VULNERABILITY ASSESSMENT OF CLASSICAL COLUMNS WITH DISLOCATED DRUMS

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ABSTRACT

Classical columns are articulated structures, made of several discrete bulgy stone blocks (drums) put one on top of the other without mortar. Due to their unique structural system, many of these structures have survived several strong earthquakes over the centuries. However, in many cases past earthquakes have caused drums dislocation. Here, we study the effect of drum dislocations on the vulnerability of these systems. For this purpose, we use a performance-based seismic risk assessment methodology and we obtain the fragility of the damaged columns. The Discrete Element Method (DEM) is adopted in order to simulate the three dimensional response history of the system. We calculate limit-state exceedance probabilities using Monte Carlo simulation and synthetic ground motion records of varying magnitude and distance. Our results pinpoint cases where the drum dislocations affect the vulnerability of these structures, while the methodology proposed can be a valuable decision-making tool for the restoration of classical columns.

INTRODUCTION

Classical monuments are particular masonry structures made of discrete bulgy stone blocks. A common structural element of these ancient structures is the multidrum column (Figure 1), which consists of bulgy discrete drums stacked one on top of the other without mortar. During earthquakes, the columns respond with intense rocking, wobbling and, depending on the incipient ground motion, with sliding of the drums. In some cases, steel connections (dowels) are provided at the joints, which restrict, up to their failure, sliding but do not affect, in general, rocking.

Several investigators have examined the seismic response of classical monuments and, in general, of stacks of rigid blocks using analytical, numerical and experimental methods, mostly in two dimensions (Allen *et al.* 1986; Konstantinidis & Makris, 2005; Psycharis, 1990; Sinopoli, 1991 among others). Three dimensional analyses are fewer (e.g. Dasiou *et al.* 2009; Psycharis *et al.* 2003; Stefanou *et al.* 2011a,b) but necessary for the exact representation of the dynamics of these systems. The aforementioned studies have shown that the response is strongly non-linear and quite sensitive even to small changes in the geometry, the mechanical properties and the ground excitation. This is a profound characteristic of these systems and it is observed even to the simplest case of a single rigid block under rocking (Housner, 1963). Previous analyses of the seismic response of classical columns have shown that these structures, despite their apparent instability to static horizontal loads, are, in general, earthquake resistant (Psycharis *et al*. 2000), which is also proven from the fact that many classical monuments built in seismic prone areas have survived for almost 2500 years. However, many others have collapsed.

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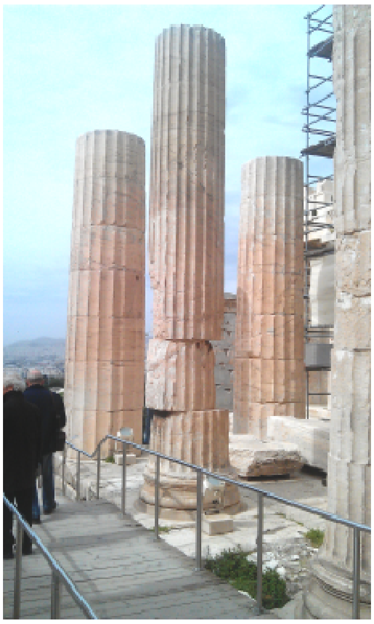

Figure 1. A column at Propylaia of Acropolis hill in Athens, Greece. Drum dislocation is observed above the first drum.

The assessment of the seismic reliability of a monument is a prerequisite for rational decision-making during restorations. The seismic vulnerability of the column is vital information that can help the authorities decide the necessary interventions and establish their policy, not only in what concerns the collapse risk, but also the magnitude of the expected maximum and additional residual displacements of the drums. This assessment is not straightforward, not only because fully detailed analyses for the near-collapse state are practically impossible due to the sensitivity of the response to small changes in the geometry and the difficulty in modeling accurately the existing imperfections, but also because the results depend highly on the ground motion characteristics.

The manuscript investigates the seismic risk of a multi-drum column with dislocated drums in order to assess the effect of pre-existing dislocations on its stability. A specifically tailored performance-based framework is proposed for classical monuments. The probability of exceedance of preset limit states is calculated and presented in the form of fragility surfaces. The dislocations can be seen as a form of pre-existing "damage" to the column that may have been caused either due to past seismic events or due to other factors related to human activity. The seismic performance of a free-standing "damaged" column, with the gross geometry of the Propylaia column (Figure 1), was compared to the performance of the "intact" column, i.e. a column of the same geometric characteristics but without pre-existing dislocations. In order to account for the random nature of seismic ground motions and the strong non-linearities of the system at hand, the Monte Carlo method was applied using near-source synthetic ground motions. The response of the columns was calculated and compared for 35 M_w–R scenarios. The Discrete Element Method (DEM) and in particular the code 3DEC of Itasca (Itasca Consulting Group) was used for the three dimensional numerical simulations of the intact and the damaged column. 3500 simulations were performed in total.

MODELING OF THE COLUMNS

In order to explore the effect of drums' dislocations on the seismic performance of the column, two different configurations of the same column were considered. The "intact" column (Figure 2a) is made of seven drums of diameter equal to1.00 m, and height equal to 0.85 m. The "damaged" column has the same size and number of drums with the intact one, but above the first drum there is a dislocation of 15% of the drum's diameter, i.e. 0.15 m (Figure 2b). This dislocation may be attributed to previous earthquake events or to human activity (e.g. an explosion as in the case of the Propylaia column of Figure 1).

The Discrete Element Method (DEM) and in particular the code 3DEC of Itasca was used herein for the three dimensional numerical simulations. Past experience has shown that a quite important factor for the numerical analysis is the selection of the appropriate constitutive laws that govern the mechanical behavior of the joints. In the present paper we use a Coulomb failure criterion and the parameters used are listed in Table 1. Past analyses have indicated that the stiffness is a parameter that affects considerably the results of the analysis. A parametric investigation performed by Toumbakari & Psycharis (2010) showed that stiff joints might lead to larger permanent dislocations of all drums for strong ground motions compared with joints of soft stiffness. The values presented in Table 1 correspond to marble columns and were calibrated against shaking table experimental results of free-standing columns (Dasiou *et al.* 2009; Papantonopoulos *et al.* 2002). The proposed model parameters offer a good agreement with the experimental results with respect to both the maximum top displacement and the residual displacements of the drums. It must be pointed out, however, that different values should be assigned to the stiffness parameters for materials other than marble of good quality. One way to approximate the stiffness parameters for a specific column is by calibrating the stiffness against ambient vibration measurements (e.g. Ambraseys & Psycharis 2012).

Artificial (numerical) damping was introduced to the system only towards the end of the ground motions. According to the results presented by (Papantonopoulos *et al.* 2002), damping should be set to zero during the intense rocking response, while non-zero damping should be considered at the tail of the seismic excitation in order to dissipate the free vibrations and make possible to determine the permanent deformation.

No connections were considered between the drums, as the only connectors that are often present in such structures are wooden dowels, the so-called ‘empolia’, which were used to center the drums during the erection of the column. The shear strength of the wooden dowels is small and has only marginal effect on the seismic response of the column (Konstantinidis & Makris 2005). For this reason, the wooden dowels were not considered in the numerical model.

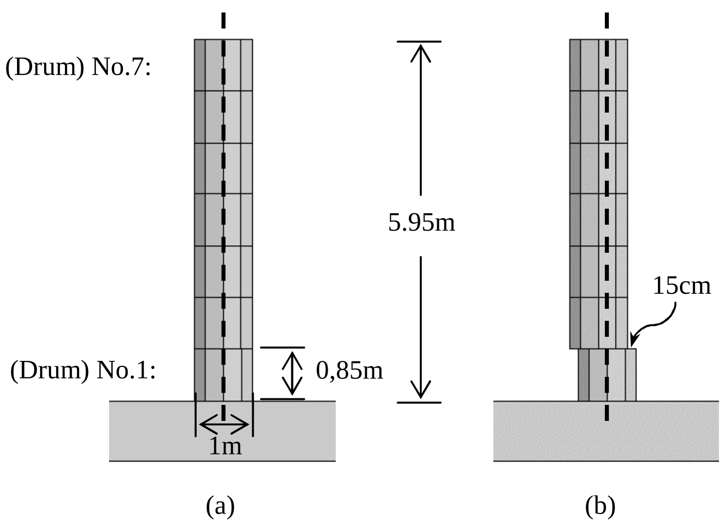

Figure 2. Column considered in the numerical analyses: (a) intact column; (b) damaged column with the drums over the first one having been dislocated for 15cm (15% of the drums’ diameter). The dashed lines represent the column reference axis.

Table 1. Constitutive parameters for the Coulomb frictional model considered for the mechanical behavior of the joints between the drums (Psycharis *et al.* 2013).

Parameter	Value
Normal Stiffness	1 GPa/m
Shear Stiffness	1 GPa/m
Friction Angle	37°
Cohesion	0 MPa
Tensile strength	0 MPa

PERFORMANCE-BASED RELIABILITY ASSESSMENT OF CLASSICAL MONUMENTS

Performance-Based Earthquake Engineering (PBEE) and seismic risk assessment combine computational tools and reliability assessment procedures to obtain the system fragility for a wide range of limit states. The seismic risk assessment requires the calculation of the failure probabilities of a pre-set number of performance objectives. According to PBEE, the acceptable level of damage sustained by a structural system depends on the level of ground shaking and its significance. For example, under a frequent earthquake a building should be able to tolerate minor, non-structural, damage, but a critical facility (e.g. a bridge or a hospital) should remain intact and fully operable. Thus, the target in risk assessment is to obtain the probabilities of violating the stated performance levels, ranging from little or no damage for frequent earthquakes to severe damage for rare events. Today, these concepts are well understood among earthquake engineers, but when classical monuments are considered the performance-based criteria differ considerably. For example, to retrofit an ancient column one has to decide what is the acceptable level of damage for a given seismic intensity level. The approach for making such decisions is not straightforward. A consensus among various experts in archaeology and monument preservation is necessary, while a number of non-engineering decisions have to be made.

Performance levels

In order to assess the seismic risk of a monument, the performance levels of interest and the corresponding levels of capacity of the monument need first to be decided. Demand and capacity should be measured with appropriate parameters (e.g. stresses, strains, displacements) at critical locations, in accordance with the different damage (or failure) modes of the structure. Subsequently, this information has to be translated into one or a combination of engineering demand parameters (*EDP*s), e.g., maximum column deformation, drum dislocation, foundation rotation. For the *EDP*s chosen, appropriate threshold values that define the various performance objectives, e.g. light damage, collapse prevention etc., need to be established. Since such threshold values are not always directly related to visible damage, the *EDP*s should be related to damage that is expressed in simpler terms, e.g., crack width, crack density or exfoliation surface area. In all, this is a challenging, multi-disciplinary task that requires experimental verification, expert opinion and a rigorous modeling formulation.

A single engineering demand parameters (*EDP*) is here adopted for the assessment of the vulnerability of the intact and the damaged column. This is the maximum displacement of the top drum (drum no. 7) over the whole time history normalized by the base diameter (D_0), i.e. $u_{\mathrm{top}} = \max(\delta_{\mathrm{top,t}})/D_0$, where $\delta_{\mathrm{top,t}}$ is the displacement of the top drum measured from the reference axis of the column (see Figure 2). Note that the top displacement usually corresponds to the maximum displacement among all drums. This is a parameter that provides a measure of the column deformation during ground shaking and also shows how close to collapse the column was brought during the earthquake. For example a u_{top} value equal to 0.3 indicates that the maximum displacement was 1/3 of the bottom drum diameter and thus there was no danger of collapse, while values of u_{top} larger than one imply intense ground shaking and large deformations of the column, which, however, do not necessarily lead to collapse. It is not easy to assign a specific value of u_{top} that corresponds to collapse, as collapse depends on the 'mode' of deformation, which in turn depends on the ground motion characteristics.

Based on the above defined *EDP*, the performance criteria of Table 2 have been adopted. In particular, three performance levels were selected, similarly to the ones that are typically assigned to modern structures (e.g. buildings). The first level (damage limitation) corresponds to weak shaking of the column with very small or no rocking at all. At this level of shaking, neither damage, nor any severe additional residual deformations are expected. The second level (significant damage) corresponds to intense shaking with significant rocking/wobbling and evident residual deformation of the column after the earthquake; however, the column is not brought close to collapse. The third performance level (near collapse) corresponds to very intense shaking with significant rocking and probably sliding of the drums. The column does not necessarily collapse if this level is exceeded, (u_{top}>1), but it is certainly brought close to collapse and, in most cases, collapse does occur. The values of u_{top} that are assigned at every performance level are based on the average assumed risk of collapse.

Table 2. Proposed performance criteria concerning the risk of collapse.

u_{top}	Performance level	Description
0.15	Damage limitation	No danger for the column. No significant permanent drum dislocations expected.
0.35	Significant damage	Large opening of the joints with probable damage due to impacts and considerable residual dislocation of the drums. No serious danger of collapse.
1.00	Near collapse	Very large opening of the joints, close to partial or total collapse.

Seismic ground motion records

The assessment of the seismic reliability that is presented herein is based on synthetic ground motions, representative of near-fault sites. The reason of using synthetic instead of natural ground motions is the limited number of the latter for the range of pairs M_w–R (Magnitude–Distance) that are examined, especially for stiff soil conditions on which monuments are typically founded. The synthetic records were generated using the process that has been proposed by Mavroeidis & Papageorgiou (2003), which allows the combination of independent models that describe the low-frequency (long period) component of the directivity pulse with models that describe the high-frequency component of an acceleration time history. In the present paper, the generation of the high-frequency component was based on the stochastic (or engineering) approach discussed in detail in Boore (2003). Based on a given magnitude–distance scenario (M_w–R), and depending on a number of site characteristics, the stochastic approach produces synthetic ground motions. A point source model was adopted, although for near source problems the high-frequency component should be obtained from the superposition of several ground motions generated along the raptured fault. The point source assumption is a simplification that is not expected to considerably influence the risk assessment of the monument. Furthermore, it is noted that, due to the high nonlinear nature of the rocking/wobbling response and the existence of a minimum value of the peak ground acceleration that is required for the initiation of rocking, the high frequency part of the records is necessary for the correct simulation of surrogate ground motions. Long-period directivity pulses alone, although they generally produce devastating effects to classical monuments (Psycharis *et al*. 2000), might not be capable to produce intense shaking and collapse (Psycharis *et al.* 2013), as the maximum acceleration of pulses of long period is usually small and not strong enough to even initiate rocking. For more details regarding the creation of the synthetic ground motions used herein we refer to Psycharis *et al*. (2013).

FRAGILITY CURVES

The proposed fragility assessment methodology was applied to the column of Figure 2. The response of the column was calculated for 35 M_w–R scenarios. For every M_w–R scenario 100 Monte Carlo Simulations (MCS) were performed, thus resulting in total to 3500 simulations for every column (intact and damaged). Figure 3 presents the collapse probabilities of the intact and the damaged column as function of the magnitude of the earthquake and the distance from the fault. Collapse is considered independently of whether it is local (collapse of a few top drums) or total (collapse of the whole column). Apparently, the number of collapses is larger for smaller fault distances and larger magnitudes. For instance, for M_w = 7.5 and R = 5 km, 70% of the simulations of the intact column and 95% (almost all) of the simulations of the damaged column resulted to collapse. However, practically zero collapses occurred for both columns for magnitudes less than 6.0. As expected, compared to the intact column, the damaged column is more prone to collapse.

Concerning the mean top displacement during the seismic motion, Figure 4 shows that for both columns and for small distances from the fault, up to approximately 7.5 km, the mean value of u_{top} increases monotonically with the magnitude. However, for larger fault distances, the maximum u_{top} occurs for magnitude M_w=6.5 and for larger M_w the top displacement decreases. This counter-intuitive response is attributed to the saturation of the *PGV* for earthquakes with magnitude larger than M_{sat}=7.0, while, according to commonly used ground motion prediction equations, the period of the pulse increases exponentially with the magnitude. As a result, the directivity pulse has small acceleration amplitude for large magnitudes, which is not capable to produce intense rocking. A more detailed discussion on this phenomenon can be found in Psycharis *et al*. (2013).

Comparing the response of the intact and the damaged column, Figure 4 shows that the maximum displacements, u_{top}, follow the same trend for both columns. Nevertheless, for less strong earthquakes the maximum displacements of the damaged column are somehow lower. This is due to the initial damage of 15% dislocation that was considered herein (Figure 2). It has to be mentioned that the simulations that lead to column collapse were excluded from these plots and therefore, Figure 4 has to be examined in combination with Figure 3.

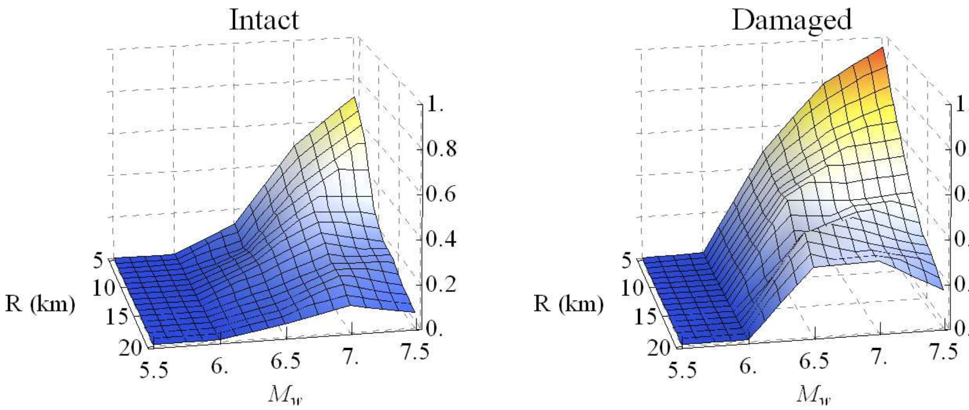

Figure 3. Collapse probabilities for the intact column (left) and for the damaged column (right). The damaged column is evidently more prone to collapse.

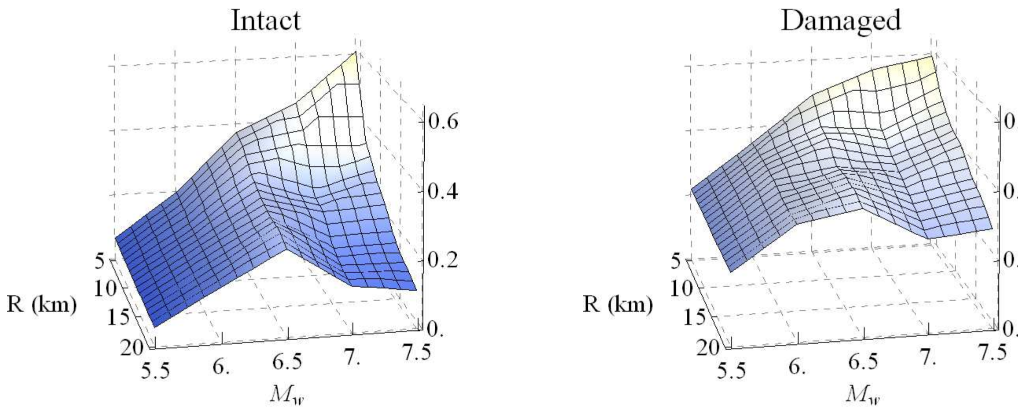

Figure 4. Mean maximum normalized top displacements, u_{top} , for the intact (left) and for the damaged column (right).

In Figure 5 we present the fragility surfaces of the columns for the three performance levels of u_{top} ranging from *significant damage* (u_{top} > 1) to *damage limitation* (u_{top} > 0.15). It is reminded that u_{top} > 0.15 means that the maximum top displacement during the ground shaking is larger than 15% of the base diameter and u_{top} > 1 corresponds to intense rocking, close to collapse or actual collapse. When *damage limitation* is examined (Figure 5c), the exceedance probability for the intact column is high (0.6) for M_w = 6 and increases more for ground shakings of larger magnitude. For the worst scenario among those examined (M_w = 7.5, R = 5 km), the probability that the top displacement is larger than 15% of D_{base} during ground shaking is equal to unity (certainty), while in the range M_w = 6.5 to 7.5 and R > 15 km a decrease in the exceedance probability is observed (likelihood). For the damaged column, the probability of exceedance of the *damage limitation* (u_{top} > 0.15) is one, because of the initial dislocation of 15 cm considered.

Similar observations hold for the exceedance of the *significant damage* limit state (u_{top} > 0.35), but the probability values are smaller. For the *near collapse* limit state (u_{top} > 1.0), the probability of exceedance reduces significantly for large distances, even for large magnitudes. Notice that the u_{top} > 1.0 fragility surface is quite similar to the probability of collapse of Figure 3, which shows that, if the top displacement reaches a value equal to the base diameter, then there is a big possibility that the column will collapse a little later. The fragility curves presented in Figure 5 show that, generally, the damaged column exhibits larger displacements than the intact one during earthquakes and that it is more probable to collapse.

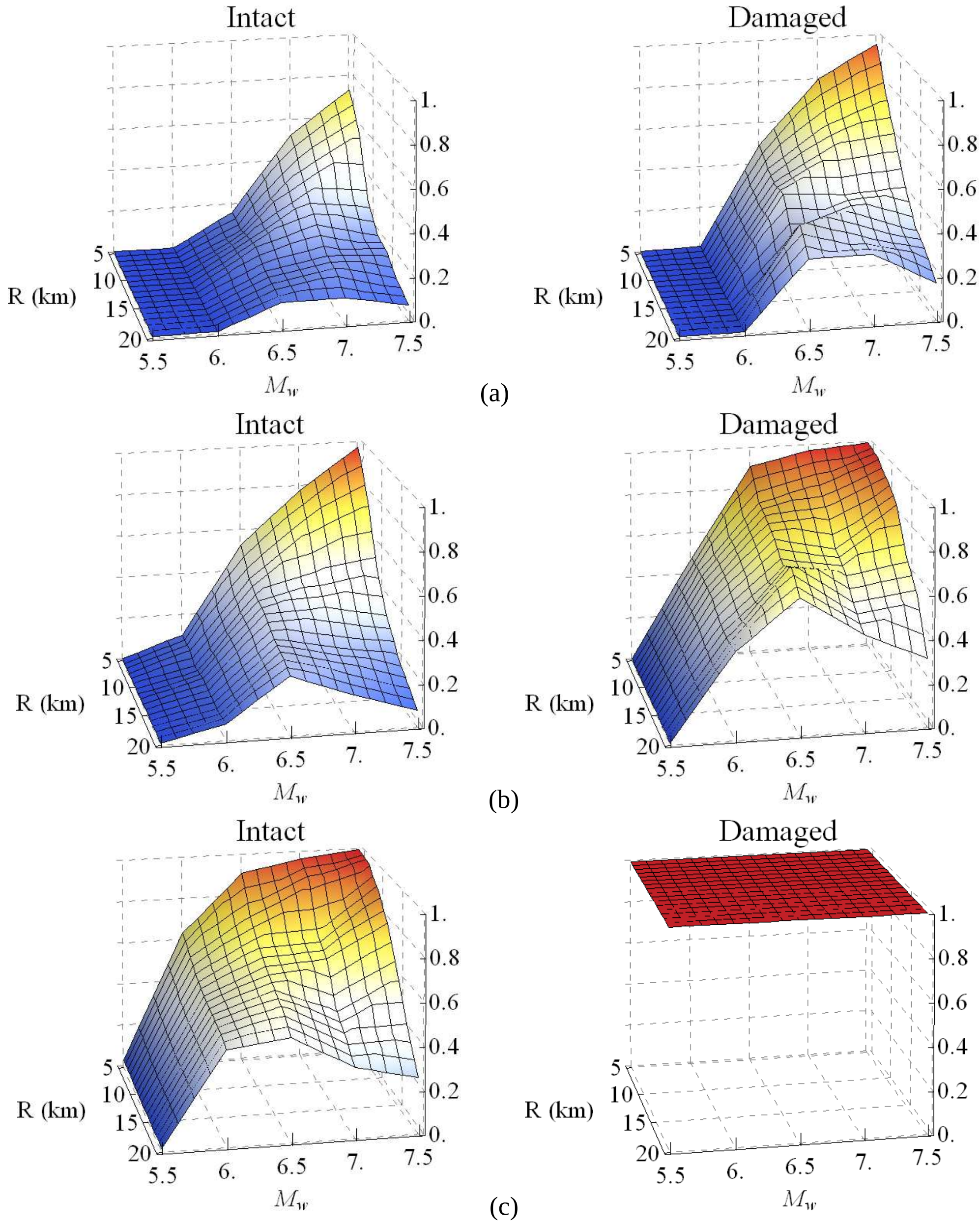

Figure 5. Fragility surfaces related to column collapse for the intact column (left) and the damaged one (right) for the performance levels of: (a) $P(u_{top} > 1.0)$; (b) $P(u_{top} > 0.35)$; (c) $P(u_{top} > 0.15)$.

Comparing the behavior of the intact column studied herein (Figure 2) with the behavior of a typical column of the Parthenon Pronaos, which was studied by Psycharis *et al*. (2013) following the same methodology, we observe that both the probability of collapse and the probability of exceedance of the related *EDP* (u_{top} >1.0) are considerably lower for the column of the Parthenon Pronaos. This is in accordance with the fact that larger columns are more stable than smaller ones with the same aspect ratio of dimensions (cf. also Housner 1963).

DAMAGE BUILD-UP

The ability of spinal systems to wobble and dissipate seismic energy through sliding and block impacts is accompanied at the end of the seismic motion (t=t_{end}) with the accumulation of permanent relative displacements (dislocations) between the drums. This damage build-up can be seen in classical monuments and is usually of small extent, i.e. of some centimeters (1 to 2% of the drums' diameter). However, it is not straightforward whether the observed permanent displacements are due to seismic actions or due to other events that may have taken place during the long life of a monument. This holds also for the damaged column at hand that shows excessive damage (15% of the drums' diameter).

In order to quantify the permanent dislocations caused by a single earthquake event we introduce a new parameter, u_d, which provides a measure of how much the geometry of the column has been altered after a seismic event. In other words, u_d expresses the damage build-up because of a single earthquake. The drum dislocations are measured from the initial (t=t_0) deformed/damaged shape of the column, and u_d is defined as $u_d = \max[\Delta u_{i,top} - \Delta u_{i,t0}]/D_i$, where $\Delta u_i(t) = \delta_i(t) - \delta_{i-1}(t)$ and i = 1 to 7 represents the drum index equal to 7 for the top drum and 0 for the base.

Figure 6 depicts the mean maximum additional permanent drum dislocations u_d for the considered combinations of M_w–R for the intact and the damaged column. We observe that the maximum mean residual displacement between the drums of both columns is approximately 2% of the base diameter (1 cm) which is in accordance with field observations. Consequently, the initially considered dislocation of 15% (15 cm) could hardly be the result of a single earthquake event. Therefore, as there is no evidence that several strong earthquakes have hit Athens in the past (Ambraseys & Psycharis, 2012), it seems that in the case of the columns of Propylaia that were studied herein, the observed dislocation of u_d = 0.15 should be attributed to other factors than seismic activity (e.g. human activity, collapse of adjacent parts of the monument, impacts, explosion etc.).

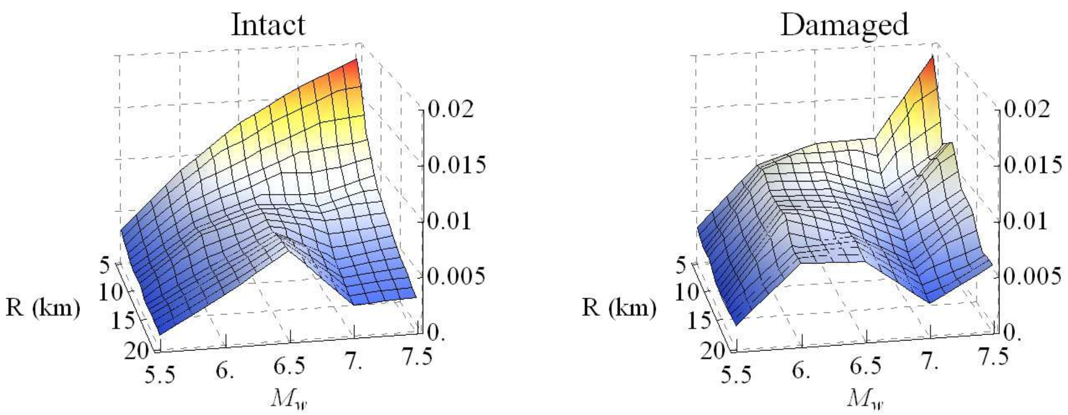

Figure 6. Mean maximum normalized residual deformations, u_d, for the intact column (left) and the damaged column (right). In the latter case, the initial dislocation of the upper part of the column (see Figure 2) is not included in the value of u_d. It is noted that the damaged column cannot develop significant additional permanent displacements without collapse.

Figure 7 presents the probabilities of exceedance of certain earthquake damage build-up thresholds. For instance, the probability of having a residual damage of 1.5% (Figure 7a) after an earthquake of magnitude M_w = 6 is quite small ($p_f \approx 0.1$), thus showing that only 'strong' earthquakes may result to significant damage build-up. Finally, the differences in damage build-up probabilities between the two columns are not very significant (Figure 7c).

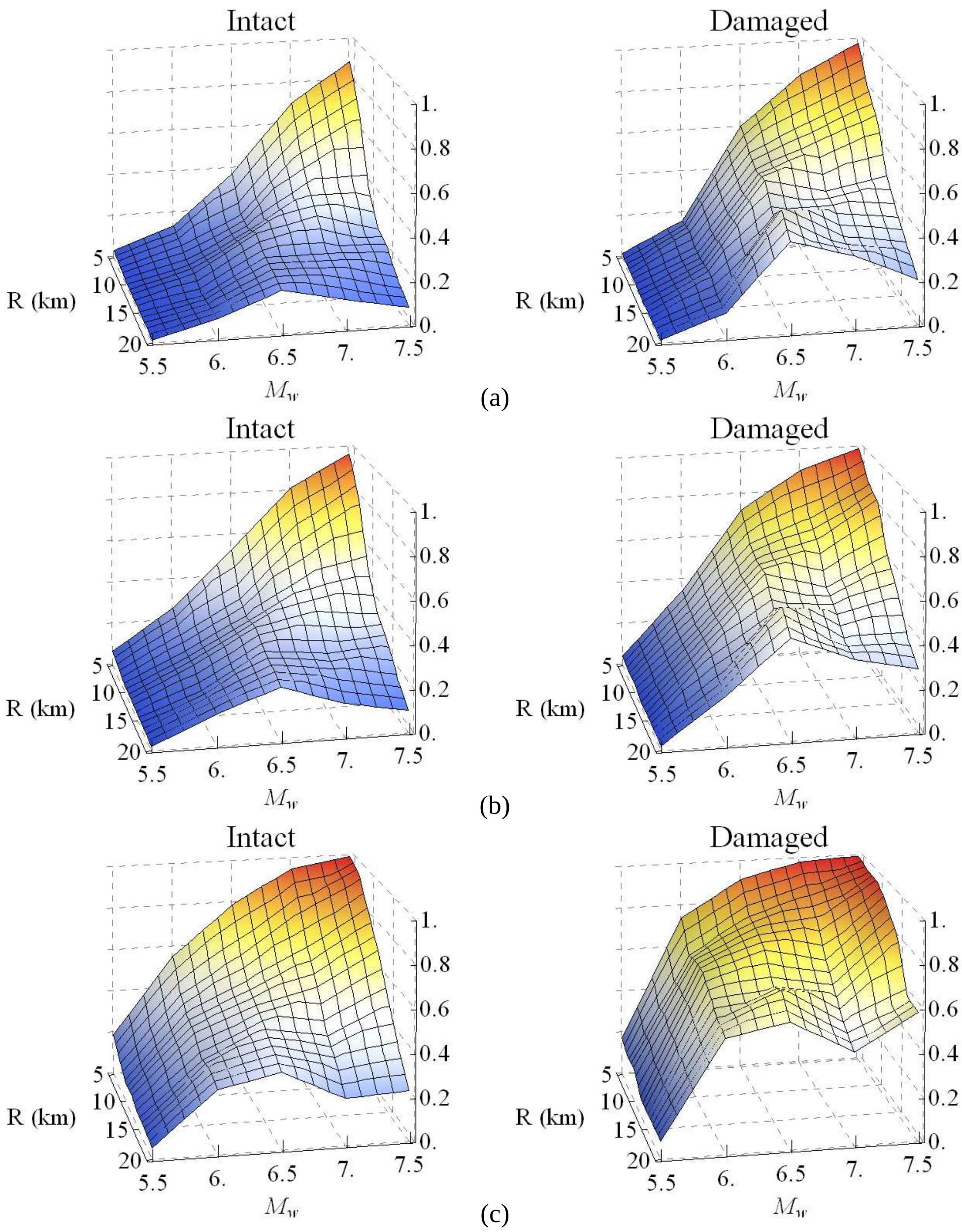

Figure 7**.** Probabilities of exceedance of certain damage build-up thresholds, for the intact column (left) and the damaged one (right): (a) $P(u_d > 0.015)$; (b) $P(u_d > 0.01)$; (c) $P(u_d > 0.005)$.

CONCLUSIONS

A seismic risk assessment of a multi-drum column with dislocated drums was performed in order to assess the effect of preexisting dislocations on the stability of classical columns under earthquake actions. The dislocations can be seen as a form of preexisting “damage” to the column that may have been caused either due to seismic events or due to other factors including human activity. The seismic performance of a “damaged” column was compared to the performance of an “intact” one, i.e. to a column of the same geometric characteristics but without preexisting dislocations (Figure 2). In order to account for the probabilistic nature of the seismic events and the strong non-linearities of the dynamical system at hand, the Monte Carlo method was applied using synthetic ground motions which contain a high- and a low- frequency component. The response of the columns was calculated and compared for 35 M_w–R scenarios.

An engineering demand parameter (*EDP*) related to the column collapse risk was adopted for the assessment of the vulnerability of the considered classical columns. The fragility analysis showed that the risk of collapse is quite important and even higher for the damaged column (95% vs. 70%). Nevertheless, the damage build-up because of a single seismic event was similar between the two columns and of the order of 2% of the drum's diameter. Therefore, as there is no evidence that several strong earthquakes have hit Athens in the past (Ambraseys & Psycharis, 2012), it seems that in the case of the columns of Propylaia the observed excessive dislocation should be rather attributed to other factors than seismic activity (explosion of 1687, collapse of adjacent parts of the monument, impacts with falling pieces during the collapse of the roof etc.). Finally, by comparing the results of the present analysis with the results of previous analyses (Psycharis *et al.* 2013) we corroborate the fact that larger columns are more stable than smaller ones with the same aspect ratio of dimensions.

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