NUMERICAL ANALYSIS OF ANCIENT MULTI-DRUM COLUMNS WITH EPISTYLES UNDER DYNAMIC LOADINGS

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ABSTRACT :

In this research work, the Discrete Element Methods (DEM) is utilized to investigate the response of ancient multi-drum columns during harmonic and earthquake excitations by simulating the individual rock blocks as distinct rigid bodies. The drums can undergo rocking either individually or in groups resulting in several different and alternating shapes of oscillations. A specialized software application has been developed, using modern object-oriented programming technologies and computer graphics to effectively perform efficient seismic simulations of multi-block structures. The contact stiffness and damping coefficients are estimated by performing small scale experiments and comparing the response with a corresponding numerical simulation. The effect of the coefficient of friction is numerically examined, since its value can significantly influence the overall response. The sliding effect under dynamic loading is examined both experimentally and numerically. Using the developed software, parametric simulations of multi-drum columns are performed in order to investigate and understand the influence of different characteristics of earthquake excitations as well as the various mechanical and geometrical characteristics of these structures on their seismic response. Furthermore, columns with an epistyle are examined under harmonic excitations, in order to assess the influence of the excitation frequency and the number of drums that compose each individual multi-drum column on the dynamic behavior and response of a colonnade.

KEYWORDS: Multi-drum Columns, Earthquake Response, Engineering Software Development

1. INTRODUCTION

High-intensity earthquake excitations have damaged several ancient monuments, such as classical columns and colonnades of great archeological significance, which can be abundantly found in high seismicity areas in the Eastern Mediterranean, such as Greece, Turkey, Italy and Cyprus (Figure 1). Multi-drum columns are constructed of stones that are placed on top of each other, usually without connecting material between the individual blocks. The seismic behavior of these structures exhibits rocking and sliding phenomena between the individual blocks, which very rarely appear in modern structures. Specifically, the drums may rock either individually or in groups resulting in several different shapes of oscillations.

Figure 1. Ancient columns from ancient temples in Limassol, Cyprus.

The understanding of the seismic behavior of ancient columns contributes to the rational assessment of potential proposals for their structural rehabilitation and strengthening, while it may also reveal some information about past earthquakes that had struck the respective region. As ancient monuments 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 extended several centuries. Therefore, it is very useful to understand the mechanisms that allowed them to avoid structural collapse and destruction during several strong earthquakes. Since analytical study of such multi-block structures under strong earthquake excitations is practically impossible for large numbers of blocks, while laboratory tests are very difficult and costly to perform, numerical methods can be used to simulate their dynamic behavior and seismic response.

Beskos [1] published a very extensive review of the literature on the usage of numerical methods for the analysis of monuments until 1993. The dynamic behavior of infinitely rigid bodies during horizontal excitations was studied by Housner [2], who estimated the minimum horizontal acceleration of the support base that is required in order to overturn an infinitely rigid body. Other researchers [3-10] investigated further both analytically and experimentally the overturning of rigid bodies due to ground accelerations.

In this paper, a numerical approach based on actual distinct bodies is employed to computationally investigate the response of these structural systems, aiming to gain a better understanding of their overall structural behavior. Although the Finite Element Methods (FEM) can be used for the analysis of problems with some discontinuities, the FEM are not suitable for the analysis of discontinuous systems that are characterized by continuous changes of the contact conditions among the constituent bodies. On the contrary, Discrete Element Methods (DEM) have been specifically developed for systems with distinct bodies that can move freely in space and interact with each other with contact forces, providing an automatic and efficient recognition of all contacts.

Research efforts to use the DEM in simulations of ancient structures have already shown promising results, indicating a potential for further utilization of this method. Recent research work based on commercial DEM software applications (Papantonopoulos [8], Psycharis [3]), demonstrated that the DEM can be effectively used for the analysis of such structures. However, they have reported a sensitivity of the response to small perturbations of the characteristics of the structure or the excitation, which has also been observed in experiments with classical columns (Mouzakis [9]). Therefore, it is important to have the capability to perform large numbers of simulations with varying earthquake characteristics and design parameters to properly assess and interpret the simulation results in terms of the overall seismic behavior of these structural systems.

A specifically designed DEM software has been implemented using a modern Object-Oriented Programming (OOP) language in order to enable efficient performance of large numbers of numerical simulations with varying parameters. In this simulation environment, the individual rock blocks are modeled using independent distinct bodies, as they are actually constructed. The seismic response of ancient columns is numerically computed in order to assess the influence of different characteristics of earthquake excitations as well as the various mechanical and geometrical parameters of these structures on their seismic behavior.

2. SIMULATION APPROACH

2.1 Discrete Element Methods

The DEM were originally proposed in 1971 for the solution of problems of rock mechanics, using distinct elements to simulate rock masses. In simulations using the DEM, each distinct body has its own geometric boundaries that separate it from all other bodies in the system. The distinct bodies are usually assumed to be infinitely rigid, even though it is possible to consider their deformability in cases where that would be necessary. Contact forces are exerted only between colliding bodies, as soon as a contact between the bodies is detected. The contact interactions between colliding bodies can be due to recently detected contacts, existing contacts, or relative displacements and rotations between bodies already in contact. A distinctive capability of the DEM is the automatic and efficient recognition of contacts between simulated bodies, as well as detachments of bodies that were previously in contact. In this research work, infinitely rigid bodies are used, considering that the overall deformation of such a system is due to the relative displacements and rearrangements of the constituent bodies rather than due to the deformations of the individual bodies.

2.2 Contact interactions and forces

The contact interactions between colliding bodies is an extremely complicated phenomenon that involves stress and strain distributions within the colliding bodies, thermal, acoustical and frictional dissipation of energy due to the contact, as well as plastic deformations. In this work, the contact interactions are modeled using contact springs and dashpots to evaluate the contact forces based on the interpenetrations between bodies in contact. In DEM, the interactions between two bodies in contact are automatically applied, as soon as 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. In order 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 determined at each simulation step. The bodies may slide along the contact plane relatively to each other, whenever the tangential force exceeds the maximum allowable force in that direction.

At any simulation step, when two bodies come in contact, equivalent springs and dashpots are automatically generated, in the normal and tangential directions, so as to estimate the contact forces that must be applied to the bodies to push them apart. During contact some overlapping of the colliding bodies is allowed, which is justified by the deformability at the vicinity of the 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 elastic and damping contact forces in the normal and tangential directions are computed using the following equations, respectively, based on the area of the overlap region and considering the interpenetrations and the relative velocities between the colliding bodies:

$$ {}^{t+\Delta t}F_N = {}^{t+\Delta t}F_N^{elastic} + {}^{t+\Delta t}F_N^{damp} = {}^{t}A_c \cdot K_N + V_N^{rel} \cdot C_N \tag{1} $$

$$ {}^{t+\Delta t}F_T = {}^{t+\Delta t}F_T^{elastic} + {}^{t+\Delta t}F_T^{damp} = {}^{t}F_T^{elastic} + V_T^{rel} \cdot \Delta t \cdot K_T + V_T^{rel} \cdot C_T \tag{2} $$

The indices N and T, in the above equations, indicate the normal and the tangential directions, respectively. K_N and K_T are the stiffness in the normal and tangential directions, respectively, and A_C is the area of the contact region, V_N^{rel}, V_T^{rel}, C_N and C_T are the relative velocities and the damping coefficients in the normal and tangential directions, respectively. Furthermore, the Coulomb friction law is used to limit the tangential contact force, ${}^{t+\Delta t}F_T$, below a certain magnitude taking into account the magnitude of the normal contact force, ${}^{t+\Delta t}F_N$, and the minimum of the coefficients of friction, μ, of the bodies in contact.

$$ \left| {}^{t+\Delta t}F_T \right| \le \left| {}^{t+\Delta t}F_N \cdot \mu \right| \tag{3} $$

2.3 Equations of motion

Taking into account the contact forces, which are applied at contact points during impact, together with the gravity forces, the equations of dynamic equilibrium are formed. The motion of a discrete body at time $t+\Delta t$ is determined from the equations of motion at time t and the known displacements up to that time. The equations of motion are numerically integrated using the Central Difference Method (CDM), in order to compute the displacements at time $t+\Delta t$ from Equations 4 to 6:

$$ U_x\left(t+\Delta t\right) = \frac{\Delta t^2}{m} \cdot \left\{ F_x^{contact} - \frac{m}{\Delta t^2} U_x\left(t-\Delta t\right) + \frac{2m}{\Delta t^2} U_x\left(t\right) \right\} \tag{4} $$

$$U_y\left(t+\Delta t\right)=\frac{\Delta t^2}{m}\cdot\left\{F_y^{contact}+m\cdot g-\frac{m}{\Delta t^2}U_y\left(t-\Delta t\right)+\frac{2m}{\Delta t^2}U_y\left(t\right)\right\} \tag{5}$$

$$\Theta_z\left(t+\Delta t\right)=\frac{\Delta t^2}{I_0}\cdot\left\{M_z^{contact}-\frac{I_0}{\Delta t^2}\Theta_z\left(t-\Delta t\right)+\frac{2I_0}{\Delta t^2}\Theta_z\left(t\right)\right\} \tag{6}$$

U_x, U_y and Θ_z are the displacements at x and y direction and rotation about z axis respectively; F_x, F_y and M_z are the forces in the x and y directions and the moment about z axis, respectively; Δt is the time step, which should be sufficiently small; m and I_0 are the mass and the rotational inertia of the body, respectively. At each time step, after computing the displacements and rotations of all bodies, their new positions are determined and used in the computation of the next time step. A new cycle of contact detection, contact resolution, application of forces and numerical integration of the equations of motion follows, based on the updated positions of the bodies. This iterative procedure iteratively continues until the end of the simulation.

3. SOFTWARE DEVELOPMENT

The DEM software application, which is used in the simulations, was specifically designed and implemented to enable efficient performance of two-dimensional (2D) seismic simulations of multi-block structures, while maintaining the necessary extensibility towards spatial (3D) analysis in the future. Modern OOP and Java technologies have been employed in the software development, taking into account the significant advantages that these technologies offer for engineering simulations. Performing large numbers of dynamic simulations of columns with varying mechanical and geometrical characteristics of drums and columns under the action of various harmonic oscillations and earthquake excitations provides an insight into the behavior of these structures during strong earthquakes. The custom-made software application that has been developed facilitates the specific needs of this work, without being limited to the general capabilities of a commercial general-purpose DEM program.

4. SMALL SCALE EXPERIMENTS AND SOFTWARE VERIFICATION

Numerical simulations of multi-drum columns, using the previously described methodology, showed that the response of these systems is very sensitive to small perturbations of the contact parameters, such as the contact stiffness and damping coefficients. The contact parameters can be determined by performing analyses of problems for which either an analytical solution is known or experimental results are available, in order to properly calibrate the contact parameters to approximately match the expected response. Since analytical solutions are available only for systems with only a couple of bodies under very simplifying assumptions and conditions, in this work small-scale experiments were used as a guidance to estimate the proper values of the contact parameters that are required in the numerical simulations.

Although there is an influence of scale on their dynamic response, small-scale experiments have been conducted, using a “Quanser Shake Table II”, to investigate certain characteristics of the response and validate the developed software (Figure 2.a). The specimen columns were composed of seven individual bodies (48x48x29 mm), with the bottom one fixed on the shake table. The coefficient of friction μ was measured to be equal to 0.68. The weight of each drum was measured to be 135.5 grams. A number of experiments was conducted using up to 2.15 m/s^2 peak ground accelerations, by changing the frequency and amplitude of harmonic excitations, considering one horizontal direction. Snapshots were taken to capture the failure mode at different excitation frequencies. A parallel set of numerical simulations was performed, using the developed software, in order to numerically simulate the small-scale columns of the experiments. The numerical simulations (Figure 2.b) exhibited responses similar to the ones observed experimentally (Figure 2.a).

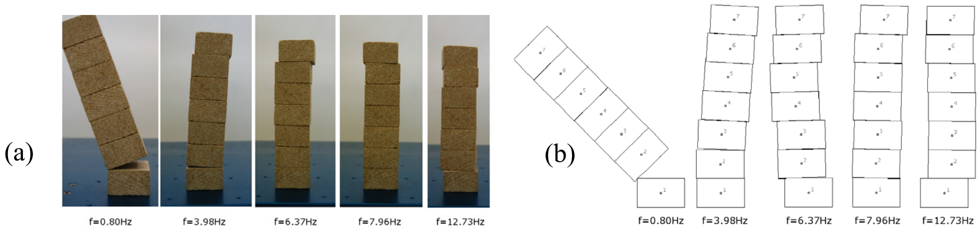

Figure 2. Dynamic response using (a) small-scale experiments (b) numerical simulations.

Small-scale experiments of columns with an epistyle were also conducted (60x60x150 mm, 1140 gr). Specifically, two different cases were investigated where columns of the colonnade were either monolithic (60x60x100 mm, 750 gr) or consisted of two drums (60x60x50 mm, 750 gr).

Firstly, the experiments show (Figure 3) that with the increase of the excitation frequency the required acceleration to initiate either rocking or sliding decreases. Secondly, it is indicated that as the excitation frequency decreases, rocking is more dominant. For extremely low frequencies overturning occurs in the first few excitation cycles. With the increase of the excitation frequency the sliding effect dominates the response without overturning the system. Furthermore, the experiments reveal that energy dissipation through sliding mechanisms improves the overall stability of the system with an epistyle. Colonnades with an epistyle that are constructed with more drums seem to be more stable than monolithic colonnades. It is also observed that for monolithic colonnades, both the required acceleration to initiate rocking or siding, and the acceleration required to overturn the system, are less than those required for columns that are constructed with more drums. Finally, it is observed that for monolithic colonnades, the sliding effect appears in higher frequencies compared to the colonnades that are constructed with more drums.

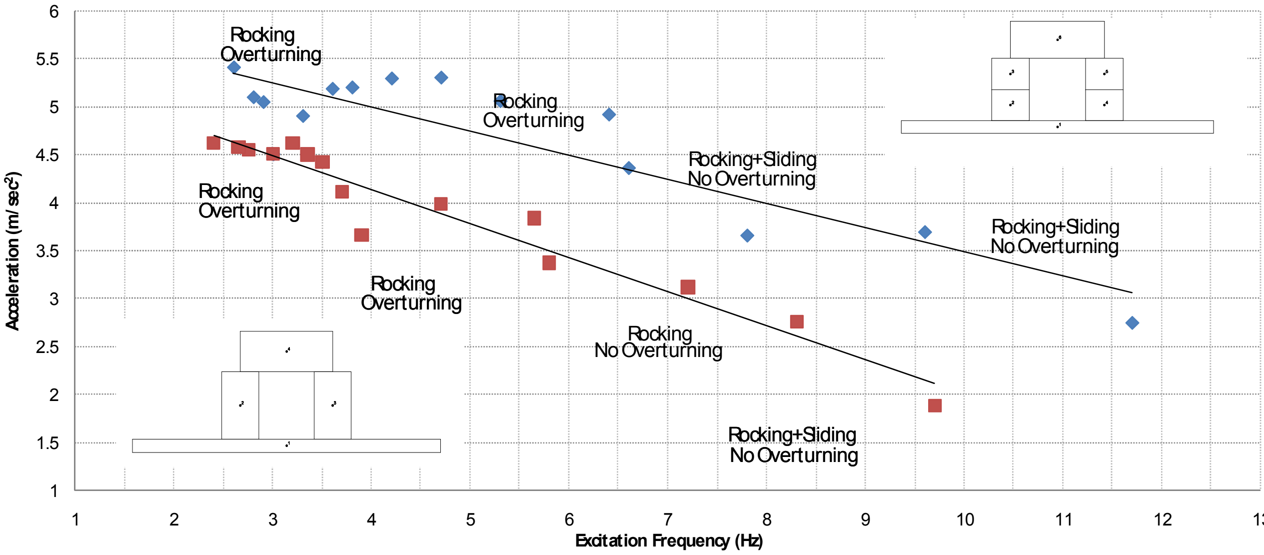

Figure 3. Required base acceleration so that sliding or rocking can occur.

5. INFLUENCE OF ACCELERATION AND FREQUENCY IN HARMONIC EXCITATIONS

A large number of numerical simulations of the small-scale columns was performed to study the influence of the excitation frequency in the total sliding and rocking of the columns. In particular, using a specific peak ground acceleration (2.15 m/sec^2) and three different values for the coefficient of friction, the total sliding and rocking of the simulated columns was measured with respect to the corresponding excitation frequency (Figure 4.a). Furthermore, using a specific coefficient of friction (μ=0.68) and four different values for the magnitude of the peak acceleration of a harmonic ground excitation, the total sliding and rocking of the simulated columns were measured with respect to the corresponding excitation frequency (Figure 4.b).

The numerical simulations exhibited similar responses to the ones observed in the experiments (Figure 2.b). In particular, the results indicate that for low frequencies, rocking is the prevailing failure mode. Increasing the frequency, both sliding and rocking occur, while for very high frequencies only sliding occurs. The computed responses suggest that for higher excitation frequencies, lower accelerations are required to initiate rocking. Conversely, as shown from the parametric analyses (Figure 4.b) the acceleration needed to overturn a column increases as the excitation frequency increases.

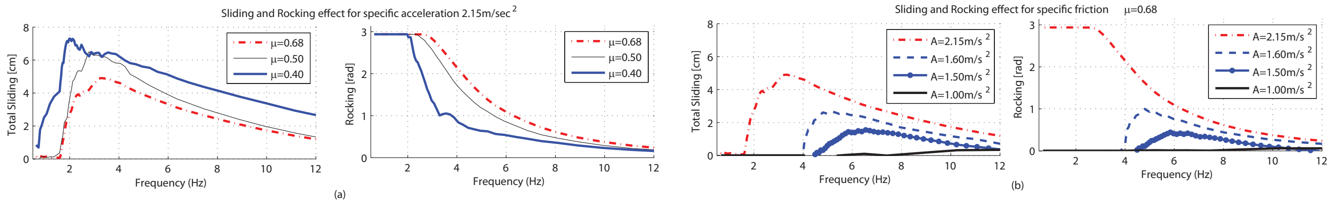

Figure 4. Total sliding and rocking computed in numerical simulations for (a) different coefficients of friction and (b) different acceleration magnitudes (peak ground accelerations).

Furthermore, full-scale multi-drum columns were numerically simulated, using the developed software, for various harmonic excitations with an amplitude of 0.25 m. Figure 5 shows time-history snapshots of the computed responses for 0.5, 2 and 20 Hz excitation frequencies, respectively, in order to identify the influence of the excitation frequency, while keeping the amplitude constant. The numerical simulations indicate that for very low frequencies, the response does not exhibit any sliding or rocking. In those cases, the entire column moves together with the movement of the base, remaining essentially undeformed. Conversely, for very high frequencies the base slides from the rest of the column, which seems not to have the time to react to the rapid excitation, remaining essentially undeformed (Figure 5c). In this case, the ratio of the total sliding to the total base movement is approximately equal to 1.0. Between these frequencies both rocking and sliding occurs, where for lower frequencies rocking dominates the response (Figure 5a).

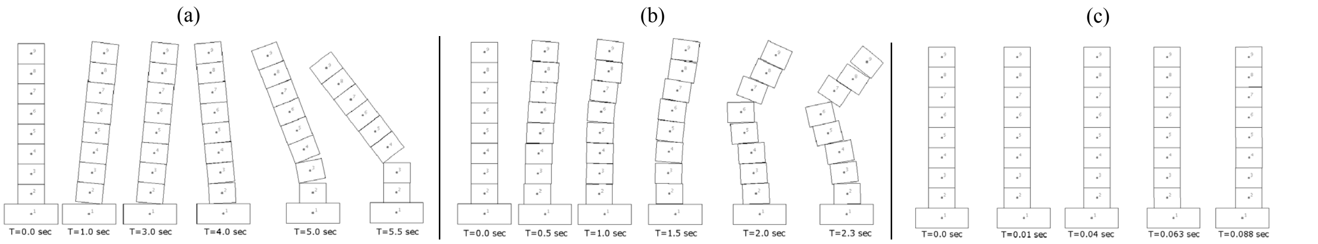

Figure 5. Response of a multi-drum column under a harmonic excitation with 0.5 Hz (a) , 2 Hz (b) and 20 Hz (c) frequency and 0.25 m amplitude.

Figure 6 shows the total sliding and total rocking of colonnades with an epistyle analyzed with the developed software for harmonic base excitations of 0.5 Hz (Figure 6.a) and 2.0 Hz (Figure 6.b). The maximum base acceleration in both cases was 2.47 m/sec2. Three different columns of the same height where analyzed in each case, constructed of one, two, and four drums, with a coefficient of friction equal to 0.60.

The results for these analyses show that with the increase of the excitation frequency, while keeping the maximum acceleration constant, the colonnades become more stable. For a constant maximum acceleration of 2.47 m/sec2 and 0.5 Hz excitation frequency, these colonnades overturn, although they remain stable at an excitation frequency of 2.0 Hz. The number of drums of a column also affects the stability of the overall system. It seems that with the increase of the number of drums, thus increasing the energy dissipation through sliding mechanisms, increases the total sliding that is observed.

(a) (b)

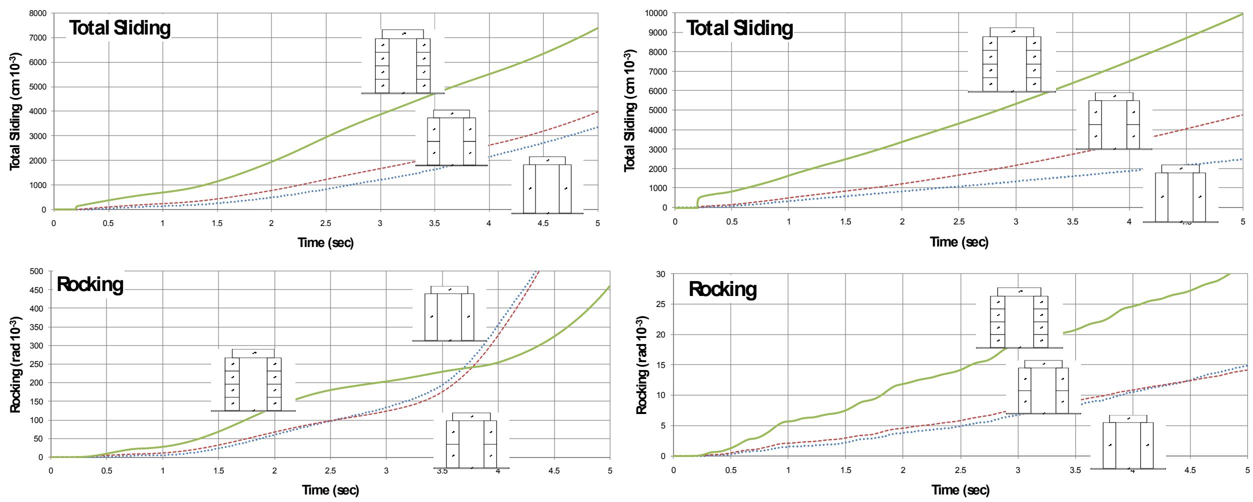

Figure 6. Response of columns with an epistyle analyzed for (a) harmonic base excitations of 0.5 Hz, 0.25 m amplitude and (b) 2.0 Hz, 0.015 m amplitude.

6. RESPONSE TO STRONG MOTION EXCITATIONS

In order to investigate how the response of a column under strong seismic motion is influenced by the earthquake excitation, three earthquakes with different characteristics were selected and used in the simulations. The predominant frequencies of these earthquakes vary from 0.45 Hz to 8.3 Hz. Numerical simulations were performed after scaling the earthquakes appropriately to cause failure (Table 1). Figure 7 shows snapshots from the time-history response of the simulated full-scale multi-drum columns, for the Athens, Kalamata, and Mexico City earthquake respectively, which were scaled appropriately to cause failure.

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

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

(a) (b) (c)

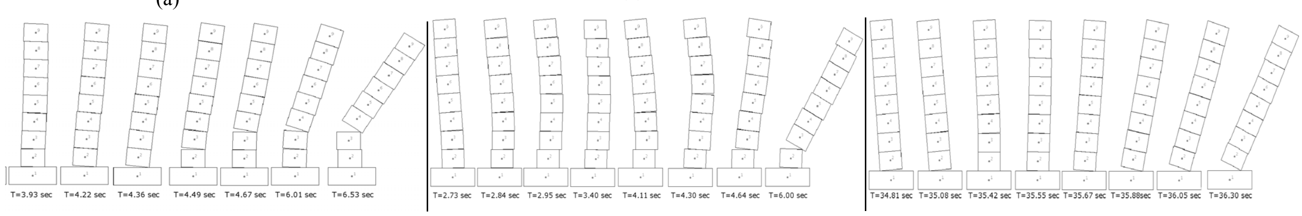

Figure 7. Time-history response of a multi-drum column under the Athens (a), Kalamata (b) and Mexico (c) earthquake scaled appropriately to cause collapse.

The simulation results indicate that earthquakes with relatively low predominant frequencies need much less acceleration to overturn the columns that were considered in our numerical simulations. Earthquakes with high predominant frequencies, such as the ones that usually occur in regions where many of these monuments exist, do not seem to easily endanger the simulated columns. The mode of failure of a column under an earthquake excitation seems to be similar with the ones that have been observed under harmonic ground excitations with frequencies similar to the earthquake's predominant frequencies. For earthquake excitations with relatively low predominant frequencies mostly rocking occurs (Figure 7c), where for excitations with higher frequencies (Figure 7a and 7b) both rocking and sliding are involved. For earthquakes with low predominant frequencies, such as the Mexico earthquake (Figure 7c), the columns collapse during the first strong cycle of the excitation.

7. CONCLUSIONS

Parametric studies were performed by varying the excitation frequency and acceleration, as well as the friction coefficient and the geometric characteristics of the simulated columns in order to assess the influence of these parameters in the seismic response of the structure. The analysis results indicate that the frequency and the peak ground acceleration of the excitation, significantly affect the seismic response of multi-drum columns. In particular, for low frequency harmonic excitations, the exhibited response is dominated by rocking, while sliding prevails in cases of harmonic excitations with very high frequencies. In between the two extremes, the response contains both rocking and sliding phenomena. Furthermore, the results indicate that the required acceleration to initiate rocking or sliding decreases as the excitation frequency increases. The acceleration that is needed to overturn the column also increases as the frequency increases. By examining the stability of multi-drum columns for earthquakes that were selected from regions, where these monuments are often built, such as the Eastern Mediterranean regions, the simulations reveal that the columns have the capacity to successfully withstand strong earthquakes. The mode of failure under harmonic excitations is similar to that under earthquake excitations with similar predominant frequencies. The required acceleration to overturn a column decreases as the predominant frequency of the earthquake decreases.

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