Earthquakes and Structures, *Vol. 10, No. 3 (2016) 495-521*
DOI: http://dx.doi.org/10.12989/eas.2016.10.3.495

Two-dimensional numerical investigation of the effects of multiple sequential earthquake excitations on ancient multi-drum columns

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(Received April 19, 2015, Revised January 13, 2016, Accepted January 23, 2016)

Abstract. Ancient monuments of Greek and Roman classical architecture usually consist of multi-drum columns that are constructed of stone blocks placed on top of each other. Several research studies deal with the seismic behaviour of such structures, since earthquakes are common causes of destruction of such monuments. This paper investigates the effect of multiple earthquakes on the seismic performance of multi-drum columns, through numerical simulations and parametric analyses. The Discrete Element Method and an appropriate contact model have been implemented in a specially developed software application that is able to efficiently perform the necessary simulations in two dimensions. Specifically, various strong ground excitations are used in series for the computation of the collective final deformation of multi-drum columns. In order to calculate this cumulative deformation for a series of ground motions, the individual deformation of the column for each excitation is computed and then used as initial conditions for the next earthquake excitation. Various multi-drum columns with different dimensions are also considered in the analyses in order to examine how the geometric characteristics of columns can affect their seismic sequence behaviour, in combination with the excitation frequency content.

Keywords: ancient columns; rigid bodies; earthquake sequence; aftershock; rocking; discrete element method

1. Introduction

Strong earthquakes are common causes of destruction of ancient monuments of classical architecture, such as ancient Greek and Roman temples, consisting of multi-drum columns and colonnades. Multi-drum columns are constructed of solid stone blocks, or ‘drums’, that rest on top of each other, often without any connecting material between the individual blocks. Today, the remains of most of these structures are often limited to series of columns with an epistyle

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http://www.techno-press.com/journals/eas&subpage=7 ISSN: 2092-7614 (Print), 2092-7622 (Online)

Fig. 1 Standalone columns, Jerash, Jordan (Left) and Amathus, Cyprus (Right)

or standalone columns. Such examples of ancient classical columns, which are of great archaeological significance, can be abundantly found in high seismicity areas in the Eastern Mediterranean region (Fig. 1).

These ancient monuments, in contrast 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 under strong earthquakes. The investigation of the dynamic response of such monumental structures combined with the research fields of paleoseismology and archaeoseismology, may also reveal certain information from past strong earthquakes that had struck the respective regions. For example, the investigation of the response of multi-drum structures under different ground motions can help in estimating the dominant frequency content of old destructive earthquakes. Recent relevant studies followed this approach to investigate the damage in ancient monument structures and propose various quantitative models to test the seismogenic hypothesis of observed damage (Hinzen *et al*. 2009, Hinzen *et al*. 2011).

Moreover, the understanding of the seismic behaviour of these structures can contribute to the rational assessment for their structural rehabilitation, in order to withstand future earthquakes. Finally, the investigation of the seismic behaviour of such monuments is also scientifically interesting, since the behaviour of these structures under seismic excitations involves complicated rocking and sliding phenomena between the individual blocks, which are very rare in common modern structures.

Several research studies have been performed in order to investigate the response of ancient multi-drum columns under seismic excitations, using analytical approaches (Omori 1900, Omori 1902, Kimura *et al*. 1934, Housner 1963, Ishiyama 1982, Psycharis *et al*. 1983, Psycharis 1990, Pompei *et al*. 1998, Konstantinidis and Makris 2005, Kounadis 2010, Kounadis *et al*. 2012, Kounadis 2013a, Kounadis 2013b, Kounadis 2014a, Kounadis 2014b) or by conducting experiments (Makris *et al*. 2001, Manos *et al*. 1991, Manos *et al*. 2001, Vassiliou and Makris 2015 Mouzakis *et al*. 2002, Makris 2014, Drosos and Anastasopoulos 2014). However, the analytical study of such multi-block structures under strong earthquake excitations is practically difficult, if not impossible for large numbers of blocks, while, on the other hand, laboratory tests are very difficult and costly. Therefore, numerical methods are becoming the most efficient approach for the simulation of their seismic response, considering the increasing computer power available. It must be noted however, that analytical and experimental methods of solution are very useful for providing insight into the behavior of the system and serving as valuable benchmarks for calibration and validation of numerical methods of solution. Such experimental results from previous studies have demonstrated high sensitivity of the behaviour to slight changes of the geometry or input motion characteristics and have shown that in general the problem is a size dependent phenomenon.

Beskos (1993, 1994) has published an extensive review of the literature on the usage of various numerical approaches, such as the Finite Element Method (FEM), for the analysis of monuments until 1993. Nevertheless, the Discrete Element Method (DEM) seems to be the most appropriate in such cases, since it has 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 (Connor *et al*. 1993, Barbosa and Ghaboussi 1989, Feng and Owen 2002).

Several research efforts to use the DEM in the simulation of ancient structures have already exhibited promising results, motivating further exploitation of this method. Specifically, recent numerical studies based on commercial general-purpose DEM software applications (Psycharis *et al*. 2003, Papantonopoulos *et al*. 2002, Papastamatiou and Psycharis 1993, Psycharis *et al*. 2000, Mitsopoulou *et al*. 1998), 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, this does not seem to be necessarily resulting from numerical errors, since 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. Therefore, based on this necessity and instead of using commercial software, Papaloizou and Komodromos (Komodromos *et al*. 2005, Papaloizou and Komodromos 2009) developed a custom software application that implements the DEM, utilising modern object-oriented design and programming, in order to parametrically examine the behaviour of multi-drum columns and colonnades under harmonic and earthquake excitations. Similar parametric investigation have been conducted also by other researchers (Ambraseys and Psycharis 2011, Michaltsos and Raftoyiannis 2014, Stefanou *et al*. 2011, Konstantinidis and Makris 2005, Kounadis 2010, Kounadis *et al*. 2012, Kounadis 2013a, Kounadis 2013b, Kounadis 2014a, Kounadis 2014b) to reveal that among other influencing factors, the characteristics of the ground excitation, such as the predominant frequencies, duration and intensity, play a very important role in the overall performance and behaviour of such multi-body structures.

Strong seismic events are very often followed by aftershock events of lower or similar intensities, which in the case of conventional structures, such as buildings, may induce further damage or even collapse to a structure that has already been damaged by the main earthquake. These events are usually separated by relatively short time intervals and therefore are referred as ‘multiple earthquakes’ or ‘seismic sequences’. The effect of several repetitions of a seismic excitation has been investigated by Psycharis (2007) on the response of two columns connected with an architrave. Additionally, this effect has also been examined for two standalone columns by Ambraseys and Psycharis (2012) using the DEM. Several other researchers investigated numerically by the FEM the effect of repeated earthquakes on the non-linear behaviour of structures (Fragiacomo *et al*. 2004, Li and Ellingwood 2007, Hatzigeorgiou and Beskos 2009, Efraimiadou *et al*. 2013, Hatzigeorgiou 2010a, Hatzigeorgiou 2010b, Hatzigeorgiou 2010c, Moustafa and Takewaki 2011, Moustafa and Takewaki 2012, Hatzigeorgiou and Liolios 2010, Ruiz-Garcia and Negrete-Manriquez 2011, Faisal *et al*. 2013, Guidoboni and Valensise 2015). Recently, Efraimiadou *et al*. (2013) examined the effect of multiple earthquakes on the response of adjacent reinforced concrete buildings that are subjected to seismic pounding. Stefanou *et al*. (2014) using the DEM, performed a seismic risk assessment on a multi-drum column with dislocated drums in order to examine the effect of preexisting dislocations on the stability of classical columns under earthquake actions.

This paper presents a research study that investigates, through the performance of numerical simulations and parametric studies, how earthquake excitations in sequence affect the overall seismic behaviour of ancient multi-drum columns. Specifically, various ground excitations are used in series for the computation of the collective final deformation of multi-drum columns using the DEM and an appropriate contact model that has been implemented in a specially developed software application for the particular problem. Various multi-drum columns with different dimensions and number of drums are considered in the analyses in order to examine how the geometric characteristics of columns can affect their seismic sequence behaviour, in combination with the excitation frequency content.

The performed numerical analyses can be grouped in two types, based on the considered ground excitations. The first type of earthquake excitations is the actual seismic sequences, which are recordings by the same station in a short period of time (up to three days) of a major earthquake and its accompanying aftershock seismic events. The second type of excitation is the repetitions of a particular seismic record in order to simulate the case of the ancient structure experiencing, more than one times, very similar earthquakes through the ages of its lifespan.

2. Methodology and assumptions

For this study, the Discrete Element Method (DEM) is utilized by simulating the individual rock blocks as rigid distinct bodies. Specifically, the structures are simulated in two dimensions, with each rigid block being modelled as a convex polygon. Two distinct bodies are considered to be in contact when they overlap each other (Papaloizou and Komodromos 2009). The interaction forces between two or more individual blocks in contact are automatically applied to the bodies whenever a contact is detected, kept as long as the blocks remain in contact and removed as soon as the blocks are detached from each other. A special contact algorithm has been developed that efficiently estimates the direction and magnitude of the contact forces that should be applied to the blocks in contact (Komodromos *et al*. 2008, Polycarpou *et al*. 2014). According to the developed contact model, the direction of the normal and tangential contact forces is defined by the geometry of the contact region and, particularly, the nodes of intersection between the boundaries of the two colliding bodies. The line that connects the two nodes is symbolically called the ‘contact plane’ and is parallel to the tangential contact force, while the normal contact force is perpendicular to it. At each individual time step all bodies of the simulated structural system are checked against each other for contact. If contact is detected, corresponding springs and dashpots are automatically generated and applied between the contacting bodies in the normal and tangential directions. Based on the area of the overlap region and the relative velocities between the bodies in contact, elastic and damping contact forces in the normal and tangential directions are computed using the following equations, respectively

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

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

In the above equations, the symbols N and T indicate the normal and the tangential directions, respectively. Accordingly, K_N and K_T are the stiffness in the normal and tangential directions, respectively. Finally, 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. Damping is proportional to the velocity and the magnitude of the damping force is proportional to the corresponding relative velocity of the rigid blocks that are in contact.

The tangential force, $^{t+\Delta t}F_T$, is limited under a certain magnitude, so that friction is taken into account. Coulomb Friction Law is used, considering the magnitude of the normal force, $^{t+\Delta t}F_N$, and the coefficient of friction, μ, as shown by Eq. (3)

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

During impact the contact forces, as evaluated by the previous equations, are applied at the contact points of the simulated bodies, while gravitational forces are applied at the center of mass of each body. Taking into account all forces at each simulated discrete body, the equations of motion are formed and solved, providing its displacements, which define its updated position for the next simulation step. The formed equations of motion are then explicitly integrated, for each discrete body, using the Central Difference Method (CDM), computing the new displacements and rotations at time t+Δt of each body, followed by the calculation of its new corresponding position and orientation. Specifically, the motion of each discrete body at time t+Δt is determined from its dynamic equilibrium at time t, which is characterized by the following equations

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

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

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

In the above equations of motion, U_x and U_y are the displacements at the X and Y directions, respectively, while Θ_z is the rotation about the Z axis. Similarly, F_x and F_y are the forces in the X and Y directions, respectively, and M_z is the moment about the Z axis. Δt is the time step, which is selected to be sufficiently small. Finally, m and I_0 are the mass and the rotational inertia of the body, respectively. This process is iteratively repeated with new cycles of contact detection, contact resolution and numerical solution of the formed equations of motion until the simulation procedure ends.

The numerical analysis is based on the assumption that velocities and accelerations are constant within each time step. The DEM is based on the concept that the time step is sufficiently small so that during a single step, disturbances cannot propagate between one discrete element and its immediate neighbors. Therefore, very small time steps are used, of the order of 1E-6, so as to satisfactorily capture the collisions and contacts among the individual bodies of the simulated system.

Despite the fact that the current methodology may take into account the vertical seismic component $U_y(t)$, all the base motions that are used in the numerical simulations represent only the horizontal seismic component. The effect of the vertical component has been examined in previous studies, following the same methodology (Papaloizou and Komodromos 2012) and was found 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, which alters the final response of the columns.

The above methodology has been extensively validated (Papaloizou and Komodromos 2009) by comparing the computed responses associated with sliding, rocking and free vibration dynamics of rigid bodies, with the corresponding analytical solutions. Furthermore, the contact parameters are calibrated through available in the literature experimental results (Komodromos *et al*. 2008, Papaloizou and Komodromos 2009).

A specialised software application that implements the above methodology has been specifically designed and developed (Papaloizou and Komodromos 2009) using a modern object-oriented programming language. The development and usage of a custom-made software application instead of using an available ready-made general-purpose software package allows further flexibility and extensibility of the software according to current and future research needs, something that is not possible while using commercial software applications without any access to the actual software code. Furthermore, the developed software enables the efficient performance of 2D seismic simulations of multi-block structures, as well as parametric analyses, where large numbers of simulations can be performed in series, while a certain parameter is automatically varied to assess its influence on the response.

3. Limitations of the two dimensional analysis

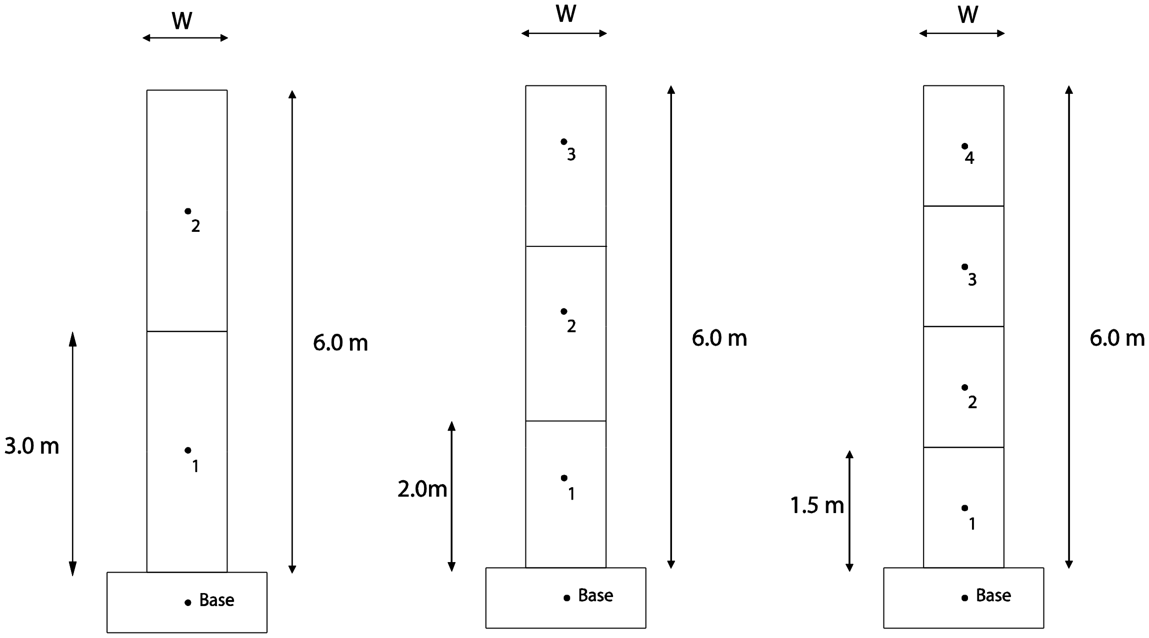
The developed software application has been specifically designed and implemented to enable efficient performance of 2D seismic simulations of multi-block structures, while maintaining extensibility towards future spatial (3D) capabilities. It is well known that the results obtained by 2D dynamic analysis of rigid block assemblies are not capable of considering phenomena that may appear in the actual 3D response of such systems, such as off-plane movements and oscillations. Numerical studies of the earthquake response of ancient columns by Papantonopoulos *et al*., using commercial 3D software, reported significant differences in the response of 2D and 3D analysis, even for plane excitations, although the models used were symmetrical about the vertical axis. The researchers also observed that very small disturbances, in the direction normal to the plane of rocking, may cause significant amplification of the response and that 2D analysis may underestimate the response, predicting greater stability. In addition, the collapse mechanisms of colonnades in many cases appear in the out-of-plane direction. Experimental work regarding the response of a scaled model of a marble classical column, presented by Mouzakis *et al.* (2002), also reported this ‘3D sensitivity’ inherent in the rocking phenomenon.

Nevertheless, numerical studies by Psycharis (2007) and Konstantinidis (2005) showed that 2D analysis can be used to capture the overall phenomenon and various parameters that affect the seismic response of multi-drum columns. Moreover, 2D can be used more efficiently and effectively when it is necessary to perform large numbers of simulations in order to study the effect of various parameters and characteristics, as 2D analysis is much more time efficient and is less sensitive to the contact parameters.

4. Geometry and material properties of the simulated columns

For this research work a free standing multi-drum ancient column of 6.0 m height, subjected to various types of seismic ground motions, is considered. The width and the number of its drums are varied in order to parametrically examine their effects on the overall response. The three different configurations of the analysed columns, regarding the number of drums, are provided in Fig. 2. The coefficient of friction between the stone blocks is taken to be μ=0.65 (Papantonopoulos *et al.* 2002, Psycharis *et al.* 2000). A normal contact stiffness coefficient of the order of 10^8 N/m^2 and a normal damping coefficient of 10^3 N·s/m are used in the simulations (Papaloizou and Komodromos 2009).

The overall size of the multi-drum columns plays an important role in the response (Psycharis 2000) and that the results observed cannot be generalized for any multidrum column of similar dimensions.



(a) (b) (c)

Fig. 2 Dimensions of the analysed columns

5. Selected ground motions

As mentioned previously, two types of seismic ground motions are used in the performed analyses. The first group of ground motions consists of real seismic sequences. A seismic sequence is a set of seismic events recorded by the same station, in a short period of time (up to 3 days) and typically includes the main earthquake along with the main aftershock events. The strong ground motion database that has been used in the current study includes five real seismic sequences, which consist of totally 13 single seismic events. The recorded events of the same sequence have the same direction and almost at the same fault distance. Specifically, the considered seismic sequences are namely, the Mammoth Lakes (May 1980, five events), Chalfant Valley (July 1986, two events), Coalinga (July 1983, two events), Imperial Valley (October 1979, two events) and Whittier Narrows (October 1987, two events) earthquakes. The complete list of these earthquakes (obtained from the strong motion database of the Pacific Earthquake Engineering Research Center 2012) appears in Table 1. The envelopes of the corresponding displacement response spectra and the acceleration response spectra of each seismic sequence are presented in Fig. 3 and Fig. 4, respectively.

Table 1 Seismic input data

Case	Seismic sequence	Station	Comp.		Date (Time)	Magnitude (M_L)	Recorded PGA (g)
1	Mammoth Lakes	54099 Convict Creek	N-S	a	1980/05/25 (16:34)	6.1	0.442
				b	1980/05/25 (16:49)	6.0	0.178
				c	1980/05/25 (19:44)	6.1	0.208
				d	1980/05/25 (20:35)	5.7	0.432
				e	1980/05/27 (14:51)	6.2	0.316
2	Chalfant Valley	54428 Zack Brothers Ranch	E-W	a	1986/07/20 (14:29)	5.9	0.285
				b	1986/07/21 (14:42)	6.3	0.447
3	Coalinga	46T04 CHP	N-S	a	1983/07/22 (02:39)	6.0	0.605
				b	1983/07/25 (22:31)	5.3	0.733
4	Imperial Valley	5055 Holtville P.O.	HPV315	a	1979/10/15 (23:16)	6.6	0.221
				b	1979/10/15 (23:19)	5.2	0.211
5	Whittier Narrows	24401 San Marino	N-S	a	1987/10/01 (14:42)	5.9	0.204
				b	1987/10/04 (10:59)	5.3	0.212

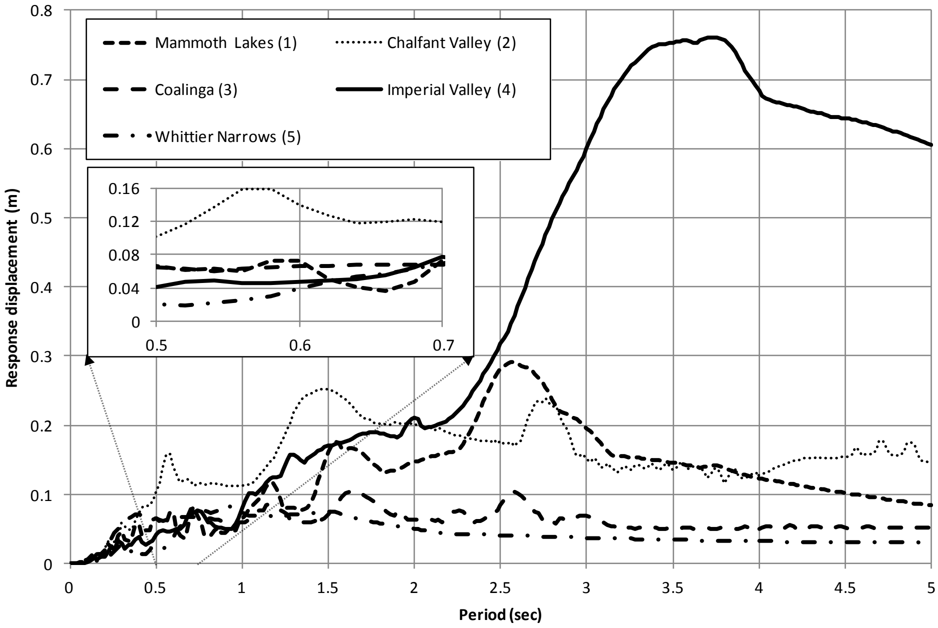
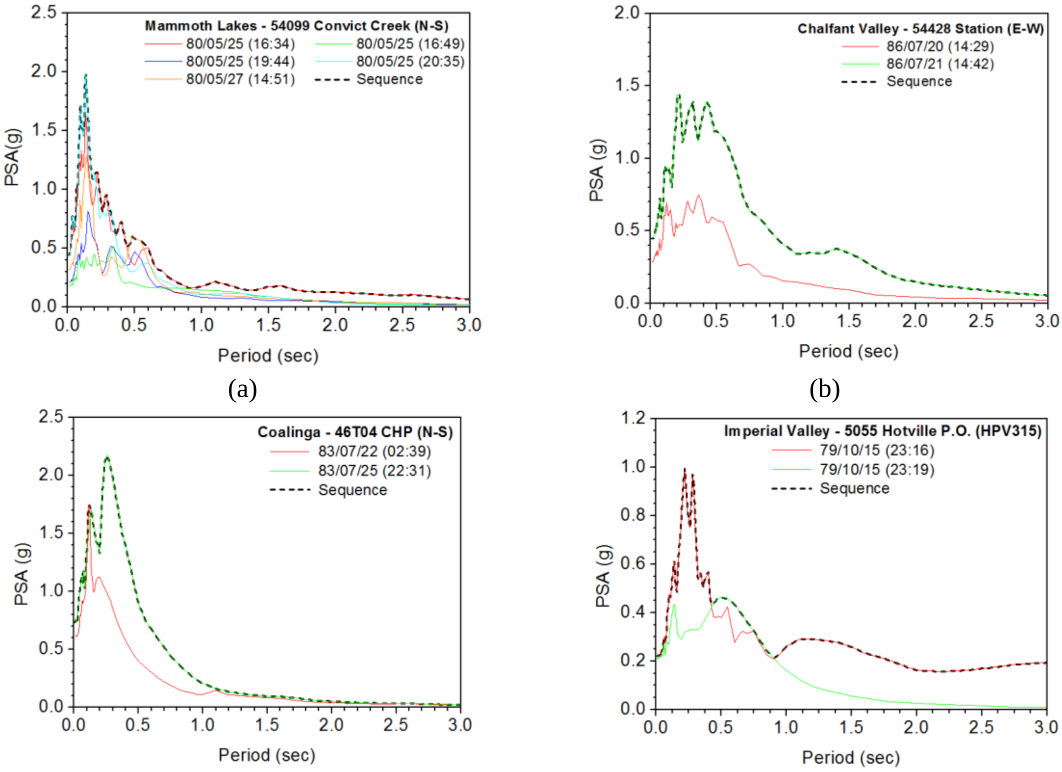


Fig. 3 Response displacement spectra



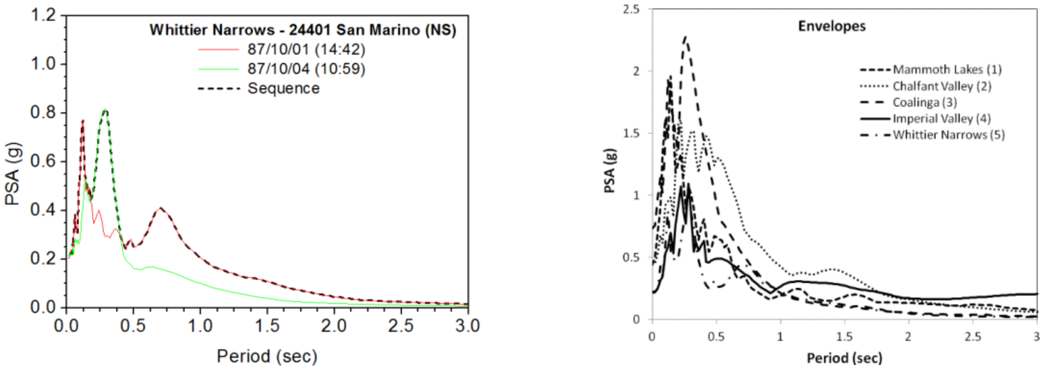
(a)

(b)

(c)

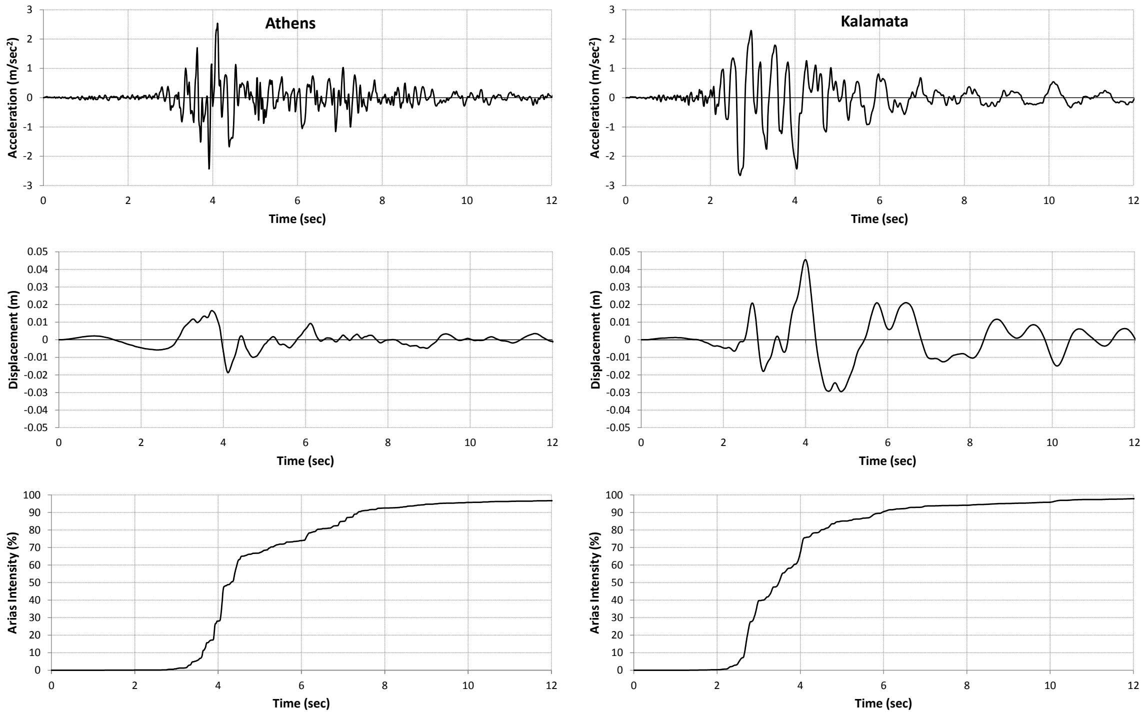
(d)

Fig. 4 Pseudo-acceleration response spectra of the five selected sequences of earthquake excitations



(e) (f)

Fig. 4 Continued



(a) (b)

Fig. 5 Acceleration, Displacement and Arias Intensity time histories for the Athens (a) and Kalamata (b) earthquakes

Table 2 Earthquake records that are 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
2	Kalamata, Greece	17:24:31, SEPTEMBER 13, 1986	KALAMATA OTE- BUILDING N10W	2.671

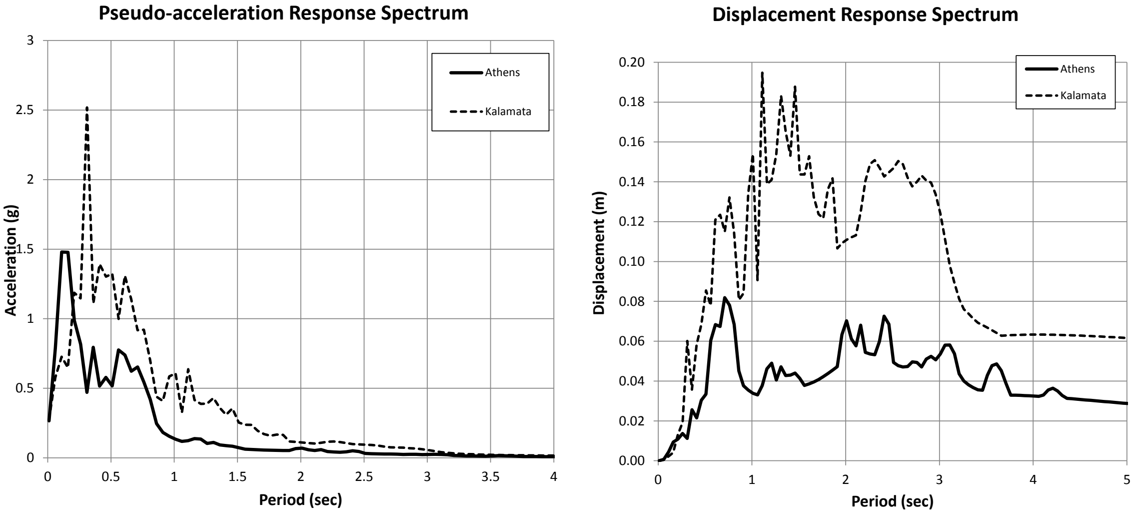


Fig. 6 Pseudo-acceleration and displacement response spectra of the Athens and Kalamata earthquake records

Apart from the five seismic sequences, the main shock events of two relatively strong earthquakes have also been selected to be used in the simulations. The two seismic recordings are taken from the Greek region where these ancient monuments are often located (Table 2). The ground acceleration and displacement time histories, as well as the Arias intensity (Arias 1970) for the Athens and Kalamata earthquakes are provided in Fig. 5. The selected earthquakes have a similar intensity (PGA), but significantly different frequency content, as shown in the corresponding response spectra of Fig. 6. Specifically, the Kalamata earthquake has lower predominant frequency content (Fig. 6(a)) and considerably higher response displacements over a larger range of periods (Fig. 6(b)) compared to the Athens earthquake. As aforementioned, each one of the ground motions of Table 2 is repeatedly applied to the simulated multi-drum columns until collapse in order to assess the behaviour of such structures when experiencing the same or similar earthquakes more than once during their lifespans. Therefore, the particular earthquakes have been selected so that they do not overturn the simulated columns from the first occurrence.

6. Response under actual seismic sequences

The column of Fig. 2(c) is selected for the dynamic analyses performed in this section. The free standing column has a total height of 6.0 m and is equally divided into four drums with a width of W=1.00 m. The 'base' that is illustrated in Fig. 2 follows the ground motion. The four-drum column is simulated for each of the 13 individual seismic events as well as for each one of the 5 seismic sequences. In the latter case the cumulative deformation of the column is computed. In order to calculate this cumulative deformation for a series of ground motions, the individual deformation of the column after each excitation is recorded and then used as initial conditions for the next earthquake. The presented results provide sliding as a measure of deformations of the simulated columns, although the movement of the drums exhibits both rocking and sliding phenomena which obviously influence each other.

Specifically, for each seismic sequence the maximum displacement at the top of the column relative to the ground (i.e., the column's base), $\max U_{Rel,Top} = \max|U_{top} - U_{base}|$, is provided, as well as the corresponding seismic event during which that maximum occurred. In addition, the total residual sliding $S_{tot,Res}$ between the drums of the column, computed for the whole sequence is compared to the total residual sliding values for each individual ground motion. The total sliding at each time step, S_{tot}, is defined as the sum of the absolute values of the relative displacements between subsequent drums of the column, as follows

$$S_{tot}(t) = \sum_{i=0}^{n-1} \left| U_{i+1}(t) - U_i(t) \right| \tag{7}$$

where i=0 corresponds to the base (i.e., the ground) displacement and n is the number of drums. The residual sliding $S_{tot,Res}$ is the corresponding value obtained at the end of the excitation. This parameter expresses the overall deformation of the specific multi-drum column under a certain ground motion.

Figs. 7 to 11 show snapshots of the deformations of the four-drum column under the seismic sequences of the Mammoth Lakes, Chalfant Valley, Coalinga, Imperial Valley and Whittier Narrows earthquake excitation sequences, respectively. These figures also include time histories of the relative horizontal displacement of the upper drum $U_{Rel,Top}$ and the total sliding between the drums, S_{tot}, of the simulated column. In addition, selected results of the performed analyses are summarised in Table 3.

It is observed that almost in all of the examined cases the total residual sliding between the drums under the entire sequence of ground motions is greater than the corresponding sliding for each one of the individual earthquake motions (see Table 3). This shows that aftershocks, although having a lower intensity (PGA) than the first seismic event in most of the cases, can induce further deformations to the multi-drum column and increase the risk of collapse.

However, in the case of the Whittier Narrows earthquake sequences (Case 5), the residual sliding after the first ground motion (1.13 cm) is greater than the total sliding at the end of the sequence (0.89 cm). The exception of Case 5 seems to occur because of the fact that the second earthquake motion in the sequence happens to have a beneficial restoring effect on the deformation of the column. This is better demonstrated in Fig. 11(c) where a time-history of the total sliding is provided. The deformation of the column due to the second excitation is such that partially restores the initially distorted position of the drums that resulted from the first ground motion of the specific sequence. This effect displaces the drums closer to their original undeformed position. Similar behavior is also observed in the case of the Mammoth Lakes series (Fig. 7(c)) where the residual sliding from the 3rd event (~1 cm) is reduced (~0.65 cm) after the 4th ground motion and once more increased after the 5th event. Nevertheless, as mentioned above, in the majority of the examined cases the aftershocks induce further deformations to the multi-drum column.

On the other hand, according to Table 3, the total sliding between all of the drums of the simulated column for each sequence of ground excitations is less than the sum of the total residual sliding under each individual earthquake excitation of the series. For instance, for Case 1 the sum of total residual sliding of the individual motions is 0.49+1.42+1.04+0.63+0.79=4.37 cm, which is greater than the total residual sliding of the sequence, which is 2.05 cm (Table 3). That means that the effect of subsequent ground motions is not exactly cumulative, but is more complicated since some of the aftershock events might have a restoring beneficial effect, as described above.

Furthermore, the initial distorted position of the drums before an excitation affects the overall response of the column.

Comparing the response among the various seismic sequences, it is observed that the Chalfant Valley seismic records (Case 2) induce substantially larger deformations to the multi-drum column, compared to the rest of the earthquakes. Specifically, the residual total sliding value reaches up to 22.24 cm for the specific case, while the corresponding values for the rest of the seismic sequences range between 0.89 and 2.2 cm (Table 3). The most possible explanation for this behavior is that the response of the multi-drum column is highly affected by the range of predominant frequencies of the excitation, in combination with the column's geometric and

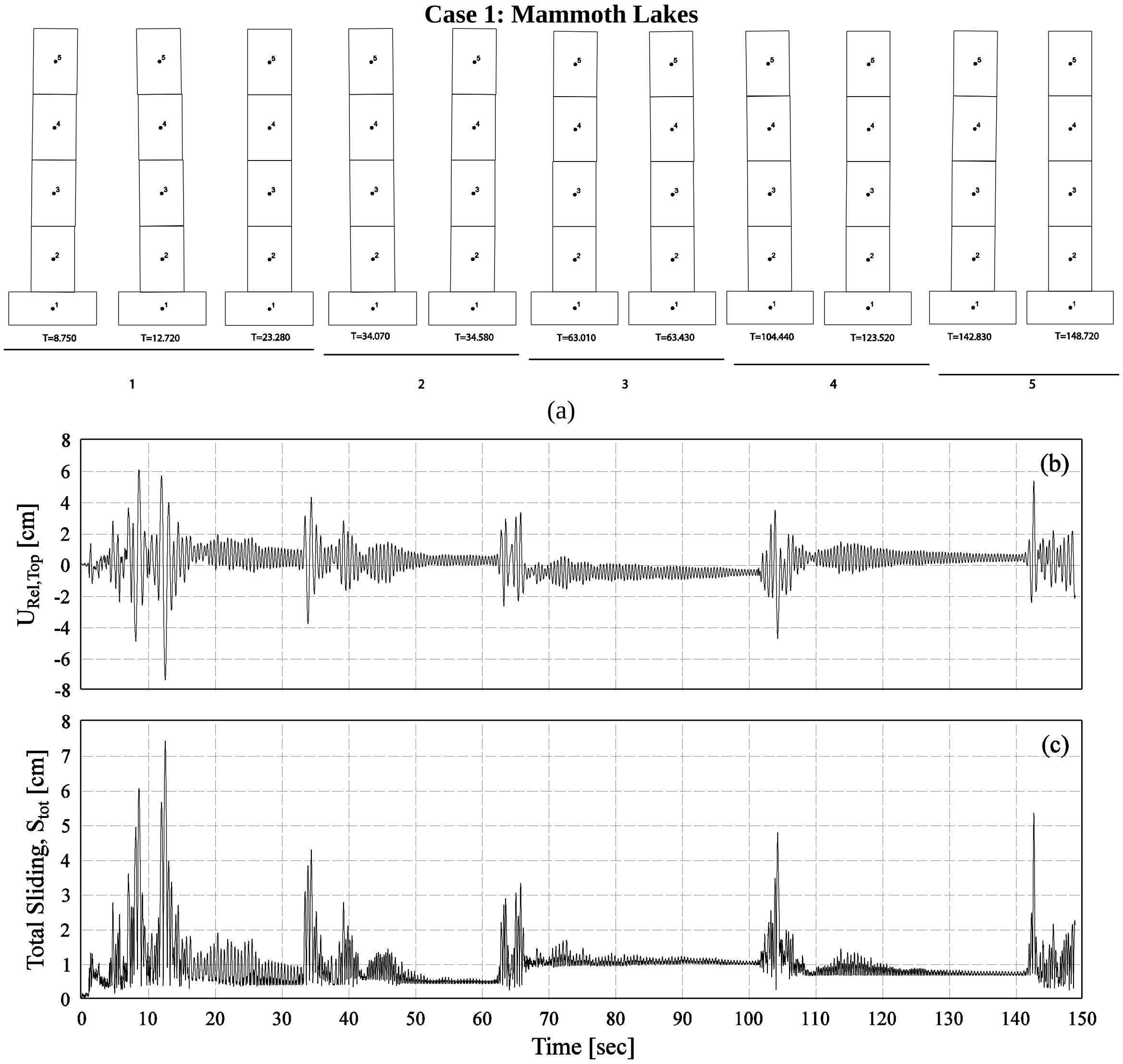


Fig. 7 Response of the four-drum column under the Mammoth Lakes series: (a) Snapshots during oscillation; (b) Top drum displacement; (c) Total sliding of drums

mechanical characteristics. In the particular case, the envelope response spectra of the Chalfant Valley Earthquake series, displayed in Fig. 3 and Fig. 4 have higher spectral displacements and accelerations, respectively, in the range of periods between 0.5 and 1.7 sec, compared to the rest of the seismic records. Conversely, sequences such as the Imperial Valley (Case 4) with much larger response displacement on higher period ranges and the Mammoth Lakes (Case 1) with larger spectral acceleration in lower periods do not affect the total sliding of the drums in the same way.

In addition, the time-histories generally show that the residual values of top-drum displacement and total sliding between the drums are much lower than the corresponding peak values that occur during the excitation. This indicates that, during a seismic excitation, any deformation of the multi-body system is eventually partially restored due to the cyclic ground motion.

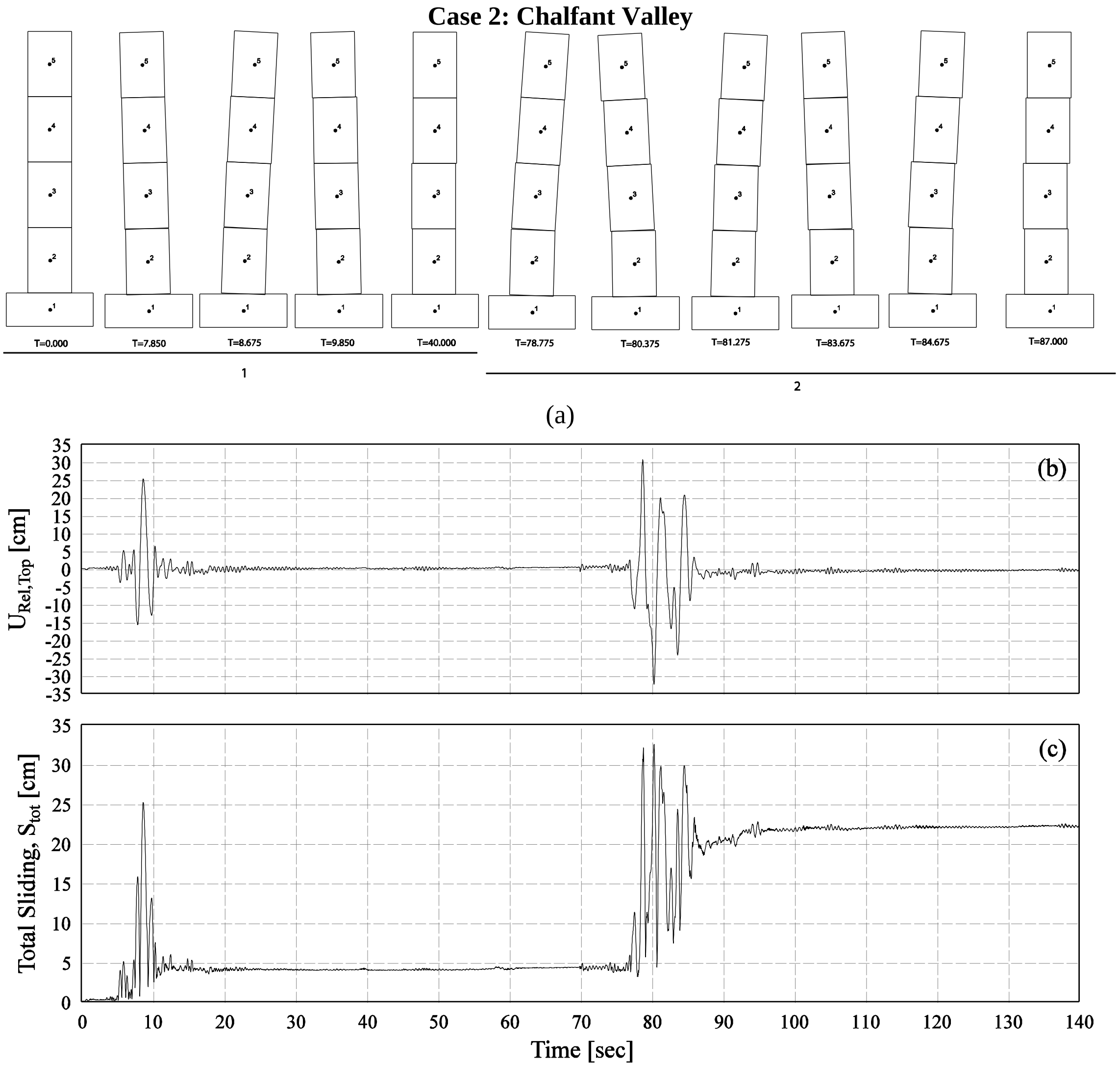
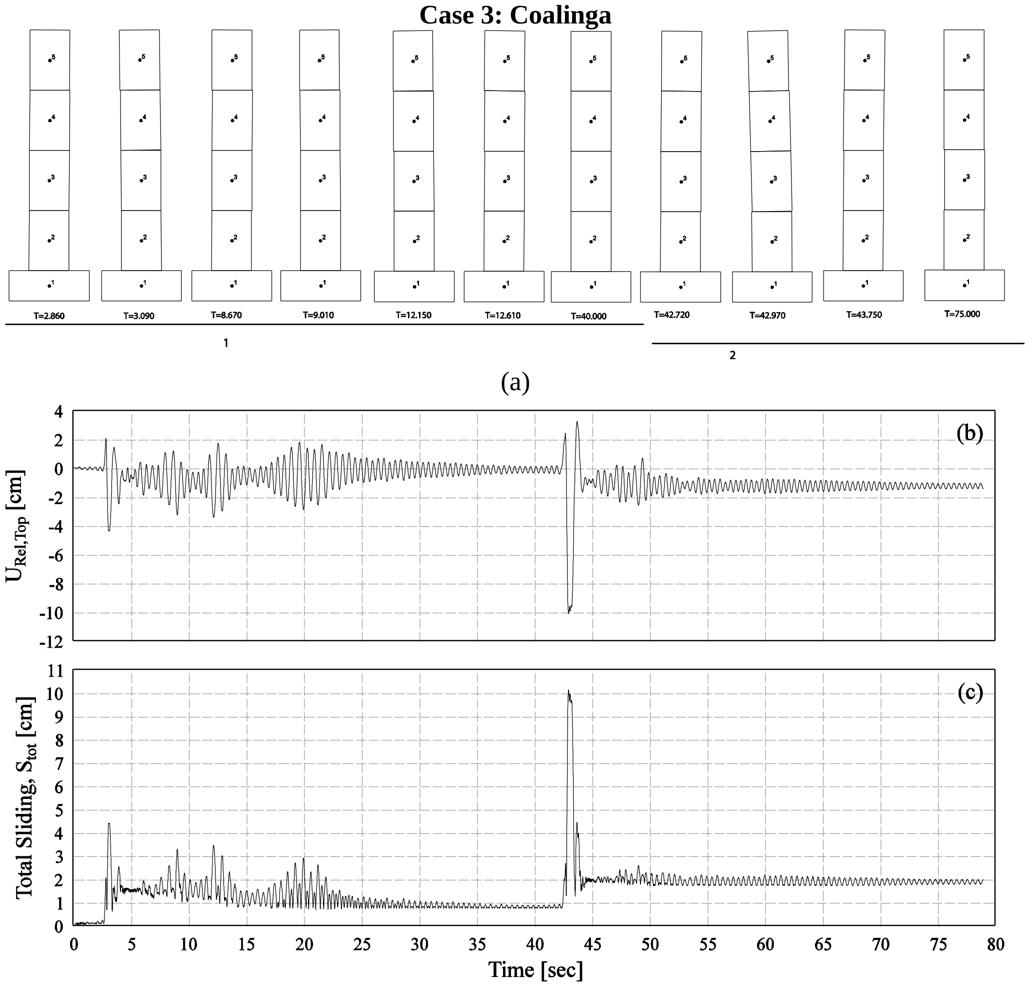
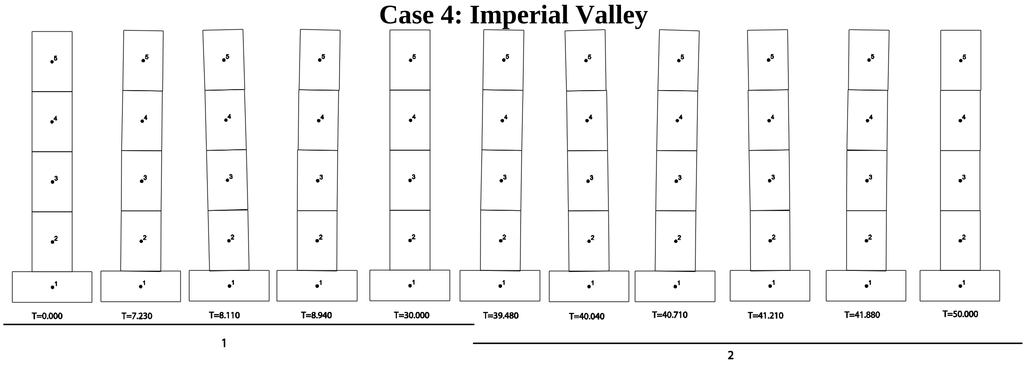


Fig. 8 Response of the four-drum column under the Chalfant Valley series: (a) Snapshots during oscillation; (b) Top drum displacement; (c) Total sliding of drums


Case 3: Coalinga

(a)

Fig. 9 Response of the four-drum column under the Coalinga series: (a) Snapshots during oscillation; (b) Top drum displacement; (c) Total sliding of drums


Case 4: Imperial Valley

(a)

Fig. 10 Response of the four-drum column under the Imperial Valley series: (a) Snapshots during oscillation; (b) Top drum displacement; (c) Total sliding of drums

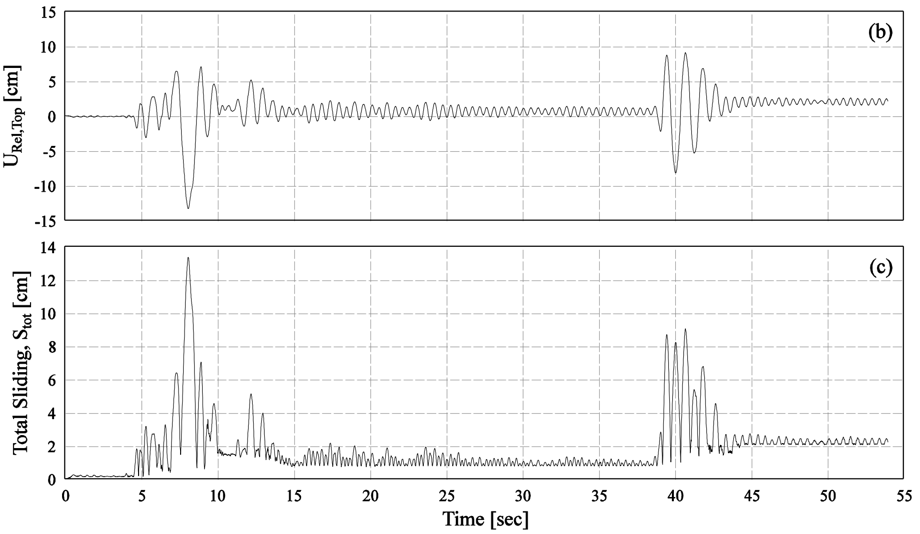


Fig. 10 Continued

Case 5: Whittier Narrows

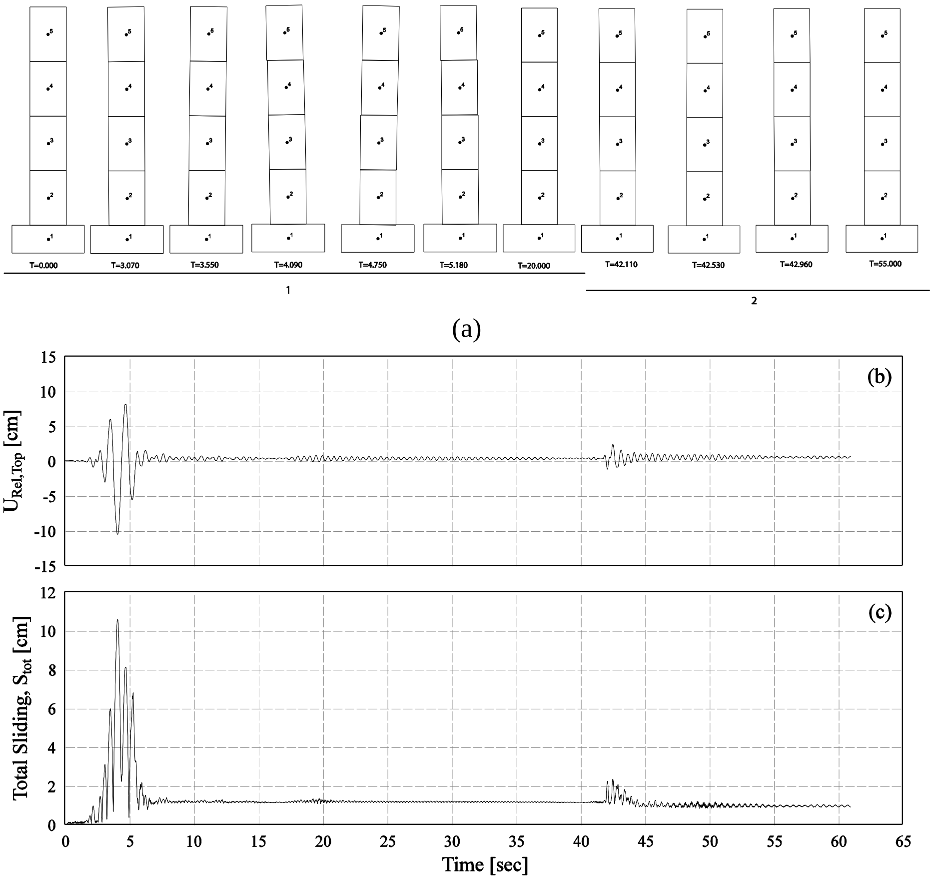


Fig. 11 Response of the four-drum column under the Whittier Narrows series: (a) Snapshots during oscillation; (b) Top drum displacement; (c) Total sliding of drums

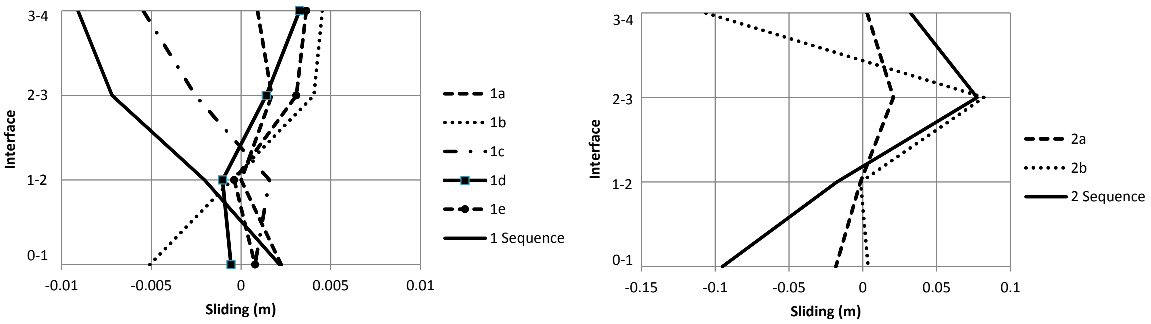
Table 3 Analyses results summary

Case	Seismic sequence	PGA (g)	PGD (m)	maxU$_{\text{Rel,Top}}$ (m)	Occurs during	$S_{tot,Res}$ for sequence (cm)	$S_{tot,Res}$ for individual earthquakes (cm)	
1	Mammoth Lakes	0.442	0.0541	0.074	a	2.05	a	0.49
							b	1.42
							c	1.04
							d	0.63
							e	0.79
2	Chalfant Valley	0.447	0.224	0.325	b	22.24	a	4.35
							b	19.35
3	Coalinga	0.733	0.052	0.101	b	1.96	a	0.84
							b	0.53
4	Imperial Valley	0.221	0.319	0.133	a	2.2	a	1.07
							b	2.12
5	Whittier Narrows	0.212	0.026	0.105	a	0.89	a	1.13
							b	0.09

The plots in Fig. 12 show the residual sliding at each interface of the column that occurs after the end of each analysis under each individual earthquake motion, compared to that of the respective sequence of earthquake excitations, shown with solid line. The residual sliding at each interface, between two drums *i* and *j* is computed as follows

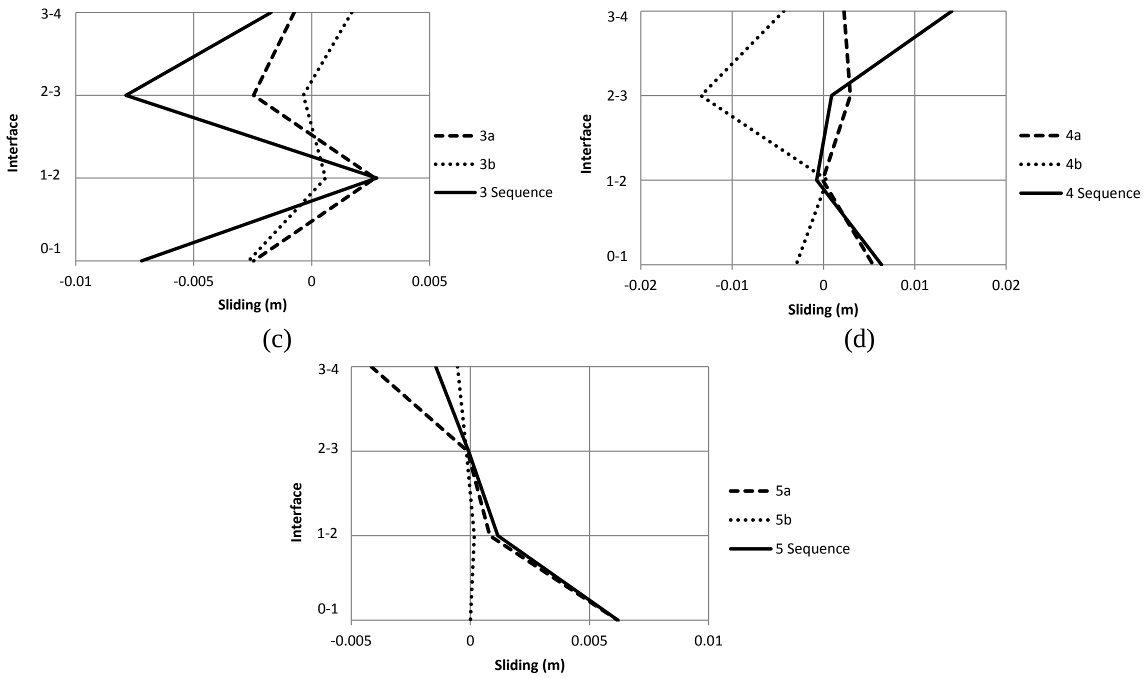
$$S_{ij,Res} = U_j^{t=T} - U_i^{t=T} \quad \text{, with: } j = i + 1 \tag{8}$$

As expected, the effect of the earthquakes in series (Fig. 12) is not cumulative and, thus, the overall response of the column under a series of seismic actions cannot be easily estimated due to



(a) (b)

Fig. 12 Horizontal sliding at drum interfaces under each individual earthquake motion and the corresponding sequence of excitations: (a) Mammoth Lakes, (b) Chalfant Valley, (c) Coalinga, (d) Imperial Valley and (e) Whittier Narrows earthquakes



(c) (d)

(e)

Fig. 12 Continued

the nonlinearity of the problem. The behaviour is complicated since the distorted position of the drums that resulted from a previous excitation substantially affects the overall response.

7. Parametric study of geometric characteristics and frequency content using repeated earthquake excitations

In order to examine the behaviour of multi-drum columns when experiencing strong earthquakes of similar characteristics more than once during their lifespan, the seismic records of Table 2 have been used as repeated ground motions in simulations until collapse of the columns. In addition to the consideration of the characteristics of the imposed earthquake excitations and their repetitions, the influence of the geometric characteristics of the simulated columns is also parametrically investigated. For this cause, various types of single standing multi-drum columns with the same overall height but with different number of drums and varying widths have been analysed. Specifically, all analysed columns in this section have a total height of 6 m and are divided into two, three or four drums of equal height (Fig. 2). Additionally, for each one of these cases the width of the column *W* is varied to parametrically investigate its effect on the overall response. In particular, four different cases of column width are considered: 1.25 m, 1.00 m, 0.75 m and 0.50 m. Therefore, totally twelve different geometry configurations of multi-drum columns are analysed under the two strong motion excitations that have been selected from a specific region where these monuments are usually built. The selected earthquakes, which have similar peak ground accelerations but different frequency content (Fig. 6), are used repeatedly in series for the computation of the collective final deformation of multi-drum columns. The cumulative deformations for the series of repeated ground motions are computed by using the remaining deformation at the end of each cycle of ground motion as initial conditions for the next cycle of the same ground motion.

Figs. 13 and 14 show snapshots of the residual deformations of the twelve aforementioned columns subjected to the repeated ground motions of the Athens and the Kalamata earthquakes, respectively. Specifically, the figures present the final deformation of the multi-drum columns at the end of the seventh repetition of each seismic record or at the time of failure if the later occurred at an earlier stage of the analysis. Firstly, it is observed that none of the considered multi-drum columns collapses from the first excitation. Conversely, as the seismic excitations are repeated successively, the sliding between the drums progressively increases on every recurrence of the earthquake, causing in some cases, instabilities and potential collapsing of the simulated multi-drum columns. The results indicate that the width of the column plays a significant role to the stability of the structure. Specifically, for both seismic excitation (Athens and Kalamata earthquakes) the wide multi-drum columns (W=1.25 m, W=1.00 m), regardless of the number of drums, do not fail, even after the seventh repetition (Fig. 13 and Fig. 14, cases (a) to (f)). On the contrary, the relatively slender columns (W=0.75 m, W=0.50 m) collapse at fewer repetitions of the imposed ground motion.

Moreover, the results show that as the number of drums increases, the maximum residual sliding at each drum interface decreases. Especially in the case of the column with a drum width equal to 0.75 m, the repetitions needed for collapse increase when increasing the number of drums (Fig. 13 and Fig. 14, cases (g), (h) and (i)). However, in the case of a very slender column (W=0.5 m), where rocking response prevails, the increase of the number of drums does not have the same effect.

Figs. 15 to 18 show selective time-history results concerning the three-drum and the four-drum columns of a width of W=0.75 m, excited by a series of repetitions of the Athens and Kalamata earthquakes.

In particular, Figs. 15 and 16 show the horizontal sliding between subsequent drums for the two aforementioned columns, under a series of seven repetitions of the Athens and Kalamata earthquake, respectively. The results show that a four-drum column seems to be more stable than a three-drum column under both series of excitations, since the later collapses at fewer repetitions. It is also observed that in all cases sliding increases as the drum interface is in a higher position in the column. Furthermore, failure occurs with the collapse of the top-drum. It is interesting to observe that after the failure of the top-drum, sliding between the remaining drums starts to increase mainly due to the reduction of the normal force applied on each remaining drum.

Fig. 17 and Fig. 18 depict the absolute total sliding and the average rotation of the drums under a series of repetitions of the Kalamata and the Athens earthquakes of the three-drum, and four-drum columns (W=0.75 m), respectively. An important observation is that the response of the multi-drum columns under repeated earthquakes is quite different from the case of actual series of earthquakes, presented in the previous section. Specifically, according to the plots of Fig. 17(a) and Fig. 18(a), repeating the same ground motion results in cumulative effects, increasing progressively the total sliding of drums until collapse, in contrast to the case of actual series of seismic events of different intensity and frequency content where some of these ground motions might have a beneficial restoring effect on the multi-drum column's stability (see Section 5).

Moreover, the plots in Fig. 17 and Fig. 18 show that, although the two ground motions have very close PGA values, the Kalamata earthquake induces significantly larger responses (i.e.,

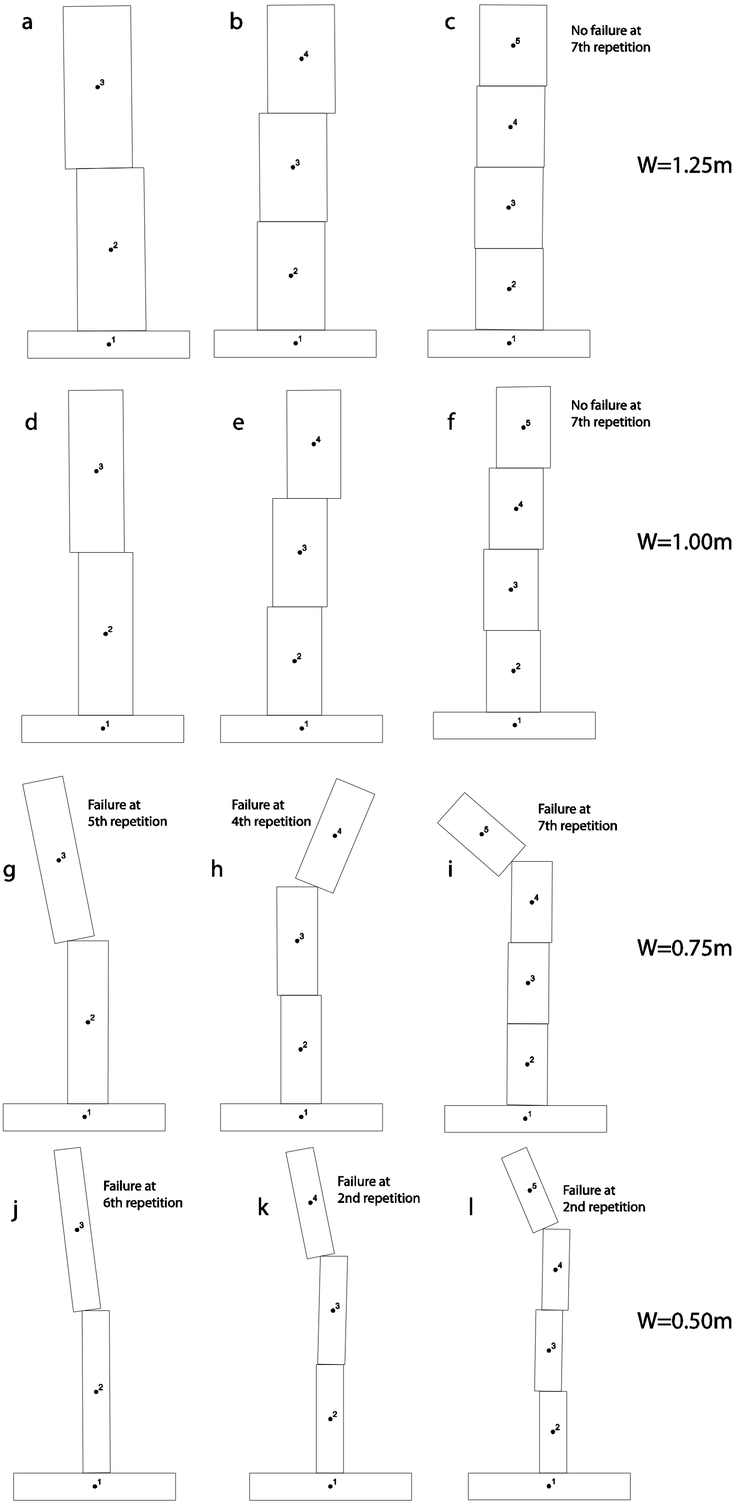


Fig. 13 Response of twelve columns with different geometries under the Athens 1999 earthquake, repeated seven times

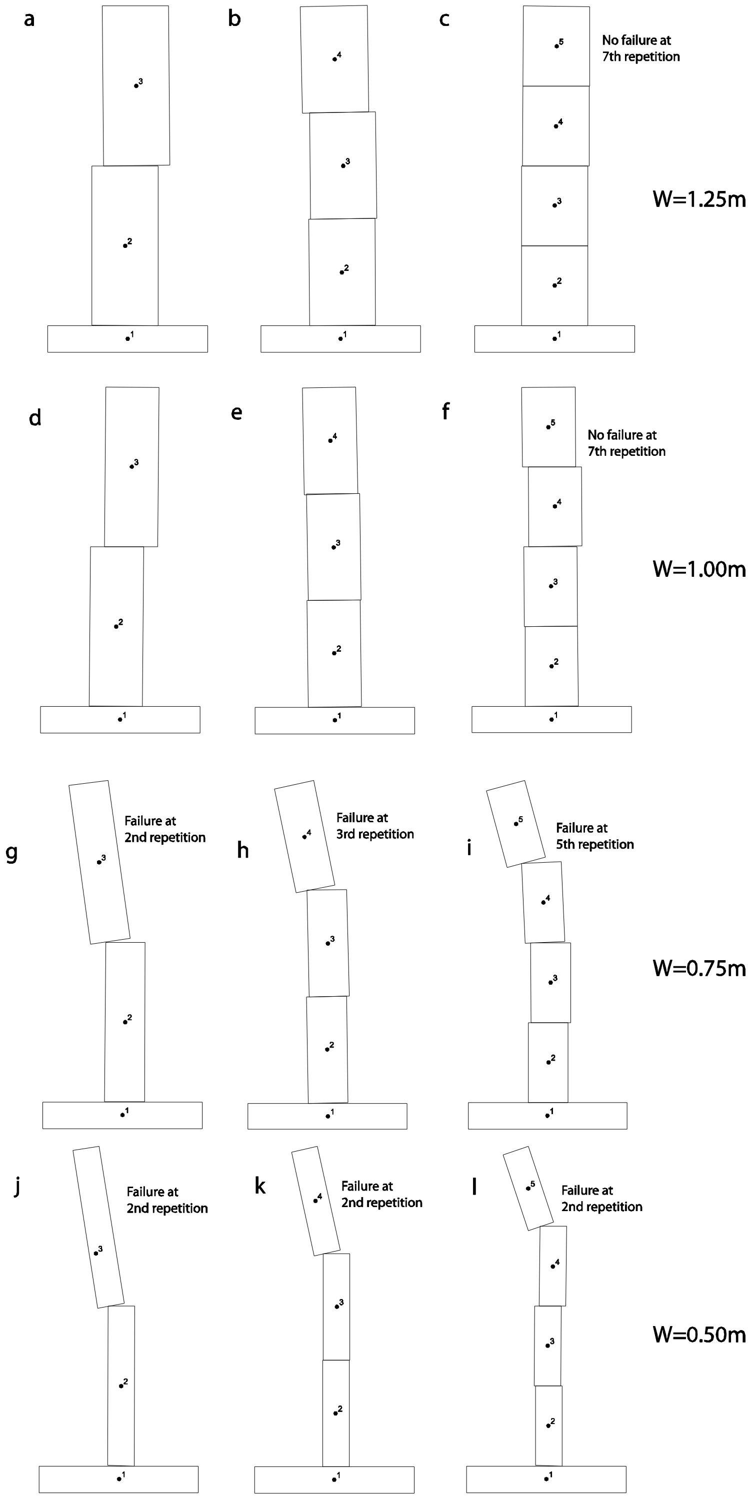


Fig. 14 Response of twelve columns with different geometries under the Kalamata 1986 earthquake, repeated seven times

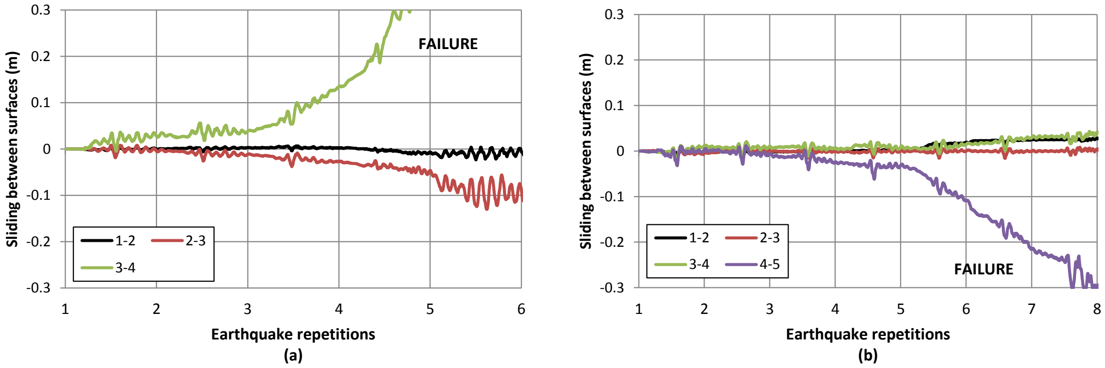


Fig. 15 Horizontal sliding at the interfaces of (a) the three-drum column and (b) the four-drum column with a width *W*=0.75 m, under a series of repetitions of the Athens earthquake

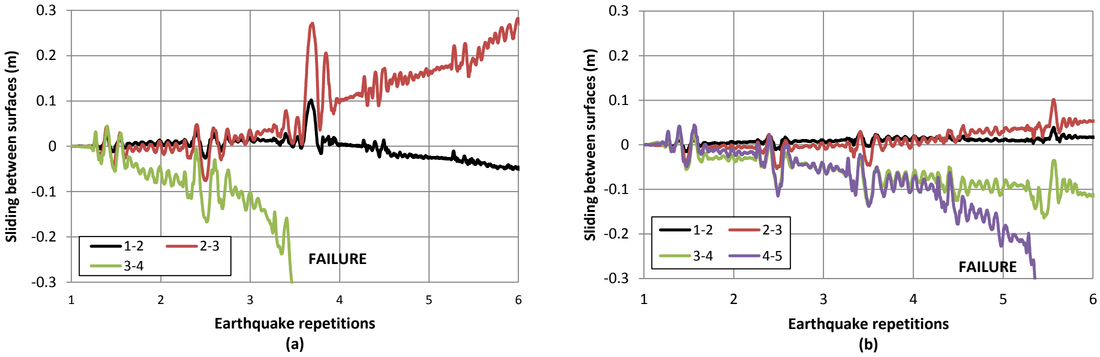


Fig. 16 Horizontal sliding at the interfaces of (a) the three-drum column and (b) the four-drum column with a width *W*=0.75 m, under a series of repetitions of the Kalamata earthquake

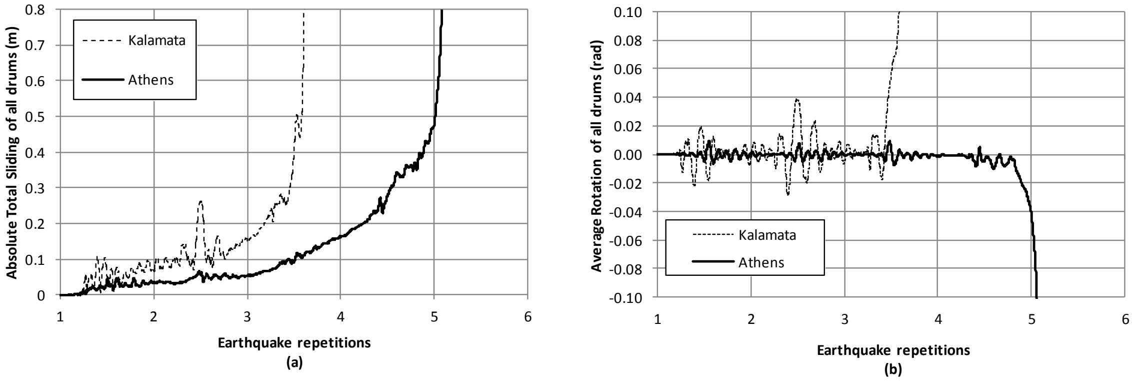


Fig. 17 Absolute total sliding (a) and average rotation (b) of a three-drum column under a series of repetitions of the Kalamata and the Athens earthquake

excessive sliding and rocking between drums). Obviously, this happens because of the significantly higher response spectra (acceleration and displacement) values, compared to the case

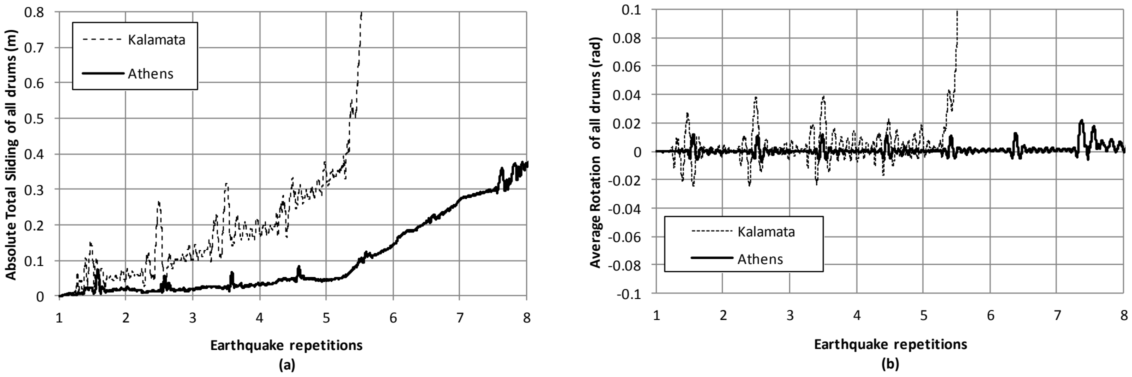


Fig. 18 Absolute total sliding (a) and average rotation (b) of a four-drum column under a series of repetitions of the Kalamata and Athens earthquake.

of the Athens earthquake (Fig. 6). It is known that high accelerations induce sliding, while the low frequency content is responsible for the rocking phenomena. Kalamata earthquake combines the aforesaid characteristics and, therefore, results in such pronounced effects, compared to the Athens earthquake.

The results presented are in agreement with Stefanou *et al.* (2014), who reported that hat the risk of collapse of an already damaged multi-drum column is higher that the risk of collapse of an intact column.

8. Conclusions

The aim of the current study was to investigate the effect of multiple earthquakes on the response of ancient multi-drum columns. For this purpose, a typical single-standing four-drum column has been numerically simulated under various actual seismic sequences, while twelve columns with different geometrical characteristics have been analysed using repeated ground motions as excitations. The following conclusions are based on the numerical results of a number of 2D analyses of the multi-drum columns described in previous sections and may not be directly applicable to other columns with similar geometry or under different excitations, due to the high nonlinearity of the problem.

The computed results indicate that subsequent seismic events, which may occur in relatively short time after an earthquake, despite the fact that in most of the cases they have lower intensity (PGA) than the first seismic event, can induce further deformations to a multi-drum column that has survived through the main shock and, thus, increase the risk of collapse. However, there are few exceptional cases where such aftershock events may have a beneficial restoring effect on the deformed column’s behavior. Nevertheless, there are no indicative characteristics of the excitation that may help for the prediction of such a behavior and, therefore, there is an uncertainty in defining a design sequential excitation for a particular multi-drum structure. On the other hand, in the simulations where the same ground motion has been repeatedly applied at various types of multi-drum columns, to simulate the fact that such structures may experience very similar seismic events more than once during their long life-spans, the total sliding between drums is progressively increased at each repetition until collapse.

Moreover, the results indicate that there is a strong influence of the ground motion characteristics on the overall performance of the multi-drum columns. Specifically, as also noted by other researchers, the response is highly affected by the predominant frequency content of the ground motion, while the peak ground acceleration doesn't seem to play a significant role.

In addition, the width of the multi-drum column affects the stability of the column under repeated earthquakes. Specifically, slender columns of relatively small width are more vulnerable to rocking phenomena and may collapse under fewer repetitions of a strong earthquake during their life-spans, compared to wider columns where sliding prevails. Furthermore, the number of drums seems to increase the stability of a column under certain circumstances. For example, in the case of relatively large widths increasing the number of drums without increasing the total height of the column seems to have a beneficial effect, while in the case of slender columns, where rocking prevails, the increased number of drums does not improve the column's stability.

As previously noted, the results and conclusions of the current research study are based solely on numerical simulations, using a methodology that has two notable limitations: (i) the dynamic analyses are performed in two-dimensions and (ii) only horizontal seismic components are considered. Therefore, these considerations can be set as aims for potential future extensions of this research work. For example, it would be interesting to compare the results from such numerical simulations with experimental results, even using small-scale experiments. Moreover, the presented methodology and the specialised software could be extended to enable three-dimensional simulations, in order to consider more influencing parameters in such a complex structural behaviour.

Finally, in the presented research study, the accumulation of damage due to successive earthquakes is represented only by the geometric changes due to sliding and rocking, assuming infinitely rigid drums. However, in practice, the drums may undergo deformation and local damage due to rocking phenomena in the form of cracks and corner breakages, which are omitted in the presented methodology. Such effects could be considered in future extensions of this research work.

Acknowledgements

This project with protocol number "ΑΝΘΡΩ/0609(ΒΕ)/23" is co-funded by the European Regional Development Fund and the Republic of Cyprus through the Research Promotion Foundation.

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