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Earthquake vulnerability of ancient multi-drum columns with a single epistyle

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Abstract

In this research work the seismic behaviour of structures with multi-drum columns under a single epistyle is investigated. In particular, the Discrete Element Method (DEM) is applied in the study of ancient columns undergoing strong ground excitations, by simulating the individual rock blocks as distinct bodies. A specialized software application is developed and utilized, using a modern object-oriented programming language, in order to enable the effective simulation of multi-drum columns and colonnades. Parametric studies are implemented in order to investigate the effect of excitation characteristics on the behaviour of multi-drum columns under earthquake excitations.

The analysis results indicate that the frequency and peak ground acceleration of an excitation, significantly affect the dynamic response of the columns. Particularly, for low frequency ground excitations, the exhibited response is dominated by rocking, while sliding prevails in cases of excitations with very high predominant frequencies. In between the two extremes, the response contains both rocking and sliding phenomena. Furthermore, according to the conducted simulations the acceleration that is needed to overturn multi-drum columns with a single epistyle also increases as the frequency increases.

By examining the stability of multi-drum colonnades with a single epistyle under earthquake excitations that were selected from regions where these monuments are often found, such as the Eastern Mediterranean region, the simulations reveal that the columns have the capacity to withstand strong earthquakes without collapse. In addition, the epistyle seems to be the most vulnerable to failure part of the structure under these loads. Finally, the required acceleration to overturn such a system with a single epistyle seems to decrease as the predominant frequency of the earthquake decreases.

Keywords: DEM; Ancient Columns; Earthquake Engineering; Numerical Methods

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1. Introduction

The preservation of ancient classical columns that can be abundantly found in great numbers in the Eastern Mediterranean areas is of great archaeological significance. Unfortunately, these regions are often exposed to strong earthquakes that are a common cause of destruction of ancient monuments, such as ancient columns. 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 their dynamic response may help us to assess the earthquake vulnerability of such monumental structures.

Different types of columns can be found in various sizes and with many variations of their geometric characteristics. The columns are typically assembled of stone or marble blocks that are placed on top of each other, usually without connecting material between them. Today's remains of such ancient monuments are typically monolithic or multi-drum standalone columns, or series of remaining columns. Figure 1 shows single standalone columns and colonnades with epistyles in Jerash, Jordan. It is very captivating to understand why classical columns and colonnades, which have been exposed to large numbers of very strong earthquakes, throughout their lifetimes, are still standing today. It may also be useful to distinguish the mechanisms that allow them to evade structural collapse and destruction after experiencing several strong earthquakes.

Fig. 1. Columns and colonnades of stone blocks that are placed on top of each other, Jerash, Jordan.

Analytical study of such multi-block structures under strong ground motions is extremely complicated, if not impossible, for more than a couple of distinct blocks. Laboratory experiments are very difficult and costly to perform. For this study, numerical methods are employed to simulate their dynamic responses and evaluate their seismic behaviour.

The dynamic response of rigid blocks is complex even for a single rigid body. Figure 2 shows the response of a rigid body left from an initial inclination angle to oscillate freely. The position of the block at different time increments reveals that the motion involves both rocking and sliding motion.

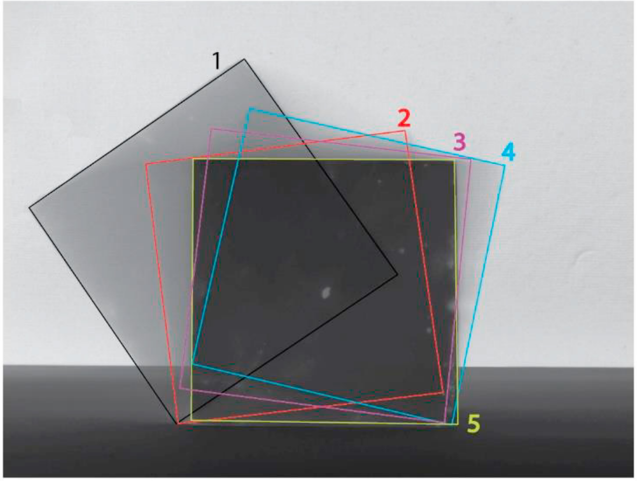

Fig. 2. Motion of a rigid body left to oscillate freely from an initial inclination angle.

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. Research work based on commercial DEM software applications by Psycharis et al. (2003) and 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 by 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.

Latest research studies in the fields of paleoseismology and archaeoseismology by Hinzen et al. (2010) and 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 (2011) 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. Papaloizou et al. (2019) investigated of the effects of multiple sequential earthquake excitations on ancient multi-drum columns.

A custom-made DEM software has been specifically designed (Papaloizou and Komodromos (2011)) 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 us to assess 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 by 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 and results

In order to investigate various parameters that may affect the response of multi-drum colonnade a system with a single epistyle connecting three columns is used in the analyses. The system is analyzed under strong motion excitations. The simulations have been conducted using the developed software application.

Three ground acceleration records from the Athens, Kalamata, and Mexico City earthquakes, which have different characteristics (Table 1), have been selected and used to investigate how the response of these columns under strong seismic motion is influenced by the characteristics of the earthquake excitation. The predominant frequencies of these earthquake records vary from 0.45 to 8.3 *Hz*. Dynamic analyses are performed after scaling the earthquakes appropriately to cause failure to a free-standing column of the same dimensions.

Table 1. List of earthquake records that have been used in the analyses.

Record No.	Date and Time	Earthquake Component	PGA (m/sec^2)	Predominant Frequencies (*Hz*)	Acceleration to overturn (m/sec^2)	Scale Factor
1	9/7/1999 (11:56:50)	ATHENS, Greece (KALLITHEA, N46)	3.01	4.1-8.3	23.4	7.77
2	9/13/1986 (17:24:31)	KALAMATA, Greece (OTE, N10W)	2.67	2.9-3.5	18.7	7.00
3	9/19/1995 (13:19CT)	MEXICO CITY (COMP 270)	0.98	0.45-0.53	2.7	2.76

Figure 3 to Figure 8 show snapshots from the computed time-history responses of multi-drum colonnades with epistyles for the Athens, Kalamata and Mexico City earthquakes, scaled as described earlier. For columns with three drums the analyses show that failure appears under the Mexico City Earthquake (scaled), while for the Athens and Kalamata Earthquakes (scaled) no failure has occurred.

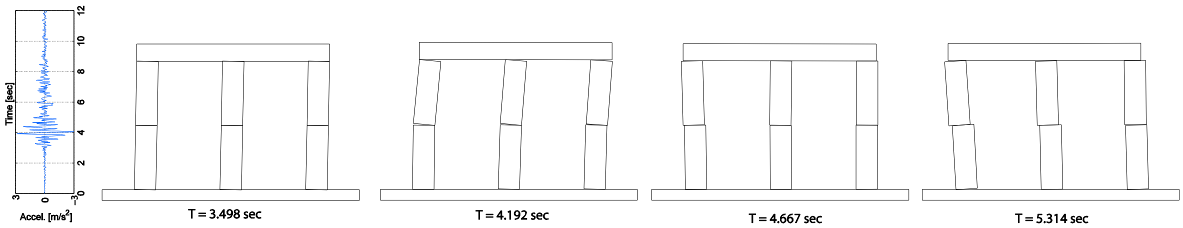

Fig. 3. Time-history response of a colonnade with two drums under an accelerogram from the Athens Earthquake scaled to a PGA of 32.21 m/sec2.

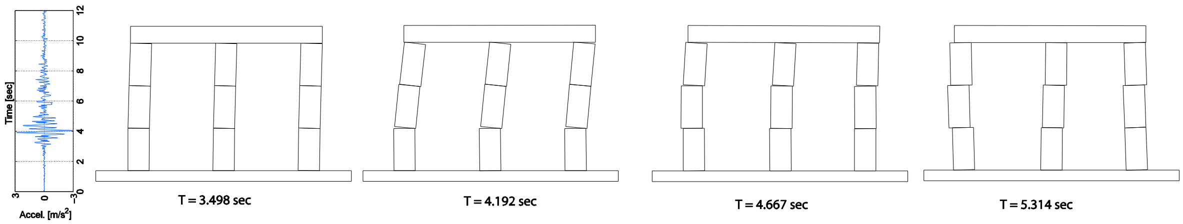

Fig. 4. Time-history response of a colonnade with three drums under an accelerogram from the Athens Earthquake scaled to a PGA of 32.21 m/sec2.

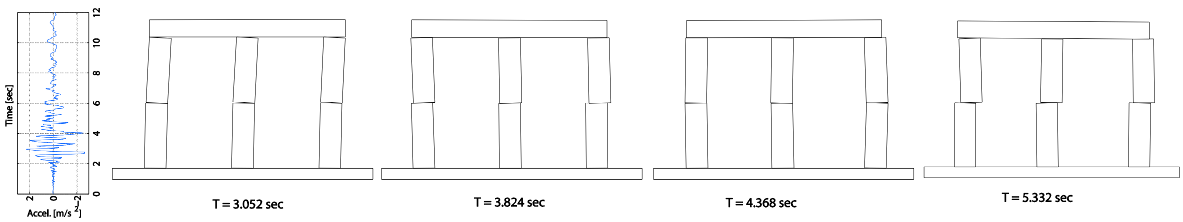

Fig. 5. Time-history response of a colonnade with two drums under an accelerogram from the Kalamata Earthquake scaled to a PGA of 17.35 m/sec2.

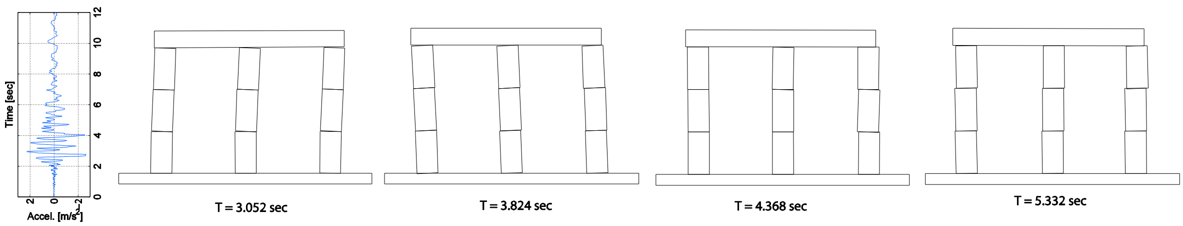

Fig. 6. Time-history response of a colonnade with three drums under an accelerogram from the Kalamata Earthquake scaled to a PGA of 17.35 m/sec2.

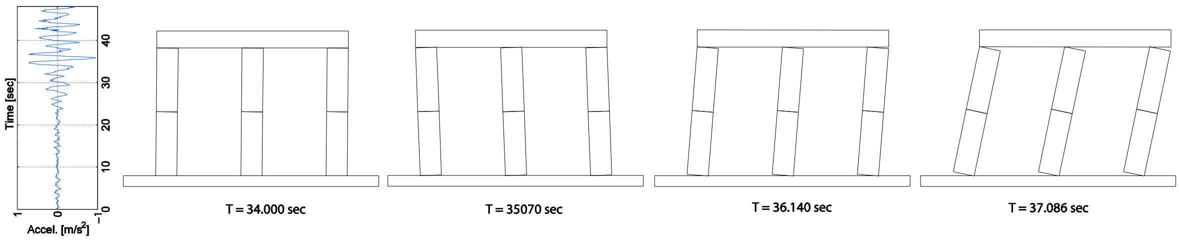

Fig. 7. Time-history response of a colonnade with two drums under an accelerogram from the Mexico City Earthquake scaled to a PGA of 2.45 m/sec2.

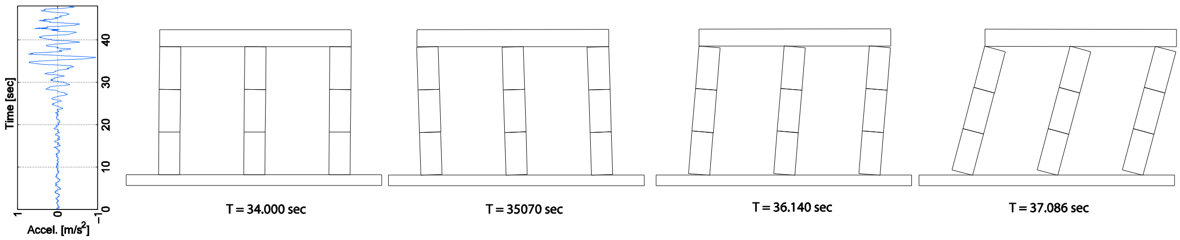

Fig. 8. Time-history response of a colonnade with three drums under an accelerogram from the Mexico City Earthquake scaled to a PGA of 2.45 m/sec2.

For columns with two drums the analyses show that failure appears under the Mexico City and Athens Earthquake (scaled), but not for Kalamata Earthquake (scaled).

4. Conclusions

The response of multi-drum colonnades with a single epistyle exhibits important similarities with the response of standalone multi-drum columns reported by Komodromos et al. (2008). For earthquakes with higher predominant frequencies, the response contains both sliding and rocking phenomena. For the Mexico City Earthquake, which has lower predominant frequencies, rocking dominates the seismic response. Moreover, earthquakes with relatively low predominant frequencies require lower acceleration to overturn the colonnades than earthquakes with higher predominant frequencies.

As observed in the response of standalone columns, in cases of low predominant frequency earthquakes, like the Mexico City Earthquake, the number of drums that assemble a colonnade does not affect the seismic response of the system, since all of the drums of the columns tend to rotate in a single group, similar to a monolithic column. Therefore, no seismic energy is dissipated at the interfaces between each block, since no sliding occurs between adjacent discrete bodies.

Furthermore, the conducted analyses show that colonnade systems with single epistyles require higher accelerations to overturn than the corresponding standalone columns with the same dimensions and number of drums Komodromos et al. (2008).

Additionally, by examining the stability of multi-drum colonnades with a single epistyle under earthquake excitations that were selected from regions where these monuments are often found, such as the Eastern Mediterranean region, the simulations reveal that the systems have the capacity to withstand strong earthquakes without collapse. On the other hand, the systems seem to be more vulnerable under earthquakes with very low predominant frequencies. The epistyle seems to be the part of the structure with the most risk of failure under these loads.

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