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ORIGINAL RESEARCH PAPER

Experimental investigation of the seismic response of classical temple columns

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Abstract Remnants of Greek Temples are found all over the Mediterranean, surviving in most cases in the form of free-standing columns. The drums are resting on top of each other without any connection, being considered susceptible to strong seismic shaking. Their seismic response is complex, comprising a variety of mechanisms, such as rocking of sliding of the drums relative to each other. This paper studies experimentally the seismic performance of such structures, aiming to derive insights on the key factors affecting the response. Physical models of such multi-drum columns were constructed at reduced scale and tested at the shaking table of the NTUA Laboratory of Soil Mechanics. The marble specimens were excited by idealized Ricker wavelets and real seismic records. The tested multi-drum columns were proven to be very earthquake-resistant. Even when subjected to the strongest motions ever recorded in Greece, their permanent deformation was minimal.

Keywords Multi-drum columns · Rocking response · Shake table testing · Monuments

1 Introduction

Historical monuments are among the highest pieces of heritage of a nation and, as expected, their preservation is considered to be of enormous importance both for the local communities and the mankind as a whole. Their protection against natural hazards is a very complicated and challenging task, calling for an inter-disciplinary collaboration. Greek and Roman Temples, found all over the Mediterranean, are of particular importance as they are located in an area of high seismicity. Unfortunately, only few of these monuments are intact, most of them being

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surviving in the form of free-standing columns. Such structures are composed of marble drums, resting on top of each other without any connection. Being extremely slender, they are usually considered prone to overturning. During seismic shaking, the drums may slide and rock relative to each other, further complicating the seismic response of the column. The seismic response of such structures has been studied analytically, mainly dealing with simple columns (consisting of one or two blocks) (e.g., Perry 1881; Housner 1963; Psycharis and Jennings 1983; Koh et al. 1986; Psycharis 1990; Manos and Demosthenous 1992; Makris and Roussos 2000; Apostolou et al. 2007). Multi-drum columns are much more difficult to be studied analytically, as the equations of motion are different for each mode of vibration, and the number of modes increases exponentially with the number of the drums (Kounadis 2012). Experimental simulation is also quite complicated, and as a result only few physical model tests on assemblies of blocks have been attempted, mainly focusing on the seismic response of single-block columns (e.g., Guidotti 1982; Giuffre 1986).

More realistic replicas of actual monuments have been tested more recently, such as the Colonna Antonina in Rome (Krstevska et al. 1996) and the Parthenon of the Acropolis of Athens (Mouzakis et al. 2002). Although such studies have offered valuable insights, there are several unresolved issues that have not been addressed. For this purpose, as part of the PERPETUATE research project (Lagomarsino et al. 2010, 2011; D'Ayala and Lagomarsino 2014) a series of shaking table tests were conducted at the NTUA Laboratory of Soil Mechanics, using an idealized multi-drum column as conceptual prototype. The paper presents the key findings of the experimental study, focusing on the response of single multi-drum columns. The performance of portal structures is presented in Drosos and Anastasopoulos (2013).

2 Physical modeling methodology

Although numerous classical Temples still survive around the Mediterranean (mainly in Greece, Italy, and Turkey), only few have maintained their structural integrity, and most survive in the form of free-standing columns. An example of a relatively well preserved monument of this type is shown in Fig. 1, referring to the Temple of Athena at Aegina. Given the fact that this is the current state of such monuments, the experimental campaign focused on free-standing multi-drum columns. Although the design and construction of such Temples was to a certain extend standard, there is a significant variability in terms of their geometry (Jones 2001). As discussed in more detail in Drosos and Anastasopoulos (2013), the Temple of Apollo at Bassae in southern Greece is selected as a conceptual prototype. Besides being a representative example, this specific Temple has been thoroughly surveyed by the American School of Classical Studies at Athens (Cooper 1996), and hence its geometric attributes are thoroughly documented.

Each column has a height $H = 6$ m (including the capital), while its diameter is reduced with height, varying from $d_{max} = 1.2$ to $d_{min} = 0.9$ m. The capital, sitting on top of the column, has height of 0.5 m and a variable geometry in plan, starting from a circular cross-section of $d_{min} = 0.9$ m (to sit on top of the last drum), and progressively transforming to a 1.2 m square cross-section (to provide support to the epistyle). The columns were almost always placed on top of a thick (stone or marble) pedestal: the *krepidoma*. Given the fact that most such monuments are built on rock sites, and accounting for the large thickness of the krepidoma (of the order of a meter), it was reasonably assumed that the columns are on more-or-less rigid base. To further reduce the complexity of the problem, it was decided to use 5 drums per column (the lower bound of the actual monument). It is emphasized that the physical model was meant to be a generic model of such structures, not an exact replica

Fig. 1 Part of the Temple of Athena at Aegina: a characteristic example of ancient monuments around the Mediterranean

of a specific temple. The columns were sculpted as monolithic structures, using a single block of marble, and then cut into five blocks (the drums). The capitals were constructed separately. The krepidoma was simulated with a slab of (the same) marble, rigidly fastened on the shaking table. After each shaking event, the model was re-aligned to its initial position.

Taking account of the capacity of the shaking table, a scale of 1:5 was selected for the experiments. For reduced-scale (1 g) testing, the scaling laws of Table 1 were applied. As discussed in detail in Calderini et al. (2014) and Lagomarsino (2014), if the seismic excitation is appropriately scaled in terms of time (as described in Table 1), the displacement demand on the scaled model will be compatible to the prototype and the results can be claimed to be representative. The model was constructed using the same material as the conceptual prototype (marble) and the static friction coefficient at the drum-to-drum interfaces was measured equal to 0.7 after a series of quasi-static push-over tests conducted. A detailed description of the procedure is included in Drosos and Anastasopoulos (2013). The physical model of the column is presented in Fig. 2, along with the protective cage (to prevent damage to the instruments) and the instrumentation (all dimensions in model scale). The dimensioning of the protective cage is discussed in Drosos and Anastasopoulos (2013). Accelerometers were installed at mid-height of each drum to record the horizontal acceleration at the direction of seismic shaking. Two wire displacement transducers were installed, one at the bottom and one at the top of every drum to measure its horizontal displacement and rotation. The capital was also instrumented with an accelerometer and three displacement transducers to measure the rotation about the vertical axis, as well. Two digital cameras were utilized, one opposite the specimen to capture the in-plane motion, and the second one above the column to capture the “parasitic” out-of-plane motion. After each shaking, the deformed shape of the column was photographed. The photos were used to measure the residual displacement of the drums applying image correlation techniques (Drosos and Anastasopoulos 2013).

As depicted in Fig. 3, a variety of real seismic records and idealized Ricker wavelets were used as seismic excitation. The latter have a small number of strong motion cycles, and are representative for directivity-affected seismic motions. Having a well-defined characteristic frequency, such idealized motions are ideal for parametric studies of frequency-related effects (e.g., Apostolou et al. 2007; Gazetas et al. 2009). To investigate the effect of frequency, and

Table 1 Scaling laws for 1: N reduced-scale testing

Quantity	Prototype/model
Length	N
Area	N^2
Volume	N^3
Mass	N^3
Density	1
Strain	1
Stress	N
Young's modulus	N
Time	$N^{0.5}$
Frequency	$N^{-0.5}$
Acceleration	1
Force	N^3
Moment	N^4

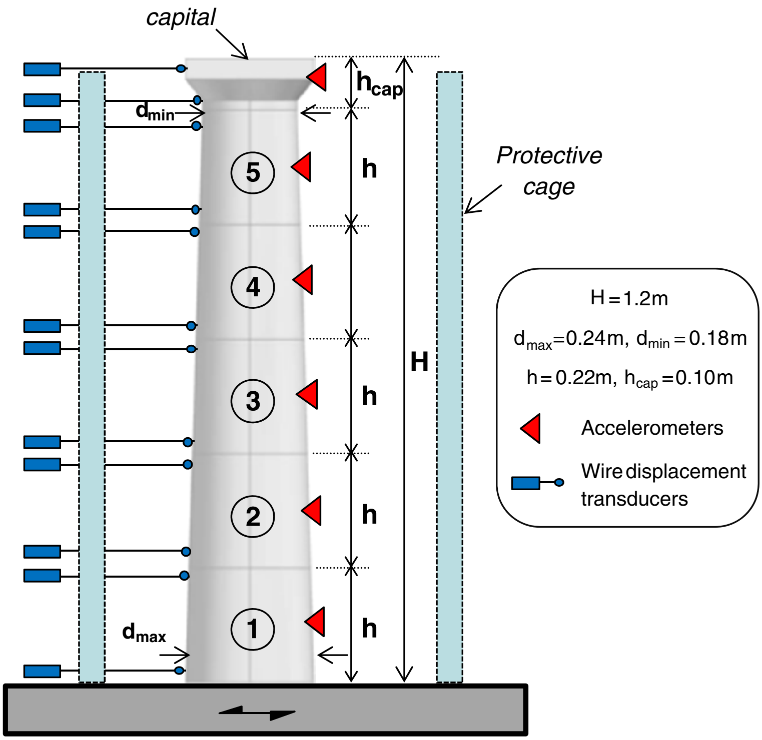

Fig. 2 Key dimensions of the physical model of the multi-drum column, along with the protective cage and the instrumentation (all dimensions in model scale)

given the capacity of the shaking table, the frequency was varied from $4p$ to $6p$, where $p = \sqrt{mgR/I_0}$ is the frequency parameter of the equivalent rigid block of mass m (assuming that the entire column is rocking as a rigid body), radius R (the distance from the block's

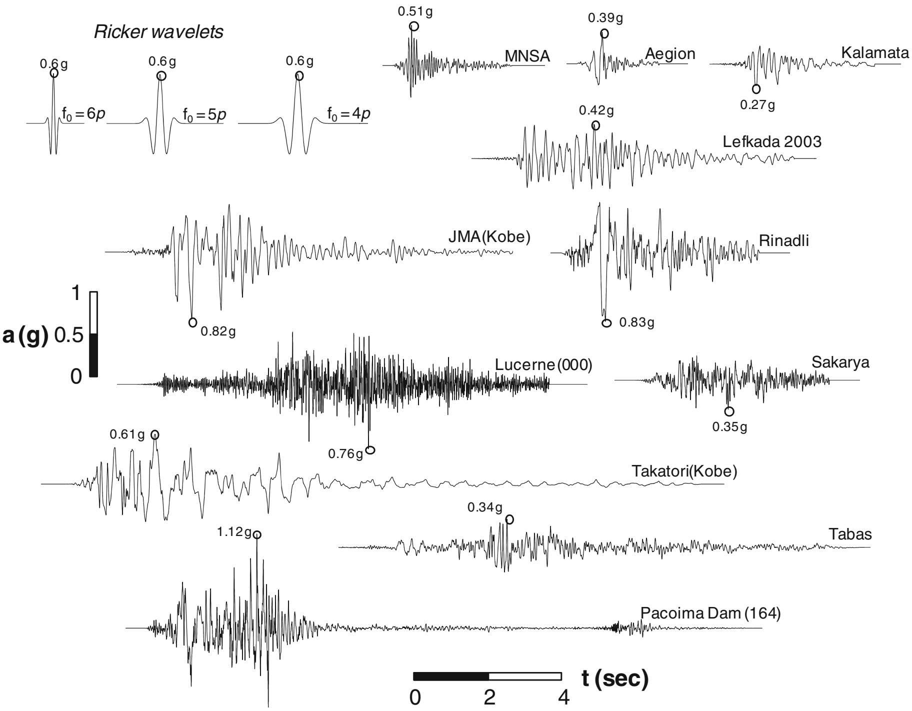

Fig. 3 Real records and artificial motions used as seismic excitation in the tests

center of mass to the pivot point), and mass moment of inertia about the centroidal axis I_0. It is well known that the oscillation frequency of a rigid block under free vibration is not constant, as it depends on the oscillation amplitude (Housner 1963). The value of p of the studied model is 1.55 rad/s (=0.25 Hz) in prototype scale, or 3.47 rad/s (=0.56 Hz) in model scale. Hence, the frequencies of the Ricker pulses ranged from 2.24 to 3.36 Hz (model scale). The amplitude was also parametrically varied, ranging from 0.2 up to 1.0 g.

3 Ricker wavelets: the effect of frequency content

As previously discussed, the Ricker wavelets were used to parametrically investigate the dynamic performance under idealized conditions. Characteristic results are presented herein, focusing on the key aspects affecting the seismic performance of multi-drum columns. The detailed experimental results are documented in Drosos et al. (2012).

Figure 4 compares the response of the column for four seismic excitations of varying frequency ($f_0 = 6p$ to $4p$) in terms of distribution with height of maximum acceleration, displacement, and rotation. While the maximum acceleration is almost constant with column height (Fig. 4a), the upper drums are subjected to much larger maximum displacements δ_{max} (Fig. 4b) and rotations θ (Fig. 4c). Quite interestingly, the differential rotation θ_{diff} (i.e., the relative rotation between two consecutive drums) is maximized at mid-height (between drums 3 and 4), probably revealing an imperfection of the corresponding drum-to-drum interface. Lower-frequency motions clearly lead to more intense rocking of the column, as clearly evidenced by the distribution of δ with height (Fig. 4b).

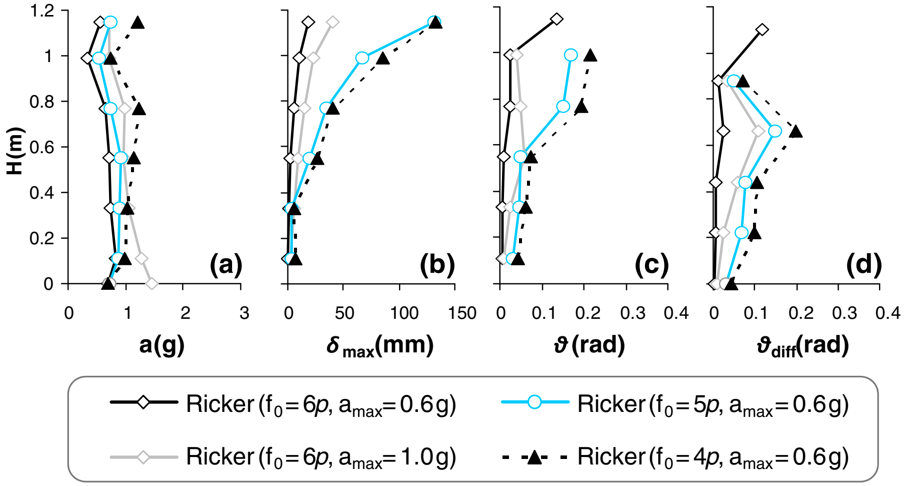

Fig. 4 Multi-drum column subjected to Ricker seismic excitations of varying characteristic frequency f_0. Distribution with column height of: **a** maximum acceleration a; **b** maximum horizontal displacement δ_{max}; **c** maximum rotation θ; and **d** differential rotation θ_{diff} between consecutive drums (erroneous measurements of the capital have been removed)

This is further confirmed in Fig. 5, which provides a comparison in terms of time histories of drum displacement. Contrary to the displacements and rotations, the maximum value of acceleration at the top of the column (i.e., recorded on drum No. 5) is almost insensitive to the frequency f_0 and the amplitude a_{max} of the seismic excitation (Fig. 6)—provided, of course, that the seismic excitation is strong enough to provoke rocking. Due to the presence of joints (between drums), the moment and shear that can be transmitted is limited by drum uplifting and sliding, respectively, leading to the observed acceleration cut-off—a quite effective seismic isolation. The observed high-frequency acceleration spikes are due to impacts between adjacent drums during rocking.

The decrease of the frequency of the excitation made possible the observation of another interesting phenomenon: although seismic shaking was applied in one direction, significant out-of-plane displacements were also observed. In fact, in some cases the predominant residual deformation of the column was in the out-of-plane direction. As discussed in Drosos and Anastasopoulos (2013), this seemingly chaotic behavior is related to the circular cross section of the drums, due to which they are prone to rolling along their perimeter. During rocking, the contact area between the drums becomes very small, and even the slightest imperfection of the drum-to-drum interface (which is practically inevitable, especially for drums that have been rocking before and their interface has been damaged in the perimeter) may lead to initiation of rolling. Although such behavior is considered quite unstable, it did not lead to collapse.

For the same excitation frequency ($f_0 = 5p$), further increase of the nominal excitation amplitude to $a_{max} = 1.0$ g finally led to collapse. As shown in the snapshot of Fig. 7a, due to its excessive (almost rigid-body) rotation, the column impacted the protective cage during the test, which impeded the collapse. In reality (i.e., in the absence of a protective cage) the column would have collapsed. In the sequel, the column was subjected to even longer-period seismic excitations of characteristic frequency $f_0 = 4p$ and progressively increasing amplitude. Up to $a_{max} = 0.6$ g, although the drum rotations were quite large, the column remained stable. Further increase of a_{max} to 0.8 g led to the collapse of the capital (Fig. 7b).

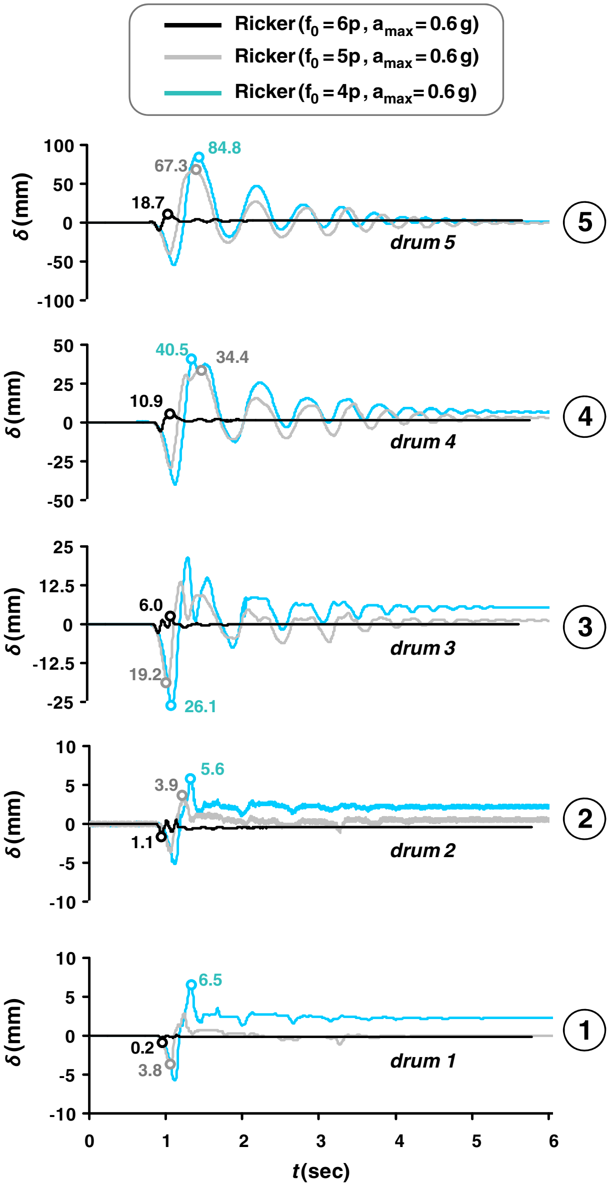

Fig. 5 Multi-drum column subjected to Ricker seismic excitations of varying characteristic frequency f_0: horizontal displacement time histories of the drums

4 Real seismic records

Ricker pulses facilitated deriving insights on the effect of excitation frequency and amplitude on the performance of multi-drum columns. Although such motions are more realistic than sinusoidal ones, they are still artificial. Therefore, the real accelerograms of Fig. 3 were

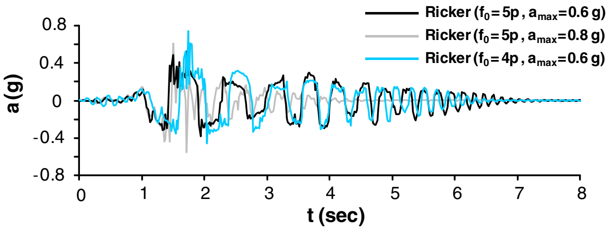

Fig. 6 Multi-drum column subjected to Ricker seismic excitations of varying characteristic frequency f_0 and amplitude a_{max}: acceleration time histories of drum No. 5

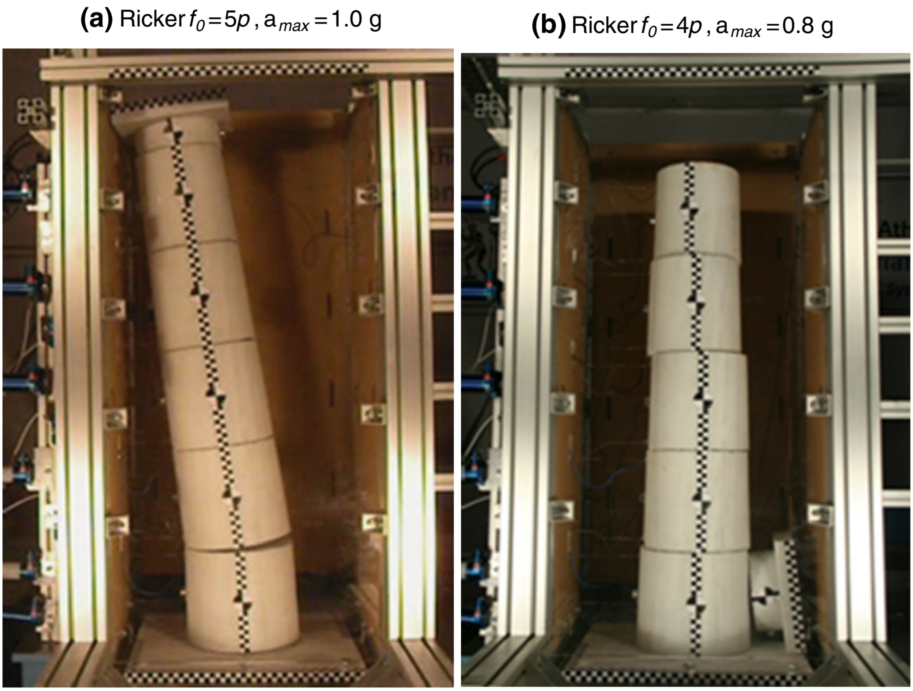

Fig. 7 Multi-drum column subjected to Ricker seismic excitations. *Snapshots* of column deformation: **a** $f_0 = 5p$, $a_{max} = 1.0$ g—column collapse was impeded by the protective cage; and **b** $f_0 = 4p$, $a_{max} = 0.8$ g—toppling of the capital

subsequently utilized to explore the seismic response of the column under more realistic conditions.

As documented in Drosos et al. (2012), the shaking sequence started with moderate intensity records from Greece. Among them, the Monastiraki (MNSA) accelerogram is of particular significance, as it was recorded at a distance of less than 1 km from the Acropolis of Athens (one of the most important monuments of this kind), during a M_s 5.9 earthquake that shook the city of Athens in 1999, causing 145 fatalities due to the collapse of 100 buildings, and severe damage to 13,000 buildings (Stavrakakis et al. 2002). In accord with what actually happened during the Athens earthquake (no damage was observed in the Acropolis' monuments), the maximum displacement at the higher drum (No. 5) did not exceed 3 mm, leaving the column practically intact. Despite its relatively large PGA of 0.51 g (which is 2.5 times larger than the pseudo-static toppling acceleration of the equivalent rigid block $a_c = 0.2$ g), the MNSA record is a high-frequency excitation, not containing enough energy to provoke intense rocking.

The shaking sequence continued with the Kalamata (KLMT) and Lefkada 2003 (LFK03) records, which led to larger maximum displacements (of the order of 10 mm), but still with negligible residual deformation. The single column was more sensitive to the Aegion (rock) record, experiencing 18 mm of maximum displacement of drum No. 5 and more than 20 mm at the capital. Still though, the permanent displacement was practically zero. Nevertheless, the performance of the column subjected to moderate intensity records from Greece was exceptional in all cases, hardly suffering any permanent deformation. Since many of these monuments are situated in Greece, this is a very important and positive conclusion.

Despite being the strongest motions ever recorded in Greece, these four records cannot be assumed to cover the entire range of possible seismic motions that such monuments may experience. Exactly for this reason, and to explore the margins of safety of such structures, a variety of strong to very strong records from all over the world were also simulated. The results of these tests are discussed in detail in Drosos and Anastasopoulos (2013). The multi-drum column managed to survive the Kobe JMA record (e.g., Nakamura et al. 1996), which is characterized by a *PGA* of 0.82 g and spectral accelerations (*SA*) in excess of 1.5 g for a wide range of periods. It only collapsed when subjected to even stronger seismic excitations: Pacoima Dam, Rinaldi, and Takatori. These three near-field accelerograms are extremely destructive, as they contain excessively strong directivity pulses and a long-period frequency content. It is therefore quite reasonable that the column did not manage to survive.

5 Summary of test results

The results of all 25 tests are summarized in Fig. 8 in terms of maximum horizontal displacement δ_{max} of drum No. 5, which is considered a reasonable damage indicator, with respect to two different intensity measures: (a) the maximum spectral displacement SD_{max}; and (b) the length scale L_p. As shown in Drosos and Anastasopoulos (2013), the *PGA* of the base excitation was found to be a very poor intensity measure. SD_{max} has been proposed by

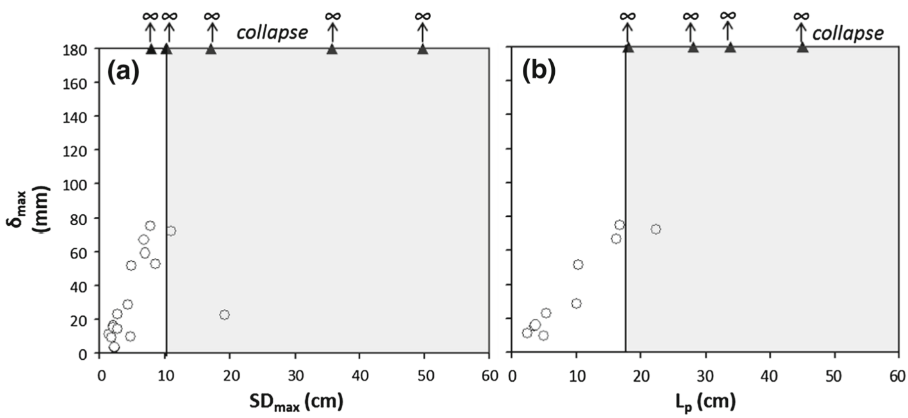

Fig. 8 Summary of test results: maximum horizontal displacement δ_{max} of d drum No. 5 (*top*) as a function of: **a** maximum spectral displacement SD_{max}; and **b** length scale L_p of the seismic excitation

Gelagoti et al. (2012) as an index of the maximum anticipated seismic displacement demand for rocking systems. Its validity has been verified for *rigid-blocks* rocking on a *rigid-base*, and for a rocking-isolated frame structure founded on nonlinear soil. Motivated by the special nature of near-field ground motions (large velocity pulses), several researchers (Veletsos et al. 1965; Makris 1997; Makris and Chang 2000; Mavroeidis and Papageorgiou 2003) have tried to approximate the main kinematic characteristics of such motions with closed-form expressions. The characteristic length scale $L_p = T_p v_p$ has been proposed by Makris and Black (2004), as an indicator of the persistence of the prevailing velocity pulse.

As shown in Fig. 8a, the correlation of δ_{max} with SD_{max} is quite meaningful, and certainly much better than the one with *PGA* (Drosos and Anastasopoulos 2013). Considering an equivalent rigid block, the required SD_{max} to provoke toppling collapse would be roughly equal to the half-width of the column, which is roughly equal to 10 cm. Although this can only be seen as an approximation, it proves quite successful: with a single exception (out of 25 tests), the column collapses only when $SD_{max} > 10$ cm. On the other hand, it is worth observing that there are several cases in which the column did not collapse, although the seismic motion had $SD_{max} > 10$ cm. This is directly related to the fact that the drums can rotate and slide relative to each other, dissipating large amounts of energy and leading to increased margins of safety compared to the equivalent rigid block.

The correlation is improved further when considering the length scale L_p (Fig. 8b). With the exception of a Ricker pulse of $f_0 = 5p$ and *PGA* = 0.8 g, there seems to be a critical L_p of the order of 18 cm, below which the column is safe. However, it is emphasized that this refers only to the records that can be approximated by a single pulse of duration T_p and velocity amplitude v_p. Hence, although L_p is better than SD_{max}, its applicability is limited to directivity-affected motions.

6 Conclusions

The paper has presented an experimental study of the seismic performance of multi-drum columns of ancient Greek/Roman Temples. Reduced scale (1:5) models of a single multi-drum column and of a twin-column portal were tested at the shaking table of the NTUA Laboratory of Soil Mechanics. This paper has focused on single columns, and the seismic performance of portal structures is discussed in Drosos and Anastasopoulos (2013). The physical model of the column was constructed of marble. Ricker wavelets and real seismic records were used as seismic excitation, and a parametric study was conducted to investigate the effect of acceleration amplitude and frequency content. Before summarizing the key conclusions, it is necessary to note certain limitations of the study presented herein. As previously mentioned, the idealized five-drum column is a realistic but simplified analogue of reality. Most importantly, scale effects may play a major role, and the experimental results presented herein should be extrapolated to prototype scale with caution.

The seismic performance of multi-drum columns is quite remarkable. At least for the cases examined herein, such structures are proven capable of sustaining moderate intensity seismic shaking almost with no damage and negligible permanent deformation. Subjected to the strongest motions ever recorded in Greece, where many of these monuments are situated, the columns hardly suffered any permanent deformation. Collapse is probable only for extremely strong directivity-affected seismic excitations. Their exceptional performance is attributed to the multitude of energy dissipation mechanisms of such systems. Besides rigid-body rocking, sliding and/or rocking between drums also take places, leading to increased energy dissipation and continuous shifting between different modes of response. In contrast to the *PGA*, the maximum spectral displacement SD_{max} and the length scale L_p are proven to be quite effective measures of intensity.

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