (1998), "Dynamics of Rigid Block due to Horizontal Ground Motion", Engineering Mechanics 124, 713-717.

[5] Makris N. and Zhang J., (2001) "Rocking response of anchored blocks under pulse-type motions", Engineering Mechanics 127, 484-493.

[6] 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.

[7] 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.

[8] 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.

[9] 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.

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

[11] Hinzen, K.-G., Fleischer, C., Reamer, S.K., Schreiber, S., Schütte, S., Yerli, B., (2010), "Quantitative methods in archaeoseismology" Quaternary International, 242, 31-41

[12] 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.

[13] 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.

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

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

[16] 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

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

[18] Efraimiadou S., Hatzigeorgiou G.D and Beskos D.E, (2013), Structural pounding between adjacent buildings subjected to strongground motions. Part II: the effect of multiple earthquakes, Earthquake Engineering & Structural Dynamics, DOI: 10.1002/eqe.2284.