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BACK-ANALYSIS OF MULTI-DRUM COLUMNS TO ESTIMATE INFORMATION ABOUT PAST EARTHQUAKES

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Summary. Ancient monuments, such as classical columns in high seismicity areas of the Eastern Mediterranean, exhibit complex seismic behaviours, including rocking and sliding, which can provide insights into past earthquakes. Using the Discrete Element Method (DEM), the researchers have found that multi-drum columns can reveal information about the peak ground acceleration (PGA) of past earthquakes, particularly when the dominant frequency is low and the failure mode mainly involves rocking motion.

1 INTRODUCTION

Strong earthquakes frequently cause the destruction of ancient monuments, including classical columns and colonnades. These ancient classical columns, which hold significant archaeological value, are commonly found in high seismicity regions of the Eastern Mediterranean. Multi-drum columns are constructed from stone blocks stacked on top of each other, sometimes with connecting material between the blocks and sometimes without. The seismic behaviour of these structures involves complex rocking and sliding interactions between the individual blocks, which are not typically observed in modern structures.

Today, the remains of many of these temples are often limited to series of columns with an entablature or only an architrave, and in some cases, only standalone columns (Figure 1). Investigating the seismic behaviour of such monuments is scientifically intriguing due to the complex rocking and sliding responses of the individual stone blocks. Understanding this seismic behaviour is crucial for assessing their structural rehabilitation and may also provide insights into past earthquakes that affected the region.

Compared to modern structures, ancient monuments have been exposed to numerous strong seismic events over their long lifespans. Those that have survived have undergone a natural seismic testing process lasting several centuries. Therefore, it is important to understand the mechanisms that have enabled these structures to avoid collapse and destruction during strong earthquakes. Given that analytical studies of such multi-block structures under strong earthquake excitations are practically difficult, if not impossible, for large numbers of blocks, and laboratory tests are both challenging and costly, numerical methods can be employed to simulate their seismic response.

Figure 1: Ancient free standalone multi-drum columns (Amathus, Cyprus).

Beskos [1] published an extensive review of the literature on the use of numerical methods for analysing monuments. Housner [4] studied the dynamic behaviour of infinitely rigid bodies during horizontal excitations, and subsequent researchers [15, 14, 6,7, 5] further investigated the conditions required to overturn rigid bodies, both analytically and experimentally. These structures can be simulated using the Discrete Element Method (DEM), which is designed for systems with distinct bodies that move freely and interact through contact forces, efficiently recognizing contacts.

Research using DEM to simulate ancient structures has shown promising results, encouraging further use of this method. Studies using commercial DEM software [15, 13] demonstrated its reliability for analysing such structures, though they noted sensitivity to small perturbations in the structure's characteristics or the excitation. Similar sensitivity has been observed in experiments with classical columns [8]. Therefore, it is important to conduct numerous simulations with varying earthquake characteristics and design parameters to accurately assess and interpret the results.

Research in paleoseismology and archaeoseismology [2, 3] examines damage in ancient monuments and proposes quantitative models to test the seismogenic hypothesis of observed damage. Papaloizou and Komodromos [9] used DEM and a modern object-oriented design approach to simulate multi-drum columns and colonnades under harmonic and earthquake excitations.

A custom-made DEM software, designed by Papaloizou and Komodromos [9, 10], enables efficient performance of numerous numerical simulations with varying parameters, modelling these structures as independent distinct bodies, as constructed in practice. These simulations help assess the influence of different earthquake characteristics and various mechanical and geometrical parameters on the seismic responses of these structures.

2 NUMERICAL ANALYSES

Multi-drum columns with different numbers of drums are examined in numerical analyses that have been performed using the developed software, to examine the influence of the frequency content and the Peak Ground Acceleration (PGA) of earthquake excitations. The analysed columns have a total width (b) of 0.9 m, a height (h) of 5.5 m and various combinations of the number of drums of each column. Several analyses are performed with records shown in Table 1 scaled to cause collapse to the respective column analysed [12]. It is assumed that the drums are placed on each other with no other connection between them.

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

Earthquake Component	Date and Time	PGA (*m/sec*^{2})	Predominant Frequencies (*Hz*)
ATHENS, Greece (KALLITHEA, N46)	9/7/1999 (11:56:50)	3.01	4.1-8.3
KALAMATA, Greece (OTE, N10W)	9/13/1986 (17:24:31)	2.67	2.9-3.5
MEXICO CITY (COMP 270)	9/19/1995 (13:19CT)	0.98	0.45-0.53

Figures 2 to 7 show time-history snapshots of the computed responses of multi-drum columns with either two or three drums for the Athens, Kalamata and Mexico City earthquakes, respectively, scaled appropriately to cause failure.

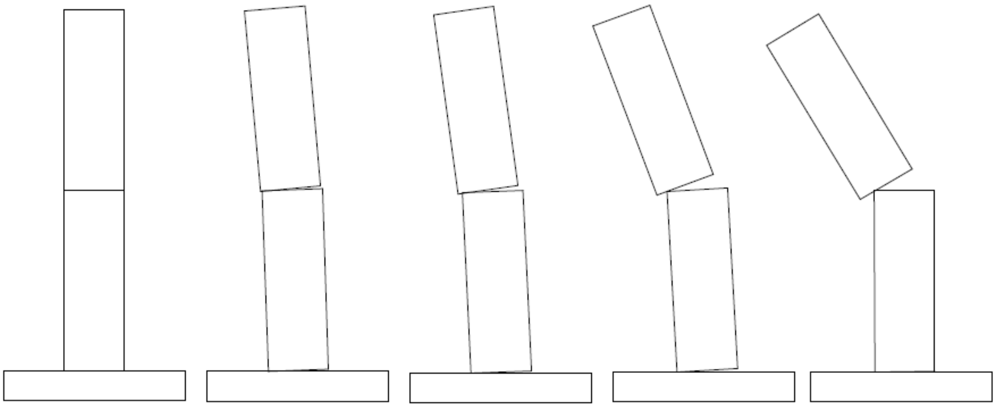

Figure 2: Time-history snapshots of the response of a two-drum standalone column under the record from the Athens Earthquake scaled to a PGA of 25.9 m/sec^2.

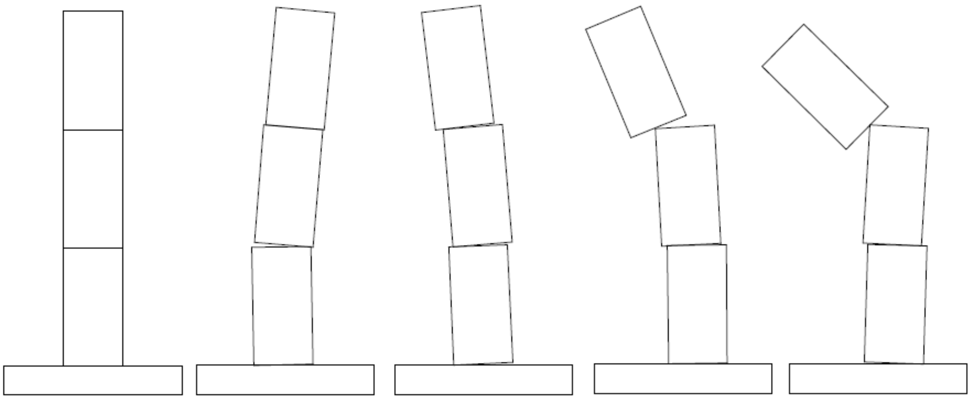

Figure 3: Time-history snapshots of the response of a three-drum standalone column under the record from the Athens Earthquake scaled to a PGA of 25.9 m/sec^2.

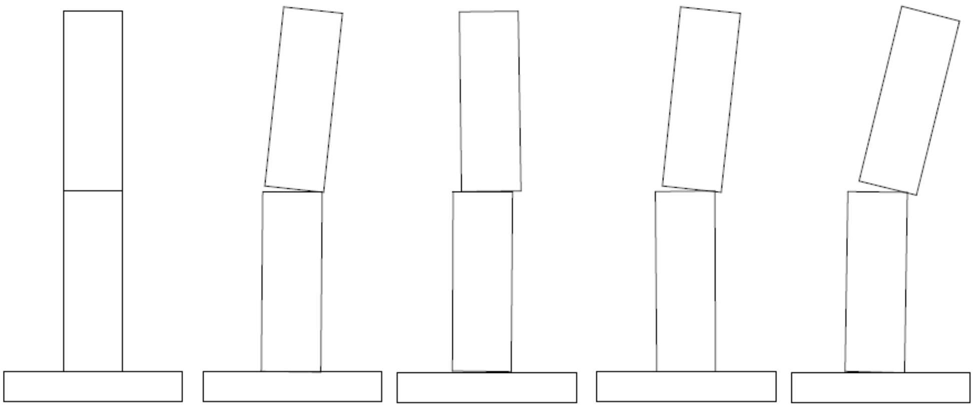

Figure 4: Time-history snapshots of the response of a two-drum standalone column under the record from the Kalamata Earthquake scaled to a PGA of 9.2 m/sec^2.

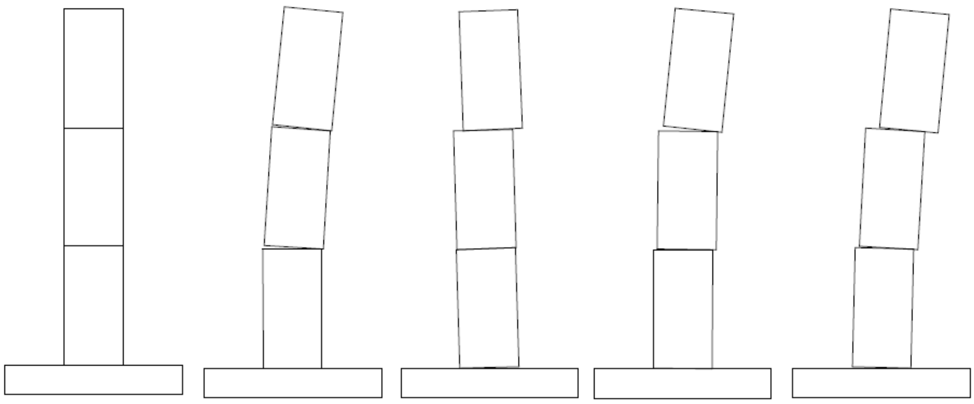

Figure 5: Time-history snapshots of the response of a three-drum standalone column under the record from the Kalamata Earthquake scaled to a PGA of 9.2 m/sec^2.

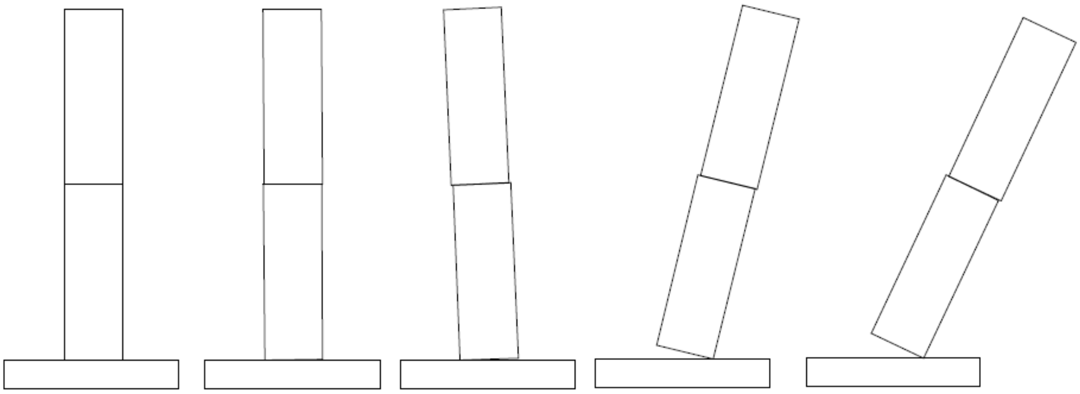

Figure 6: Time-history snapshots of the response of a two-drum standalone column under the record from the Mexico City Earthquake scaled to a PGA of 1.4 m/sec^2.

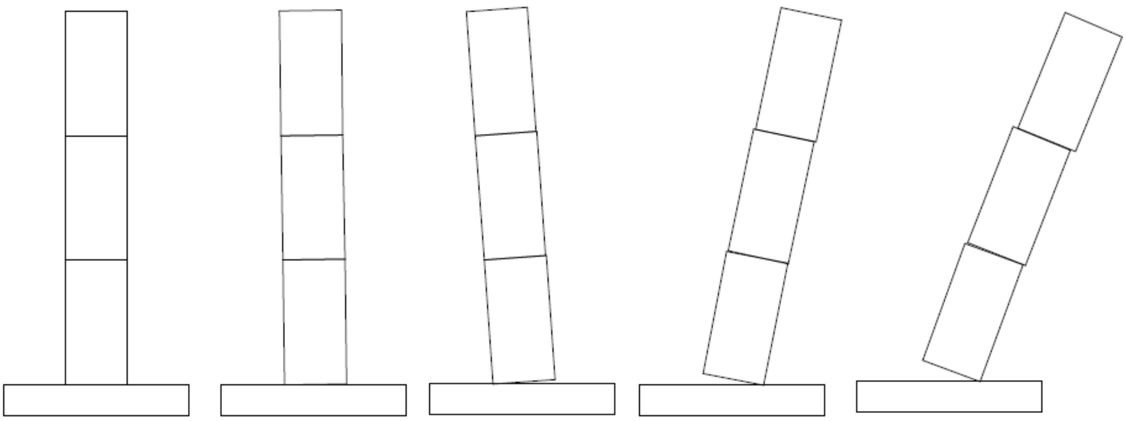

Figure 7: Time-history snapshots of the response of a three-drum standalone column under the record from the Mexico City Earthquake scaled to a PGA of 1.4 m/sec^2.

For the Athens and Kalamata earthquakes, which have high predominant frequencies, the response is highly complex, involving both sliding and rocking. This complexity is evident in Figures 2 to 5, where the drums both slide away from each other and rock. In contrast, the Mexico City Earthquake (Figures 6 and 7) is dominated by rocking, with all drums of the column rotating as a single group, like the behaviour of a monolithic column under similar frequencies [5, 11, 12]. In such cases the energy dissipation mechanisms between drums due to relative sliding are not activated.

The results also suggest that the number of drums in a column affects the overall response when both sliding and rocking phenomena occur during earthquakes with higher predominant frequencies. This effect is not observed for the Mexico City Earthquake, which has low dominant frequencies (Figures 6 and 7).

Additionally, the simulations show that the Mexico City Earthquake, with its relatively low predominant frequencies, requires much lower acceleration to overturn the column compared to the Athens Earthquake, which has much higher predominant frequencies. The peak ground acceleration (PGA) needed to overturn columns during earthquakes with low predominant frequencies, like the Mexico City Earthquake, is comparable in magnitude to the acceleration required to initiate rocking and overturning of a single rigid body, as described by the following equation [11]:

$$\ddot{u}_g = \pm \frac{b}{h} \cdot g = \pm 1.61\ m/sec\hat{}2 \qquad (1)$$

This equation is not applicable to ground motions with higher predominant frequencies, such as those observed in the Athens and Kalamata earthquakes, because of the complex response and the energy dissipation through various mechanisms.

3 CONCLUSIONS

The results indicate that the dominant frequencies of earthquakes significantly influence the acceleration required to overturn columns. The response is similar to that of standalone multi-drum columns, as reported by [5, 11, 12]. Earthquakes with higher predominant frequencies induce both sliding and rocking phenomena, while those with lower predominant frequencies, such as the Mexico City Earthquake, primarily cause rocking. Additionally, earthquakes with lower predominant frequencies require less acceleration to overturn colonnades compared to those with higher frequencies.

Back-analysis of multi-drum columns can be used to estimate information about past earthquakes that affected the region during the structures' lifetimes. The acceleration needed to overturn a multi-drum column can be estimated more accurately when the earthquake's dominant frequency is very low, and the failure mode is primarily governed by the rocking motion of the column as a single body.

Results indicate that ancient multi-drum columns could indeed reveal some information about the PGA of past earthquakes that had struck the respective region given the following assumptions:

- Earthquakes in the region have low predominant frequencies.
- Standalone multi-drum columns were not at the time of failure part of a larger monument.
- There is strong historical evidence that the standalone columns have certainly been destroyed by an earthquake.

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