EFFICIENT INTENSITY MEASURES FOR THE SEISMIC ASSESSMENT OF FREE-STANDING COLUMNS AND COLONNADES

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ABSTRACT

Ancient classical temples constitute common historic monuments of great archaeological value. Many of these monuments remain nowadays as free-standing columns or colonnades. This study aims to shed light on the efficiency of various seismic intensity measures of the base excitation to predict the stability of classical columns and colonnades subjected to uniaxial seismic shaking. A series of numerical analyses are performed for this purpose on representative structural systems using the finite element code ABAQUS. Two different multi-drum columns of diverse diameter, height and number of drums are investigated, including an Ionic column that has recently been restored at the Acropolis of Lindos in Rhodes and a Doric column of the Propylaea at the Acropolis of Athens. The latter column is used as a base for the investigation of the response of a colonnade that consists of three columns coupled with an architrave. The efficiency of numerical modelling is initially validated against experimental data from a series of shaking table tests that were performed on a scaled multi-drum model column. The validated numerical models are then used to evaluate the response of the actual columns and colonnade. The results of the parametric numerical analysis, in terms of the maximum displacement at the capital normalised by the base diameter are used as a representative performance criterion to identify optimal intensity measures for seismic assessment of this type of structures. The maximum spectral displacement $S_{D_{max}}$ of the base excitation was found to better describe the performance and stability of the free-standing multi-drum columns.

Keywords: Intensity measures; Multi-drum columns; Colonnades; Dynamic analysis; Rocking/sliding phenomena

1. INTRODUCTION

High-intensity earthquake events constitute a major threat for the stability of architectural heritage monuments in the Mediterranean, such as classical temples. Many of these monuments remain nowadays in ruinous state, consisting only of free-standing multi-drum columns or colonnades. This type of structures was commonly made of stone or marble blocks that were placed on top of each other, usually without connecting mortar. Hence, their geometric characteristics, i.e. size, height, diameter, number of drums etc. may vary significantly. Despite their present typology and their high slenderness, these structures have proved to be highly resistant to strong earthquakes over centuries, revealing a remarkably good seismic performance (Papantonopoulos 2002). However, collapse of the monument may occur, especially in the presence of imperfections on the structure (e.g. damaged drum corners; misplaced drums; missing structural components; inclined columns due to foundation failure) (Sarhosis et al. 2016).

The seismic response of multi-drum columns and colonnades is dominated by highly non-linear phenomena along the interfaces, including rocking and/or sliding of the drums during shaking (Psycharis et al. 2000). These mechanisms render their seismic response quite distinct compared to

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modern structures, where the seismic response is actually dominated by the hysteretic behaviour of the materials. In this context, it is usual to investigate the seismic response of multi-drum columns and colonnades numerically (Dimitri et al. 2011; Dasiou et al. 2013; Psycharis et al. 2013; Papadopoulos & Vintzilaioi 2014), implementing validated numerical codes. Experimental studies have also been conducted to better understand the complex dynamic response of rocking systems (Dasiou et al. 2008; Drosos and Anastasopoulos 2014a and 2014b). Both numerical and experimental studies have proved that the seismic response of rocking systems is highly sensitive to even small changes of critical parameters, such as the base excitation characteristics and the frictional characteristics of the interfaces between the drums (Mouzakis et al. 2002; Drosos & Anastasopoulos 2014a; Pitilakis et al. 2017).

Hence, all the above parameters should carefully be encountered in seismic analysis or structural vulnerability assessment of this kind of structures.

In this study, the efficiency of various seismic Intensity Measures (IMs) of the base excitation to predict the stability of classical columns and colonnades when subjected to uniaxial seismic shaking is examined. The analysis is conducted by means of three-dimensional full dynamic analyses of representative columns and colonnades, implementing the finite element code ABAQUS. In particular, two different multi-drum columns of diverse diameter, height and number of drums are investigated, including an Ionic column that has recently been restored at the Acropolis of Lindos in Rhodes, Greece, and a Doric column of the Propylaea at the Acropolis of Athens. The response of a colonnade from the Propylaea of the Acropolis of Athens, consisting of three columns coupled with an architrave, is also examined, since the response of colonnades might differ significantly from that of a free-standing column. The efficiency of numerical modelling to replicate the complex seismic response of multi-drum columns is initially validated against experimental data from a series of shaking table tests that were recently performed on a scaled column model at National Technical University of Athens (Drosos and Anastasopoulos 2014a and 2014b). The validated numerical models are then used to evaluate the response of the actual columns and colonnade for various seismic base excitations. The results of the parametric numerical analysis, in terms of maximum displacement of the capital normalised by the base diameter of the column are used as a representative engineering demand parameter (EDP) to identify the optimal seismic intensity measures for seismic assessment of this type of structures.

2. VALIDATION OF NUMERICAL MODELLING

The efficiency of the numerical modelling to replicate the complex seismic behaviour of multi-drum columns is verified against experimental data from a series of shaking table tests that were carried out on a 1:5 scaled multi-drum column at the National Technical University of Athens (NTUA).

The model column, which was made of marble, consisted of five drums and a capital atop and was rested on a marble plate that was fixed on the shaking table. The geometric properties of the model column are provided in Figure 1a. The model was subjected to a series of base excitations, comprised uniaxial idealized pulses and real strong motion records from recent earthquakes, while the response was recorded by a dense instrumentation scheme of accelerometers and displacement sensors. More details about the model set-up, the testing procedure and recorded data may be found in Drosos & Anastasopoulos (2014a; 2014b).

The free-standing column was numerically simulated as a three dimensional multi-drum structure in ABAQUS (2012). The analyses were conducted in model scale, in order to avoid problems related to the proper conversion of the highly non-linear response (e.g. rocking phenomena), from the model to prototype scale. The drums, the capital and the base (marble plate), were simulated as deformable bodies, using three-dimensional eight-node solid elements (Figure 2a). Appropriate discretization was selected, to simulate the cylindrical geometry, taking into account the positions of the recorders. The interfaces between the structural members (i.e. the drums, the capital and the base) were modelled using an advanced finite sliding ‘hard contact’ model embedded in ABAQUS. This model implements a ‘strict’ algorithm to preclude the potential penetrations of the interacting structural elements during shaking, while it allows for detachments, i.e. no tensile stresses are developed at the interfaces. The tangential behaviour of the interfaces was modelled by introducing the Coulomb friction model. The interface friction coefficient was set equal to 0.4, following Drosos & Anastasopoulos (2014a, 2014b).
A linear elastic behaviour was adopted for the all the structural members. The model was calibrated based on the following mechanical properties of the particular marble material: density $\rho$, Young’s Modulus $E$ and Poisson ratio $\nu$, set equal to 2.4 t/m$^3$, 35 GPa and 0.2 respectively. All the analyses were performed assuming a zero material damping, which might be considered as a conservative assumption (Psycharis 2014).

Figure 1. Geometric properties of (a) the model column tested at NTUA (modified after Drosos and Anastasopoulos 2014) (b) the multi-drum column at the Akropolis of Lindos in Rhodes, (c) the multi-drum column at the Propylaea of the Acropolis of Athens (modified after Dinsmoor and Dinsmoor Jr. 2004)

Figure 2. (a) Numerical model of the model column tested at NTUA, (b) simulation of ground shaking motion at the base

The analyses were performed in two steps. Initially, the gravity loads were introduced, within a static step. Subsequently, the seismic excitations were applied at the base of the marble plate in x direction following the axes convention of Figure 2b, within a dynamic implicit step. The potential second order effects were encountered throughout the analysis.

Despite the high sensitivity of the dynamic response of these rocking systems by many salient parameters, the numerical modelling was found capable to predict the collapse or stability of the
column for the large majority of the seismic excitations. As an example, figure 3 portrays typical comparisons of deformed shapes of the multi-drum model column recorded during shaking of the model column and predicted by the numerical analyses for different idealized pulses of Ricker type. The deformed shapes refer to completion of analysis (i.e. either at the end of the shaking motion, e.g. Figure 3a, or at the time step when the column collapses, e.g. Figures 3b and 3c). Generally, the numerical analyses reproduce reasonably well the actual deformation mechanisms of the column. More details regarding the numerical modelling validation are provided in Karafagka (2013) and Pitilakis et al. (2017).

Figure 3. Deformed shapes of the tested multi-drum column, observed during testing and computed by the numerical analyses for (a) a Ricker wavelet with PGA = 0.60 g and frequency $f_o = 3.30$ Hz, (b) a Ricker wavelet with PGA = 0.80 g and frequency $f_o = 2.20$ Hz and (c) a Ricker wavelet with PGA = 1.0 g and frequency $f_o = 2.75$ Hz (analysis in model scale)
3. OVERVIEW OF THE CASE STUDIES

Two different multi-drum columns of diverse size, slenderness and number of drums were examined within this study, including a smaller Ionic column that has recently been restored at the Acropolis of Lindos in Rhodes, Greece, and a larger Doric one of the Propylaea at the Acropolis of Athens. Both columns were simulated numerically, following a similar approach as for the model column described above. The numerical models accounted for the actual dimensions and material properties of the structural members. The interfaces between the structural members were simulated using the same interface model, as per Section 2. The interface friction coefficient, $\mu$, along the interfaces of the drums was set equal to 0.7, a value widely acceptable for these types of structures.

3.1 Multi-drum column at the Acropolis of Lindos, Rhodes

Southwest of the temple of Athena at the Akropolis of Lindos in Rhodes, four sections of a stylobate, carved in the rock, were found in a northwest-southeast direction, perpendicular to the temple. According to the archaeological research, these remnants are parts of the Stoa of Psithyros, which was added to restrict the access to the southern side of Acropolis and the inner courtyard surrounded by Propylaea (Markou & Pikoula 2015). The facade consisted of seven Ionic columns made of limestone. In 2013, it was decided to restore a column to its full height, using ancient and new members. The latter that were used to fill the damaged ancient member, have similar mechanical properties and analogous mass with their ancient counterparts (Karafagka et al. 2015). The column is composed of six drums and a capital and has a full height of 4.26 m. The detailed dimensions of the members are provided in Figure 1b. The restored drums and the capital were placed one on top of the other, without any connection between them. A perfect bonding between the new and ancient counterparts has been considered for the severely damaged ancient structural elements that were completed with new material. The use of a large number of titanium rods and strong mortar at the interfaces between the ancient and new counterparts ensured such a solid connection. In this context, these drums are modelled as solid structural elements.

The analyses were conducted, introducing a modulus of elasticity, $E$, equal to 1044 MPa and a Poisson ratio, $\nu$, equal to 0.2, to both the ancient and the new members (Papachristodoulou et al. 2002). The density, $\rho$, was set equal to 1.75 and 1.95 t/m$^3$ for the ancient and the new parts, respectively. An average density, ranging between 1.75 and 1.95 t/m$^3$, was set in the case of the structural members that consisted of both ancient and new parts, based on the actual volume of the new and ancient material.

3.2 Multi-drum column of the Propylaea at the Acropolis of Athens

The second column investigated herein is the west multi-drum column of the southwest wing of the Propylaea of the Acropolis of Athens. According to Dinsmoor and Dinsmoor Jr. (2004), the west column, which follows the Doric order, was taken down and built into the medieval tower that surmounted the wing. The drums of the west column, despite having been squared off and otherwise mutilated in their reuse, remained in sufficiently good condition for the rebuilding of 1957-1958, even fitting together without gaps. The column is made of Pentelic marble and composed of seven drums and a capital, while it has a total height of 5.85 m (Figure 1c).

The materials of the monument members, are modelled using the mechanical properties of the Pentelic marble, with a modulus of elasticity, $E$, equal to 45 GPa, Poisson ratio $\nu$, equal to 0.33 and the density, $\rho$, equal to 2.7 t/m$^3$, values based on the available literature data for this marble quality.

The investigated columns, along with the tested model column, are of different size and slenderness (e.g. the height to base ratios range from 5.00 for the tested scaled column at NTUA, to 7.93 for the Stoa of Psithyros column, and to 5.45 for the Propylaea column) and consist of diverse numbers of drums. Hence, they may be considered representative of a broad spectrum of multi-drum columns found today.
3.3 Colonnade of the Propylaea at the Acropolis of Athens

In addition to the previous multi-drum column cases, the colonnade of the southwest wing of the Propylaea of the Acropolis of Athens was examined. The colonnade, made of Pentelic marble, consists of three multi-drum columns connected at the top with an epistyle. The latter is composed of two orthogonal single blocks of 2.506 m in length, 0.90 m in width and 0.808 m in height. The epistyle is not connected with the three columns by any means, and is simply lying on the columns. In the present study, the three multi-drum columns are assumed to have identical dimensions with the single multi-drum column presented in section 3.2. All the structural elements, i.e. the drums, the capitals, the stylobate and the epistyle, are simulated as deformable bodies, using three-dimensional eight-node solid elements (Figure 4). The interface friction coefficient, $\mu$, along the interfaces of the structural elements is set equal to 0.7, similar to the previous analyses.

![Figure 4. Numerical model of the colonnade of the Propylaea of the Acropolis of Athens](image)

3.4 Seismic base excitations

The frequency characteristics of the base excitation are highly affecting the dynamic response of rocking systems. Thus, the selection of adequate earthquake records, to be used as base excitations, is vital for the seismic analysis of these structures. In this context, various records with diverse frequency content, along with a synthetic time history, were used in the herein study. The latter excitation was obtained through a deterministic seismic hazard analysis of the Acropolis rock (Ntinoudi 2015) and refers to an earthquake scenario related to the activation of Fili fault. Table 1 summarizes the main characteristics of the selected base excitations and the structures (i.e. Lindos column, Propylaea column, colonnade) to which they were applied. All the excitations were filtered between 0.05 and 20 Hz, using an eighth-order band pass Butterworth type filter. With the exception of the record from the Loma Prieta earthquake, the excitations were scaled up to various peak accelerations, ranging between 0.1 g and 1.0 g, so as to check the effect of seismic excitation amplitude on the seismic response of the multi-drum columns and the colonnade, for a wide range of excitation frequency characteristics.

A more rational procedure was followed to scale the record from the Loma Prieta earthquake, used in the analysis of the Lindos column. In particular, the amplitude and frequency characteristics of the record were properly adjusted so that its response spectrum to correlate with reference spectra that account for the seismicity of the region of Lindos. The reference spectra, which emerged from recent findings of the European research program SHARE (Giardini et al. 2013), correspond to return periods of 475 and 2475 years. The adjusting procedure was conducted using the SeismoMatch software (SeismoSOFT 2017). The selected excitations were imposed at the base of the numerical models, as uniaxial ($x$) horizontal shakings.
Table 1. Input motions characteristics.

<table>
<thead>
<tr>
<th>Structure applied</th>
<th>Earthquake (EQ) name</th>
<th>EQ Date &amp; Time</th>
<th>Station name</th>
<th>Magnitude (Mw)</th>
<th>Epicentral distance (km)</th>
<th>PGA (g)</th>
<th>Motion duration (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lindos column</td>
<td>Aquila, Italy</td>
<td>09/04/2009 (19:38:16)</td>
<td>L Aquila (V. Aterno - M. Pettino)</td>
<td>5.3</td>
<td>13.1</td>
<td>0.05</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Loma Prieta, USA</td>
<td>18/10/1989 (00:05:00)</td>
<td>Gilroy Array</td>
<td>6.93</td>
<td>28.6</td>
<td>0.44</td>
<td>20</td>
</tr>
<tr>
<td>Lindos &amp; Propylaea column</td>
<td>Erzincan, Turkey</td>
<td>13/03/1992 (17:18:40)</td>
<td>Erzincan (Meteorologij Mudurlugu)</td>
<td>6.6</td>
<td>13.0</td>
<td>0.33</td>
<td>16</td>
</tr>
<tr>
<td>Propylaea column</td>
<td>Kozani</td>
<td>13/05/1995 (08:47:15)</td>
<td>Kozani (Prefecture)</td>
<td>6.61</td>
<td>17.0</td>
<td>0.21</td>
<td>20</td>
</tr>
<tr>
<td>Propylaea column &amp; colonnade</td>
<td>Kalamata</td>
<td>13/09/1986 (17:24:34)</td>
<td>Kalamata (Ote Building)</td>
<td>5.99</td>
<td>11.0</td>
<td>0.23</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Fili scenario</td>
<td>Deterministic analysis</td>
<td></td>
<td>6.40</td>
<td>20</td>
<td>0.13</td>
<td>15</td>
</tr>
<tr>
<td>All</td>
<td>Athens, Greece</td>
<td>07/09/1999 (11:56:51)</td>
<td>Ano Liosia (Kipsely district)</td>
<td>6.04</td>
<td>17.0</td>
<td>0.12</td>
<td>20</td>
</tr>
</tbody>
</table>

4. EFFICIENCY OF SEISMIC INTENSITY MEASURES TO PREDICT THE SEISMIC STABILITY OF THE INVESTIGATED STRUCTURAL SYSTEMS

4.1 Multi-drum columns

The efficiency of various seismic Intensity Measures (IMs), to describe the stability of the multi-drum columns and colonnades is examined in this section, on the basis of the results of the numerical analyses carried out within this study. The structural response parameter used to describe the performance and overall stability of the structural models is the maximum displacement of the capital \( d_{\text{max}} \) computed during seismic shaking. The latter is normalised by the base diameter \( D_{\text{base}} \) of the investigated column, following Psycharis et al. (2013). The selected response parameter provides a measure of the maximum deformation level of the column (for the vast majority of the examined cases), as well as information on how close to collapse the column was during the ground shaking. The dimensionless parameters \( d_{\text{max}}/D_{\text{base}} \) calculated for all investigated cases from the numerical analyses were plotted against various earthquake intensity measures.

Figure 5 plots the normalized maximum displacement of the capitals, \( d_{\text{max}}/D_{\text{base}} \), of the examined multi-drum columns, as computed for diverse shaking motion scenarios, against the peak ground acceleration \( PGA \), the peak ground velocity \( PGV \), and the peak ground displacement \( PGD \) of the base excitation, as well as against the maximum values of the spectral acceleration \( SA_{\text{max}} \), spectral velocity \( SV_{\text{max}} \), and spectral displacement \( SD_{\text{max}} \) of the base excitation. To allow for an easy reading of the figure, the maximum displacement at the capital normalised by the base diameter in the y-axis is set equal to 1. Beyond this limit the analyses revealed toppling of the capital or total collapse of the column (these cases are noted as \( \infty \) in the figure).

Generally, the PGA of the base excitation is found to be a very poor intensity measure for this type of structures. As seen in previous studies (e.g. Psycharis et al. 2000; Pitilakis et al. 2017), the increase of the PGA of the base excitation does not necessarily lead to collapse of the column. A similarly poor correlation is observed between the normalised maximum displacement of the capital and the spectral acceleration of the base excitation \( (SD_{\text{max}}) \). The latter poor correlation is actually expected, since these structures do not possess natural modes in the classical sense (Psycharis 2014). Although the correlation between the normalised maximum displacement of the capital and the PGV of the base
excitation is better than the PGA, the results remain still scattered. The model column tested at NTUA, the column at Lindos and the column at Propylaea are found to be stable for $PGV < 0.50 \text{ m/s}$, $PGV < 0.30 \text{ m/s}$ and $PGV < 0.60 \text{ m/s}$ respectively. Similarly, these columns are found to be stable for $SV_{\text{max}} < 1.30 \text{ m/s}$, $SV_{\text{max}} < 0.75 \text{ m/s}$ and $SV_{\text{max}} < 1.45 \text{ m/s}$ respectively. So, there is not a consistent increase or decrease of the PGV or $SV_{\text{max}}$ (limit) with the dimension of the column. A better correlation is observed between the normalised maximum displacement of the capital and the PGD of the base excitation. The model column tested at NTUA, the Lindos column and the Propylaea column remain always stable for $PGD < 4 \text{ cm}$, $PGD < 11 \text{ cm}$ and $PGD < 16 \text{ cm}$ respectively, while with some exceptions, they collapse for $PGD > 4 \text{ cm}$, $PGD > 11 \text{ cm}$ and $PGD > 16 \text{ cm}$, respectively. Hence, the larger the diameter of the column the larger is the PGD for collapse, which makes sense from a physical viewpoint.

The maximum spectral displacement of the base excitation is found to be by far more efficient in the prediction of the stability of the examined columns. Indeed, the model column, the Lindos column and the Propylaea column remain always stable for $SD_{\text{max}} < 10 – 12 \text{ cm}$, $SD_{\text{max}} < 20 – 25 \text{ cm}$ and $SD_{\text{max}} < 45 – 50 \text{ cm}$, respectively, i.e. almost the half of the diameter of their base drum ($\approx D_{\text{base}}/2$). On the contrary, for $SD_{\text{max}} > D_{\text{base}}/2$, the columns collapse for the vast majority of the investigated cases. For the very few cases, where no collapse is observed for base excitations with $SD_{\text{max}} > D_{\text{base}}/2$, significant sliding and rocking along the interfaces is observed. The latter observation, which is in line with recent findings of Drosos & Anastasopoulos (2014a), is attributed to the fact that the drums can rotate and slide relative to each other in some shaking scenarios, dissipating large amounts of energy and hence leading to increased margins of safety. Although there is no theoretical basis for the better performance of $SD_{\text{max}}$ (Makris & Konstantinidis 2003), the given IM can be used as a conservative index of the maximum anticipated seismic displacement demand for rocking multi-drum columns. Additionally, its wide use by engineers, makes $SD_{\text{max}}$ a practical indicator for a preliminary estimation of the seismic risk for rocking structures (Gelagoti et al. 2012, Drosos & Anastasopoulos 2014a).

4.2 Colonnade

Generally, the seismic response of a colonnade structure is by far more complex compared to the one of a free-standing column. Generally, the analyses revealed some very high peaks on the horizontal acceleration time histories of the drums of the free-standing multi-drum columns, associated to the impacts between the drums during the rocking response of the structure. Such behaviour was highly reduced in the acceleration time histories of the colonnade structure. This observation constitutes an evidence of a more ‘linear’ response of the colonnade compared to that of multi-drum free-standing columns, confirming the experimental observations of Dasiou et al. (2008). Indeed, a comparison between the responses of the Propylaea free-standing multi-drum column and the analogous right multi-drum column of the colonnade, revealed a better seismic response of the column in the latter case (i.e. reduced deformations and higher stability) compared to the former one. The better performance of the colonnade, which has been verified in previous numerical and experimental studies (e.g. Drosos & Anastasopoulos 2014a), is attributed to the reduced rocking response of the drums offered by the increased weight on them due to the existence of the epistyle.

Similar to the analysis made for the multi-drum columns, the efficiency of various seismic IMs to predict the stability of the colonnade was examined, by plotting the, normalized by the base diameter, maximum displacement of the capital of the right multi-drum column of the colonnade, $d_{\text{max}}/D_{\text{base}}$, computed for diverse shaking motion scenarios against the examined IMs (Figure 6). The upper limit in the y-axis is again set equal to 1 for illustration purposes. Generally, the values of $d_{\text{max}}/D_{\text{base}}$ are much lower compared to those predicted for the relevant multi-drum column, verifying the better performance of the colonnade structure. Additionally, a general increasing trend of the response parameter $d_{\text{max}}/D_{\text{base}}$ with increasing IMs is observed. Since the colonnade, remains stable for all investigated excitations, it is not easy to draw a clear conclusion for the efficiency of the examined IMs to predict the collapse of colonnades.
Figure 5. Summary of numerical results for the examined multi-drum columns: variation of the normalized maximum displacement of the capital, $d_{\text{max}}/D_{\text{base}}$, with different seismic intensity measures (IMs)
Figure 6. Summary of numerical results for the examined multi-drum column of the Propylaea colonnade: variation of the normalized maximum displacement of the capital, $d_{\text{max}}/D_{\text{base}}$, with different seismic intensity measures (IMs)

5. CONCLUSIONS

Within the framework of this study, the efficiency of various seismic IMs of the base excitation, to predict the stability of classical columns and colonnades, subjected to uniaxial shaking, was investigated by means of numerical analyses. The efficiency of numerical modelling was initially validated against experimental data from a series of shaking table tests that were recently performed on a scaled column model. The adopted numerical approach has been found capable to reproduce reasonably well the general response and stability of a model multi-drum column as recorded during shaking table tests. The validated numerical modelling approach was then applied to evaluate the response of two actual multi-drum free-standing columns and a colonnade. In particular, the response of an Ionic multi-drum column that has recently been restored at the Acropolis of Lindos in Rhodes, Greece, and a Doric multi-drum column of the Propylaea at the Acropolis of Athens was investigated. In addition, the colonnade of the Propylaea from the Acropolis of Athens, consisting of three columns coupled with an architrave, was also studied.

In line with the findings of previous studies, the shaking motion characteristics affected significantly the response and stability of the investigated multi-drum free-standing columns. The results of the numerical analyses, in terms of normalised by the base diameter maximum displacement of the capital, $d_{\text{max}}/D_{\text{base}}$, were used as a representative EDP to identify optimal seismic intensity measures for seismic assessment of this type of structures. Among the examined IMs the maximum spectral displacement $S_{\text{Dmax}}$ of the base excitation was found to better describe the performance and stability of the free-standing multi-drum columns. Generally, for $S_{\text{Dmax}}$ lower than half the base drum diameter ($D_{\text{base}}/2$), the examined multi-drum columns remained stable. On the contrary, for $S_{\text{Dmax}} > D_{\text{base}}/2$, the examined multi-drum columns collapsed for the majority of the investigated cases, while significant sliding and rocking along the interfaces was observed for the very few cases, where the columns remain stable.

The colonnade exhibited a distinct seismic response compared to the multi-drum columns. Generally, for a given base excitation scenario, it was found to be more stable compared to the multi-drum columns. Since the colonnade, remained stable for all investigated excitations, it was not easy to draw a clear conclusion for the efficiency of the examined IMs to predict the collapse of colonnades.

The results of this study can be used for the seismic vulnerability assessment of this type of structures and decision making on an appropriate restoration scheme, or even being implemented for the structural assessment of modern free-standing structures.
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7. REFERENCES


