Assessment of the long-term seismicity of Athens from two classical columns

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Abstract
The two columns of Thrasyllos on the south flank of the Acropolis of Athens are free-standing for more than 2300 years and have survived all seismic motions that have hit the city serving thus as natural seismoscopes that have 'recorded' through their deformation all strong earthquakes. However, the decoding of this information in order to assess the long-term seismicity of Athens is not a straightforward procedure and, in general, does not lead to a unique solution. The main reasons for this is on one hand the non-linearity and the sensitivity of the seismic response of multidrum columns, and on the other the lack of information on the evolution of the damage and the uncertainty on the real cause of it, as it is not easy to determine how much of the damage that can be seen today must be attributed to earthquakes alone and how much of it is due to other reasons. In this paper, a systematic approach to this problem is performed starting from the literary survey and the seismotectonic investigation which show that there is no evidence that Old Athens was ever seriously damaged by earthquakes. From the detailed investigation of the current state of the columns, the damage caused by earthquakes was separated from the one caused by rusting of dowels and temperature effects. Back analyses were performed using suitable surrogate ground motions, aiming at determining the worst-case earthquake that could cause the collapse of the columns, and the maximum level of shaking that could cause the observed damage. The numerical analyses were performed using the Distinct Element Method and the models were exact reproductions of the columns based on the available data, while the joint properties were calibrated against ambient and forced vibration measurements. The results show that the mean response spectrum of the worst-case earthquakes is 15% larger than the corresponding response spectrum of EC 8, but it is possible that the maximum experienced shaking is less. More analyses are needed to draw conclusions on the latter.

Keywords: *long-term seismicity; monuments; seismic response; design spectrum; multidrum columns.*

Introduction
Previous studies have shown that the earthquake hazard of Old Athens is relatively low. Active faults are located more than 10 km away while macroseismic information of the last 300 years and seismological data of the last 100 years confirm low values for ground accelerations associated with equally low annual probabilities of exceedance. But we know also that for very long periods of time, probabilities of exceedance are beyond mathematical analysis and that we can only have recourse to the guidance of common sense, using observations and data from other sources, such as tectonic, archaeological and historical.

Our literary information and archaeological observations confirm that during its 25-century-long history the Old City of Athens has been almost free of destructive earthquakes; it has not been seriously damaged, there has been no loss of life, and earthquakes have been small and infrequent, causing no social or economic crises. There is nothing in early documents to suggest that there has ever been damage to Athens, to the Acropolis, or to the two 10-m-high columns of the Monument of Thrasyllos, which have remained free-standing on the south flank of the Acropolis for more than 2300 years. Perhaps the latter could tell us something about the long-term seismicity of Old Athens from which we could assess the maximum earthquakes that they have survived. They should have been shaken and one could say that they would not be standing perched above the monument of Thrasyllos if an earthquake in the Basin of Athens had been strong enough to push them over.

The Monument was erected on a rather inaccessible ledge cut out in the rock of the Athenian Acropolis above the Theatre of Dionysus (**Figure 1**). It is nothing more than the gateway to a natural cave in the south flank of the rock of the Acropolis, with the two standing free, unfluted Corinthian columns that decorate it, dating from the end of the classical period.

At the time of the visits to the monument by the first author in the 1970s much of the space between the columns was covered with vegetation in places rooted deep into cracks in the limestone floor of the ledge. Damage to the columns could be seen clearly, but it was not possible to say from the ground below whether some of the cracks in the stone were due to rusting of the iron dowels or due to attempts to remove them by hewing into the stone.

Work continued in the following year during which proper mapping of the columns was carried out for the first time, as well as a detailed geological and geophysical investigation of the site (**Zambas *et al.* 2011**).

After the $M_w = 5.9$ earthquake of 1999 which happened 10 km from Athens, the interest in the existence of the Thrasyllos columns was revived together with the original questions of why the columns are still standing (**Ambraseys 2010b**). It is obvious that the columns of Thrasyllos could be used as natural seismoscopes from which to estimate the worst-case earthquake-shaking of the rock of the Acropolis that could topple them, thus providing an upper limit on the ground motions experienced and consequently a quantitative constraint on ground motions from past earthquakes. Additionally, since the columns are damaged but still standing, and the worst-case earthquake that could topple them has not happened yet, we hoped to constrain the ground motions to the upper-limit earthquake which was responsible for their damage. In short, the results from such a study would be to supplement what we already knew from the seismotectonic analysis of the long term seismicity of Old Athens. Whether this could give a reliable answer was not known in advance, but it was worth trying.

(a) (b)

Figure 1. (a) General view of the south wall of the Acropolis with the cave of Thrasyllos with the two choragic columns standing on the ledge above it; (b) The columns standing on the rock ledge, which is inclined to the south by 20° to 45°.

Towards this end, back analyses were performed in an attempt to cipher out the information inherent in the current state of the columns in order to assess the long-term seismicity of Athens. The reasons that we chose for this experimentation the columns of Thrasyllos instead of other columns in Athens (Olympios Zeus, Hadrian Library, etc.) are: (i) the columns of Thrasyllos are free standing from the time they were built while the other free standing columns are the damaged remainders of structural bearing elements of monuments that have collapsed which is difficult to analyze; and (ii) the columns are relatively small in size, being thus more vulnerable to earthquakes (**Psycharis *et al.* 2000**) and, thus, a lower value for the worst-case earthquake could be derived. It is noted that another similar attempt by the second author (**Psycharis 2007**) that was based on a pair of columns of the much larger temple of Olympios Zeus (Olympieion) could not give information on the worst-case earthquake, as the columns were very stable against collapse, and was restricted only to possible scenarios that could cause the observed damage.

Earthquake hazard

A detailed re-assessment of the seismotectonics of the Basin of Athens and of the region within 150 km from the city confirms that the known active faults nearer to Athens are more than 10 km away from the Acropolis. They are all relatively shallow, of short length and normal mechanism often followed by rather long sequences of aftershocks (viz. **Goldsworthy *et al.* 2002**; **Ambraseys 2010a & b**).

It is interesting that historical sources that refer to Athens say nothing about destructive earthquakes in the city. For, had there been any notable earthquake it is unlikely that they would have escaped the notice of keen historians and travelers who would have recorded them, as they did report earthquakes in other regions around Athens such as of Oropos (40 km), Thiva (50 km), Negreponte (60 km), Corinth (70 km), Atalanti (90 km), Orchomenos (90 km), Zituni (150 km)**.** Earthquakes in Athens should have excited widespread interest and sympathy rather on account of the nature of the locality in which they occurred rather than because of their special violence.

We know that in the 6th century the strengthening of the fortifications of cities in central Greece, with the exception of Athens, was because they had been damaged in the past by earthquakes. The exception was the damage to the walls of Athens which was attributed to “the passage of time”. Equally important is indirect evidence confirming a long-term low level of hazard. There are no stories or legends handed down by tradition that the Old City had ever suffered from earthquakes. Travellers who passed through or sojourned in Athens during the last ten centuries, and who would not have omitted to mention a damaging earthquake had there been one, say nothing about earthquakes. There is nothing in Occidental, Ottoman or church documents to suggest that there was ever a need for fiscal assistance for the repair of earthquake damage on the Acropolis or to the numerous churches and monasteries in the Basin of Athens**,** during a period of strong growth of monasticism. The archives of the monasteries on the slopes of Mount Hymettus and Pendeli do not mention any earthquake except, in passing, the one in 1705. This is in contrast with what they record for nearby, equally old towns.

In the assessment of the regional long-term seismic hazard of the Basin of Athens we considered earthquakes that have happened, but also probable events that are associated with the active of regional tectonics and either have passed unnoticed or are likely to occur in the future. This lead to an estimate of the long-term seismicity of the Basin, which is based on a major re-evaluation of all the events within a radius of about 150 km from Old Athens that occurred during the last 2300 years. The results of this re-evaluation are given in detail in **Ambraseys (2009, 2010b)**.

Using these data, in the simplest possible way, the probability of exceedance of ground accelerations generated in Old Athens by events originating from within an annulus of radii 10 and 100 km were calculated and the results are shown in **Figure 2.** This was done following the classification used in ordinary earthquake building codes, that is a probability of exceedance of 10% for ordinary buildings and 2% for important structures in 50 years. This corresponds to annual probabilities of exceedance of 2×10^{-3} and 4×10^{-4}, respectively. For critical structures the annual probability decreases to 5×10^{-6} or less. As the likelihood decreases and the return period lengthens, the magnitude value of the design-magnitude earthquake increases. These estimates are in general agreement with the regulations of most seismic codes, as Eurocode 8 (EC 8). **Figure 2** implies, therefore, that, if for the long-term survival of the columns we adopt an annual probability of exceedance of 5.0×10^{-5}, the design zero-period acceleration is 0.19 g (**Ambraseys 2010a**). It is understood that this value applies to free-field ground movements on competent ground of category A.

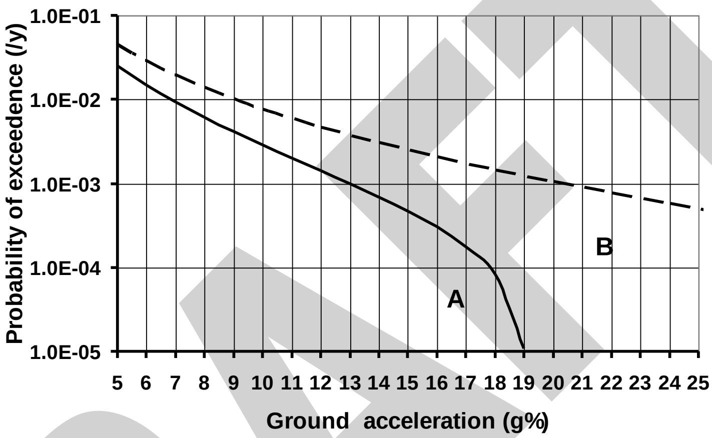


Figure 2. Probability of exceedance of ground accelerations in g% in Old Athens generated by events originating from within an annulus of radii 10 and 100 km (solid curve, A) and for events within a radius of 100 km (dashed curve, B).

The monument of Thrasyllos

The monument of Thrasyllos is set against a natural hollow at the base of the south face of the rock of the Acropolis, above the Theatre of Dionysus. It consisted of a simple façade: two steps supporting three pilasters, two wide ones at the corners and a narrow central one, flanked by doors on either side; the pilasters in turn carried an entablature on which rested the tripod base. The geology and structure of the limestone ledge was mapped (**Figure 3**) and the geophysical data available for a larger area as well as well as for the cave below the ledge were evaluated (**Zambas *et al.* 2011; Ambraseys and Psycharis 2012**).

The two columns that decorate the Monument of Thrasyllos (**Figures 1, 4**) probably date from the third or fourth century BC (**Amandry 1997).** They did not form part of any building and were specially built with triangular capitals to support votive tripods. They are composed of grey marble of Hymettus and they are of similar construction, but differ in height and diameter, the column to the west (W) being shorter than that to the east (E)**.**

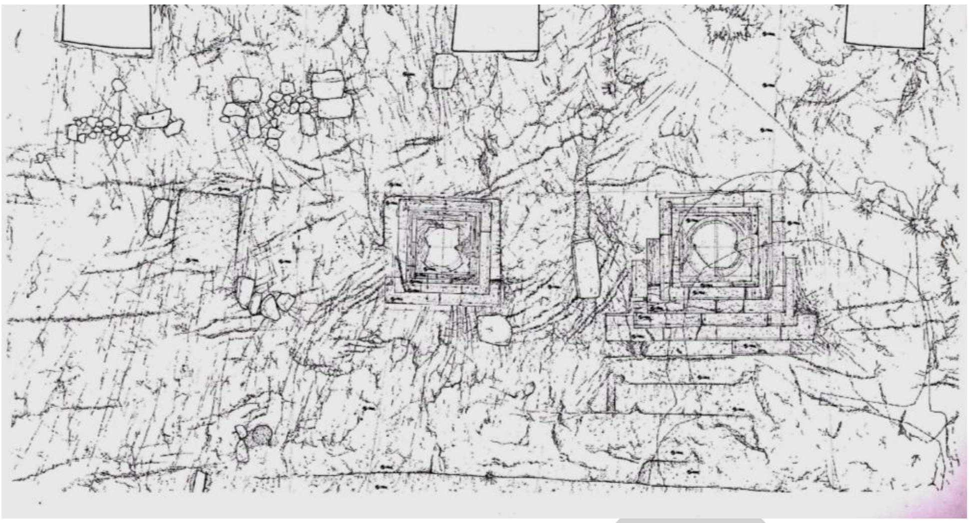


Figure 3. Plan view and fracture pattern of the limestone surface of the Thrasyllos ledge showing the pedestals of columns E and W as well as an unused foundation for a third column further west (**Zambas *et al*. 2011**).

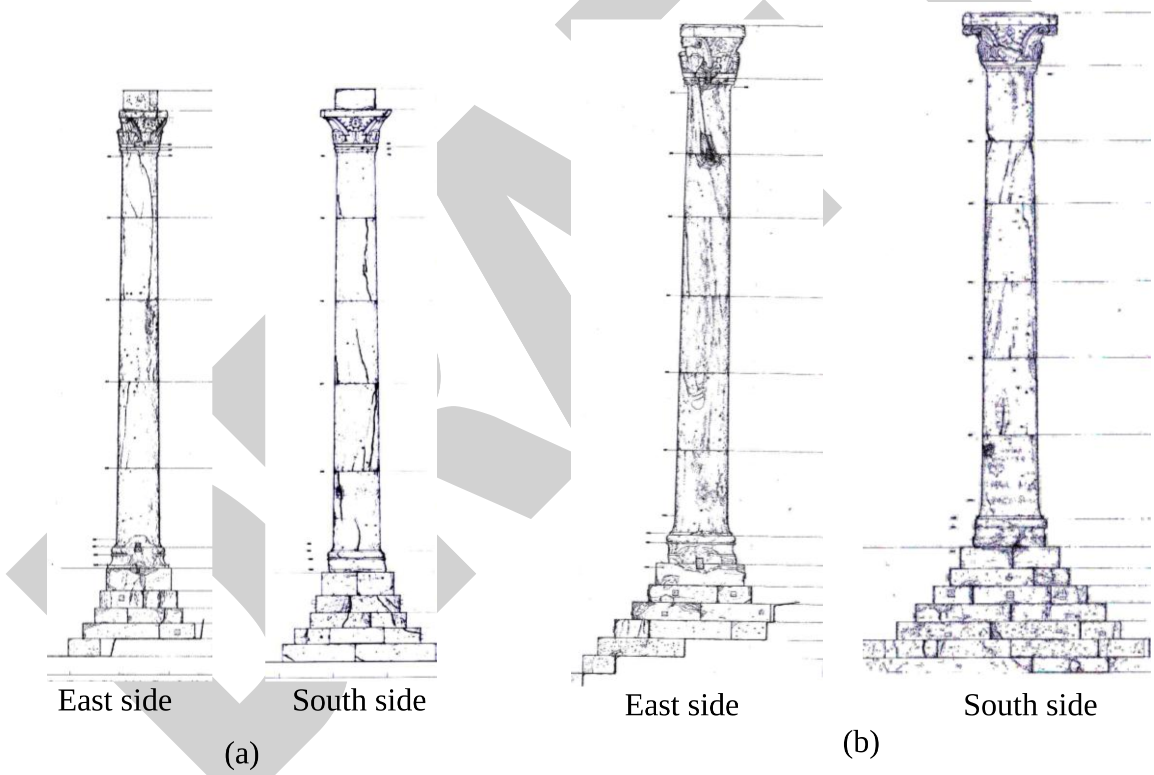


Figure 4. Geometric models of columns: (a) West (W) and (b) East (E), with the scars caused by the rusting and oxidation of dowels, thermal cracking of the stone, by the extraction of dowels, from shelling and weathering of the pedestals (**Zambas *et al*. 2011**).

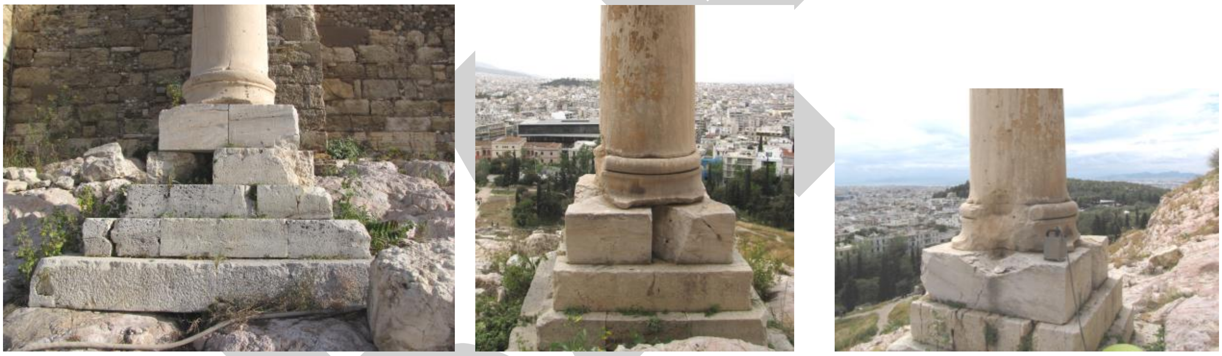
Column W

Column W (**Figure 4a**) has a total height of 10.8 m, of which 8.0 m is accounted for by the shaft and the base, consisting of five unfluted drums of average diameter 0.8 m. Its capital, which is 0.7 m high, bears a choragic plinth about 0.4 m thick, while the slabs together with the plinth constituting the pedestal of the column are 1.7 m high.

The column stands on the ledge which is inclined to the south and the rock of the ledge is cut back and levelled for the foundation of the pedestal, the back side of which is vertical. The pedestal consists of four superimposed stepped slabs of Piraeus limestone, some of them made up of a number of pieces not all of them linked together with most of their iron clumps today missing. There is also a corner piece of rock from the west part of the top slab that is missing (**Figure 5a**). The slabs, which are about 35 cm thick each look somewhat loosely packed together, particularly those near the base of the pedestal, while their contact surface with the rock foundation seems in places to be eroded. Not all of the slabs sit directly on rock leaving in front of them a space of about 25 cm for a smaller segment for a fourth slab to be added. Note that the base of the column sits on the centre of the pedestal, which in plan is almost symmetrical standing well west of the middle of the roof of the cave below.

The plinth, which is the top slab of the pedestal made out of a thick piece of marble, has a sizeable wedge-shaped piece missing from its north side (**Figure 5b**). It seems that during construction of the column, the corner of one of the two stones of which the plinth is made was damaged and that the broken part was replaced with a wedge-shaped piece of marble that was attached to the rest of the plinth with two iron clamps. The clamps and the wedge are now missing, leaving the plinth with a 25 cm wide gap (**Amandry 1976, 1997**).

Column W, like column E, had the east and west sides of their base and lower parts of the bottom drum hewed to some depth into the stone by robbers for the lead of its dowels (**Figure 5c**). Also the stone of the base and plinth has been hewn to some depth in an attempt to remove the dowel from both east and west sides. It is not known when this was done.



(a) (b) (c)

Figure 5. Column W: (a) Cracking, fragmentation and missing corner stone from the top slab of the pedestal; (b) Fractured plinth supporting the base of the column; (c) Deliberate damage of the first drum, base and plinth for the removal of their dowels.

The base of column W ends like the bottom of the first drum of columns E or W, but with a flat fillet added, replacing the torus. The flat fillet, which sits on the plinth, has been clipped all around the base systematically (**Figure 5b**), particularly on the east and west sides, most probably by robbers in order to expose the location of dowels for their removal. The clipping off of the filet at the back of the base of column W exposes the trace which the missing filet has left on the plinth. This suggests that at some stage the base and the column above it had been displaced bodily on the plinth by a small amount of about 2.5 cm to the southwest. How and when this displacement happened is not possible to say, except that the patina on the displaced column suggests that these displacements were not recent. It is possible that the base, having been robbed of its dowel, was easy for rocking to set in displacing the column by 2.5 cm. The additional question, however, remains, whether the dowel was removed before or after the alleged earthquake.

Attributing the displacement to rocking would imply that this could happen with a hinge of tilting at a contact point on the periphery of the base with the plinth. Tilting of the base could then explain the clipping off of the filet from all around the base of the column (**Figure 5b**), which is something that could happen during rocking in all directions. Numerical analyses of the earthquake response of Column W show that it is possible for the column to start rocking around its base for ground motion peak velocity less than 0.20 m/s and peak ground acceleration around 0.25 g. Ground motions of such intensity are probable to have occurred during the long life of the monument, thus this explanation for the clipping off of the base of the column due to rocking seems reasonable.

Concerning the column's shaft, which consists of 5 drums, the damage that can be seen to the stone of the drums (**Figure 6**) is due to the initiation of cracking by the swelling and oxidation of the dowels. There is also a small dislocation of two adjacent drums and two slight scars where the stone has peeled off by grazing cannon balls during the sieges of the Acropolis. In all, the column has been hit by small cannon balls in four places, which caused very little damage. Higher up, the lower corner of the 5th drum facing southeast shows a diagonal fracture and a vertical open crack which was caused by the swelling of the dowel.

The horizontal surface of the capital of column W is an isosceles triangle and has its north and southeast corners broken. It is almost identical with the capital of column E. The capital carries a choragic plinth (**Figure 4a**). Its extreme north and southeast corners are broken with no evidence that this was due to shelling or that the capital has been displaced. The plinth has remained at its original position (**Amandry 1976**) as it is fixed to the capital**.**

Figure 6. Typical damage to the shaft of column W caused by the oxidation and expansion of its dowels (**Zambas *et al.* 2011**).

Column E

Column E (**Figure 4b**) has a total height of 12.4 m, of which 9.3 m is accounted for by the shaft and the base, consisting of six unfluted drums of average diameter 0.9 m. Its capital, which is free, is 0.7 m tall, and the plinth plus slabs constituting the pedestal are 2.1 m high.

Column E also stands on the sloping rock surface of the ledge, a part of which sits on the roof of the cave underneath, which, at this point, is about 5 metres thick. Because of the sloping surface of the ledge (25°) column E needs a longer pedestal than column W, so that the rock foundation had to be cut back in a series of levelled steps (**Figure 7a**). For all practical purposes the pedestal is symmetrical in an east-west direction but not in the north-south direction.

The general impression of the pedestal of column E and to a lesser degree of column W is that the limestone slabs from which they are made are not as tightly placed together as originally, particularly the lower slabs (**Figure 7**). The two bottom slabs are slightly inclined to the south, and one of them is broken. Between them here are also a few open and displaced vertical and horizontal joints, probably caused by the growth of roots of cacti, by erosion from rainwater draining down through the Wall at the back and down the surface of the ledge and possibly from ground vibrations caused by mine explosions during the siege of 1826. **Figure**

7 shows the degree of fragmentation of the limestone stepped slabs of the front part of pedestal E after the removal of vegetation.

(a) (b)

Figure 7. Column E: (a) Fragmented limestone stepped slabs of the pedestal; (b) View from above of the condition of the limestone stepped slabs of pedestal E (facing south).

The base of the column has a normal profile with a full lower torus (**Figure 8a**). In an attempt to extract the iron dowels which held together the drum and the base, the northwest, south and southeast parts of the torus, scotia and parts of the plinth were cut back deliberately and a good part of the south part of the base was broken up stripping the base of a good part of its stone. Notice that this deliberate striping and mutilation of the stone was done where the base of the column straddles the plinth at the contact point of the two underplaying pieces of marble.

Concerning the shaft of column E, it seems that further up its east face, above the second drum, the column was displaced to the southeast on its joint by about 1.6 cm (**Figure 8b**). At this point a large flake of stone, about 1.5 cm thick, was detached from the southeast face of the 2nd drum indicating intense rocking during seismic excitation. Here and elsewhere in the column, expansion of the rusted elements caused splitting and scaling of the marble (**Figure 9**). Between the 5th and 6th drums the damage to the stone caused a relative displacement of 0.5 cm. In the upper part of the 5th drum there is spalling of the stone from the impact of a cannon ball. During the siege the column has been scarred by cannon ball at two places.

(a) (b)

Figure 8. Column E: (a) Missing double-T clamp originally connecting the two pieces of the plinth (its position is shown between the two arrows); (b) Flaking off of skin of the stone of the 2nd drum indicating rocking between 2nd and 3rd drums.

(a)

(b)

Figure 9. (a) Expansion of the stone and the formation of tension cracks due to oxidation of dowel(s) of the 5th drum. Staining action caused by corrosive metals, Rust-colored bleeding can only occur from stone that contains a high concentration of iron pyrite; (b) Detail showing damage to the stone due to swelling of oxidized dowels enhanced by temperature effects. The expansion of the skin of the drum is arrested by frictional forces at its contact with the drum below.

The capital and its base, which is in one piece and which is built to carry a choragic tripod, is damaged and displaced to the north relative to the shaft, that is, towards the Acropolis. This agrees with the assumption that this was the result of a hit from a cannon ball. The actual relative displacement of the capital is 6 cm (**Zambas *et al.* 2011**). This column did not carry a choragic plinth. The tripods could stand directly on the capital itself which is provided with the appropriate supporting.

Assessment of damage

For more than 20 centuries these columns have suffered cracking of the stone due to the rusting and swelling of iron dowels and stone, from temperature effects, warfare, high winds and natural ageing of their pedestals (**Figures 4, 6, 7, 9**). In addition to which, both columns have been damaged by robbers who cut into the stone in an attempt to remove the metal dowels (**Figures 5c, 8a**), which seriously affect the integrity of the columns.

The problem is that we do not know when these attempts were made and whether they had been successful. This is tantamount to saying that it is not known from what period onwards the vulnerability of the columns has increased.

The question now is how much of the damage that can be seen on the Thrasyllos columns today can be attributed to ageing in addition to damage caused by the vicissitudes caused by the two sieges of the Acropolis in 1687 and 1826, and quite separately, how much of it is in fact due to earthquakes alone.

At first sight, the shelling of the Acropolis during the siege by Morozini in August 1687 and the ensuing explosion of ammunition that ruined the Parthenon should have affected the vulnerability of the Thrasyllos columns. However, it is unlikely that the columns could have been damaged. Nothing is mentioned in contemporary sources about the site of Bacchus (Dionysus) where the columns are located (viz. **Dandolo Chronicon Venetum**) and images of the south flank of the Acropolis during and after the siege clearly show that the two columns of the Monument of Thrasyllos had survived.

The siege by the Ottomans in 1826-1827 was responsible for the destruction of the Monument of Thrasyllos and for some visible but minor damage to its columns (viz. **Byhern**

1833; **Pisa 1841**; **Treiber 1960**; **Gordon 1844;** ***Aion*** **1851**; **Sourmelis 1853**; **Makriyannis 1947**; **Byzantios 1901**).

Concerning major earthquakes, damage to the columns of the Monument of Thrasyllos by the earthquake of 1705 is not mentioned in Greek or in Ottoman documents. It was an insignificant site, so it is not to be expected that its damage would have attracted any attention. We may assume, however, that the earthquake perhaps did some non-structural damage to the columns, the exact nature and degree of which are not known (**Ambraseys and Finkel 1992; Ambraseys 1994**). Similarly, it is not known whether the earthquake of 24 February 1981 of magnitude M_w = 6.6, which occurred offshore in the Gulf of Corinth about 80 km west of Athens, had any effect on the columns. The same applies to the earthquake of 1999 of M_w = 5.9 which occurred at an epicentral distance of about 10 km (**Ambraseys and Psycharis 2012**).

Rusting and oxidation effects of dowels

Figure 4 shows the geometric models of columns W and E and the damage caused by the rusting of their iron dowels, the oxidation of their stone, high temperature and the robbing of their dowels. Typical damage to the stone of columns caused by the oxidation and expansion of its dowels is shown in **Figures 6 & 9**. The patina or the tarnish formed on the surface of the marble is very old, testifying to the great age of these fractures. Note that the two columns align N-85°-E so that their front part is always exposed to the sun, while their back is very close to the high wall of the Acropolis which shelters them.

It is recognized that oxidation arising from the rusting dowels is not necessarily the sole condition to cause the gradual vertical cracking of drums that we see in these columns. The mechanical stressing caused by the dowels and clamps due to intense deformation during earthquakes could explain some of the observed vertical cracks and fractures of the stone. Also, vertical cracking of a drum may result even without a dowel from the tendency of the rock to expand after quarrying, aided by anisotropic heating.

However, in the case of the Thrasyllos columns the observed damage must have been caused by the rusting of the iron dowels combined with the oxidation of the stone and high temperatures affecting the front part of the column. There are two indications that lead to this conclusion: first, the columns are covered with rust; and second, the drums have dilated to form a skin to accommodate an expanding core of marble inside it (**Figures 6 & 9**). No earthquake loading is likely to have caused such an orderly deformation of the stone which points to temperature effects.

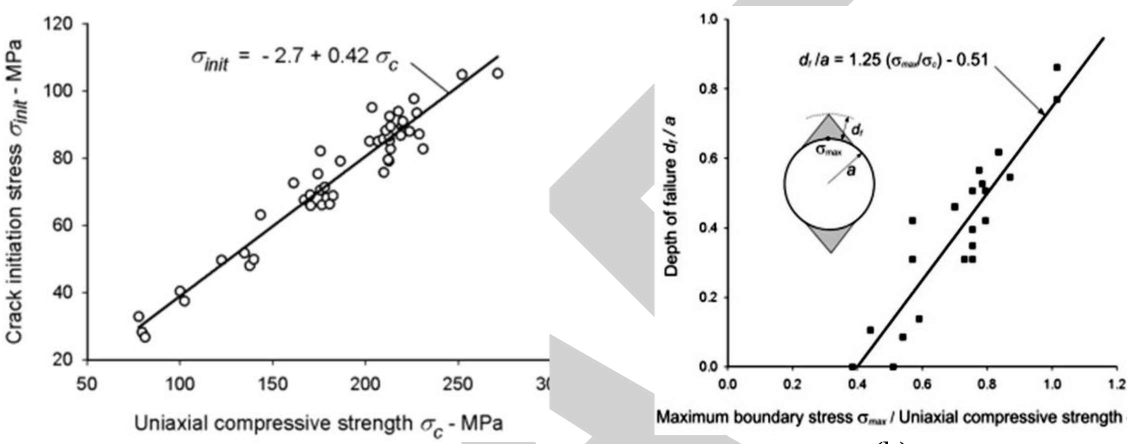
Over the centuries, the columns have been exposed to large fluctuation of temperature and at least twice to long periods of heat waves, the effects of which should have left their mark. The mechanism that can produce the damage we see is typical of the way the marble deforms to produce a sleeve for the core of the drum within to expand.

On column W we notice that, where rusting has caused fracture of the drum, this approaching the fracture boundaries at fairly shallow angles is vertical. This is typical of fractures caused from the dilation of the stone which forms a skin on the expanding stone. However, vertical cracking of drums is not a common phenomenon, so far observed in a few cases including the case of the orthostates of the Parthenon walls (**Toumbakari 2009**).

Figures 10 illustrate the inverse of the problem, that is the tensile spalling that we see on the inside of tunnels in massive brittle rock under high stresses. As **Figures 11** show, for a wide range of uniaxial strengths in these rocks, initiation of brittle fracture starts at about 40% of the Uniaxial Compressive Strength (UCS). If conditions are right, brittle fracture can propagate to form a "notch" in the tunnel wall, shown in **Figures 10b.** These notches are a reflection of the attempt of the rock to find a shape that results in equilibrium between the brittle failure conditions and the in situ driving stresses.

(a) (b)

Figure 10. (a) Spalling of rock surface of tunnel wall with a tendency to shrink shortly after its formation; (b) Spalling of rock surface of bore hole (Courtesy Prof. D. Martin).



(a) (b)

Figure 11. Crack initiation in intact rock starts at about 40% of the UCS (Courtesy Prof. D. Martin).

In the case of the Thrasyllos columns it seems a possibility that the vertical tensile fractures that we observe are the result of a combination of internal pressure due to the expansion of the oxidation and rusting of the iron dowels and the thermal stresses induced to the stone by exposure to direct daily sunshine over very long periods of time. If the fracture pattern in columns was the result of purely thermal loading, one would expect a more “onion skin” effect with the fractures approaching the boundary at fairly shallow angles.

In our case, the angle that the fracture makes with the boundary of the columns tends to be blunter and because of this blunt angle it is possible that the oxidation (dilation) of the dowels initiated the fracture which would then have grown approximately parallel to the boundary. Once initiated, the long-term thermal changes that prevail on site were more than adequate to propagate the fractures. The whole process we see depends on dilation. The dowels initiate the dilation process and the very low confining stresses allow the process to continue. As long as dilation occurs (due to oxidation, thermal effects, core extraction, stress relaxation), tensile stresses will always develop at the crack tip and hence propagate the crack in its own plane, perpendicular to σ_3 and to the boundary of the column (**Andersson *et al*. 2009, Hoek *et al*. 1998**).

The columns as physical seismoscopes

Summing up, as we have said to the best of our knowledge there has been no serious damage, loss of life, social or economic crises, in Old Athens caused by earthquakes, evidence which to some extent is testified by the two columns of Thrasyllos which, although ageing not so gracefully over the centuries, are still standing next to the Acropolis. One could say that ground motions that could topple them when they were in their original state did not happen and also that later earthquakes that could have brought about their collapse when they reached the poor state in which they are today also have not yet happened. They stand up somewhat damaged perhaps by an upper-limit earthquake-ground motion the value of which constrains the maximum ground motions that occurred in the Basin the past twenty three centuries.

The columns, therefore, may be used as natural seismoscopes from which to estimate the worst-case earthquake-shaking that could topple them, -which has not happened yet- and to estimate an upper limit of the earthquake which has happened causing some minor damage but not their collapse.

To this end, a back analysis is needed aiming: (a) to determine the minimum earthquake motions that would be required to cause collapse of the columns; and (b) to investigate whether the measured drum displacements can be explained by the seismic response of the columns.

It must be noticed that such a back analysis is not at all straight forward. Classical free-standing columns when they are first discovered they were already many centuries old and their material properties as well as those of their foundations have been affected not only by changes in their immediate environment but also by human activity and vandalism so that the state of their vulnerability is imperfectly known. A prerequisite for the proper modelling of the earthquake response of free-standing multidrum classical columns should be to start with the examination of the condition in which they were first found on site which is the final state in which they have been left perhaps after more than one damaging but not fatal earthquakes.

In general, it is not possible to say whether the observed damage to a column occurred when the column was a structural element carrying a load or when it became free-standing after the parent structure had collapsed. Therefore, the results from such an analysis, which can be made with reasonably assumed material properties and assumptions, must be considered as being more qualitative than quantitative.

Concerning the columns of Thrasyllos, they have always been standing free. However, their pedestals are damaged; with some pieces of the protruding limestone slabs badly cracked (**Figures 5, 7**). It is not known though when this happened during the long life of the monument, nor it is possible to model accurately the existing imperfections, so that it was decided to restrict the analysis to the intact columns, that is to the earthquakes that could bring the columns to collapse when the pedestals were intact. This issue is discussed later on, when the numerical model is presented.

Basic characteristics of the seismic response

The analysis of the seismic response of classical monuments and, in general, of stacks of rigid bodies, is a difficult problem which can only be treated numerically. Several investigators have examined this problem, analytically or experimentally, mostly using two-dimensional models (e.g. **Allen *et al.* 1986; Sinopoli 1989a,b; Psycharis 1990; Manos and Demosthenous 1992; Winkler *et al* 1995; Psycharis *et al.* 2000; Konstantinidis and Makris 2005; Papaloizou and Komodromos 2009** among others) and lesser using three-dimensional ones (e.g. **Papantonopoulos *et al.* 2002; Mouzakis *et al.* 2002; Psycharis *et al.* 2003, Dasiou *et al.* 2009a&c**). These studies have revealed the main features of the response which are:

- Owing to rocking and sliding, the response is nonlinear. The nonlinear nature of the response is pronounced even for the simplest case of a rocking single block (**Housner 1963**). In addition, multidrum columns can rock in various 'modes', which might alternate during the response increasing thus the complexity of the problem (**Psycharis 1990**). The word 'mode' denotes the pattern of rocking motion rather than a natural mode in the classical sense, since rocking structures do not possess such modes and periods of oscillation.

- The dynamic behaviour is sensitive to even trivial changes in the geometry of the structure or in the base-motion characteristics. The sensitivity of the response has been verified experimentally, since 'identical' experiments produced significantly different results in some cases (**Yim *et al.* 1980; Mouzakis *et al.* 2002; Dasiou *et al.* 2009a**). The sensitivity of the response is responsible for the significant out-of-plane motion observed during shaking table experiments for purely planar excitations (**Mouzakis *et al.* 2002**).
- The vulnerability of the structure greatly depends on the predominant period of the ground motion, with low-frequency earthquakes being in general much more dangerous than high-frequency ones (**Makris and Roussos 2000; Psycharis *et al.* 2000**). The former force the structure to respond with intensive rocking, whereas the latter produce significant sliding of the drums, especially at the upper part of the structure.
- **The** size of the structure affects significantly the stability (**Psycharis 1985; Makris and Roussos 2000; Psycharis *et al.* 2000**), with bulkier structures being much more stable than smaller ones of the same slenderness.

Effect of asymmetric foundation

In addition, lack of symmetry in the way a pedestal is built affects the natural period and direction of oscillation of the column (for small deformation) as well as the way in which it will respond to earthquake ground motions. It is a detail that must be taken into account in formulating the seismic response of columns. One of the reasons, for which the pedestals are asymmetric in both plan and elevation, and as such the columns sit eccentrically on them, is that they are built on an inclined foundation (**Figure 1b**), which is a common situation with other monuments too (Temple of Zeus of Aizani in Çavdarhisar, ESE face of the Temple of Hephaestus, Thesseio, etc.).

It is obvious therefore that lack of symmetry in the way the pedestal is built might affect its natural periods and direction of oscillation as well as the way in which the column will respond to earthquake ground motions. Also, in formulating the seismic response of columns lack of symmetry which will cause unequal stiffness between the front and back as well as in an orthogonal direction of the pedestal must be taken into account.

This can be appreciated from the present day state of preservation of the pedestals; the quality of rock from which the slabs are made is not very high, while few of their parts are linked with clamps, they are in places cracked or broken, not tightly packed**,** with the stack of slabs sitting on a stepped limestone foundation. Damage to the limestone slabs near the base of the pedestals by the growth of vegetation over the centuries seems to be considerable (**Figure 7**). Some of it was of invasive roots that have left their traces imbedded in the rough and weathered surface of the slabs or by abrasion, decayed roots leaving voids even displacing small parts of the limestone. Slabs near the base of the pedestal seem in places to be eroded by rainwater presumably draining through the Wall behind the columns down the ledge.

From the structural point of view, this situation results in a pedestal with an overall stiffness much smaller than what one would have expect under normal environmental conditions. What is more important for the earthquake response of the column as a whole is the way the pedestal is built, lacking symmetry and having a thickness that decreases with distance from the base of the column towards the south.

As a simplified example consider the foundation of the rigid pedestal ABCD shown in **Figure 12a** of a column on sloping ground, the horizontal stiffness of which on the back side

AD is $\alpha{\cdot}K$ and on the downhill side BC is K, where α is larger than unity as in the case of the Thrasyllos columns. The length of the pedestal is L and its width is $\beta{\cdot}L$, where $0.2 \geq \beta \geq 1.0$. The column sits at a distance $\beta{\cdot}L/2$ from the back side, where the centre of mass (CM) is located.

If the ground motion acts on the pedestal at an angle φ with respect to its downhill direction, the centre of mass of the pedestal will be displaced in a direction $\theta \neq \varphi$. However, the difference between φ and θ is not large. This is shown in **Figure 12b** for a pedestal with $\beta = 0.5$ and various ratios of α. For $\alpha = 10$, i.e. for stiffness of the back side (AD) ten times larger than the stiffness of the downhill side (BC), a ground motion with an incidence angle $\varphi = 20°$ will cause a response movement at an angle $\theta = 24°$ with respect to the long side of the pedestal.

In the case of Thrasyllos columns, the increased corrosion at the front side is expected to have affected the stiffness at the downhill side in the x-direction only. If we consider reduced stiffness in the x-direction only of the downhill side BC (**Figure 13a**) the results change, as shown in **Figure 13b** for $\beta = 0.5$. It is evident that, now, an oblique seismic force produces larger coupling of the response in the two principal directions (compare with **Figure 12b**).

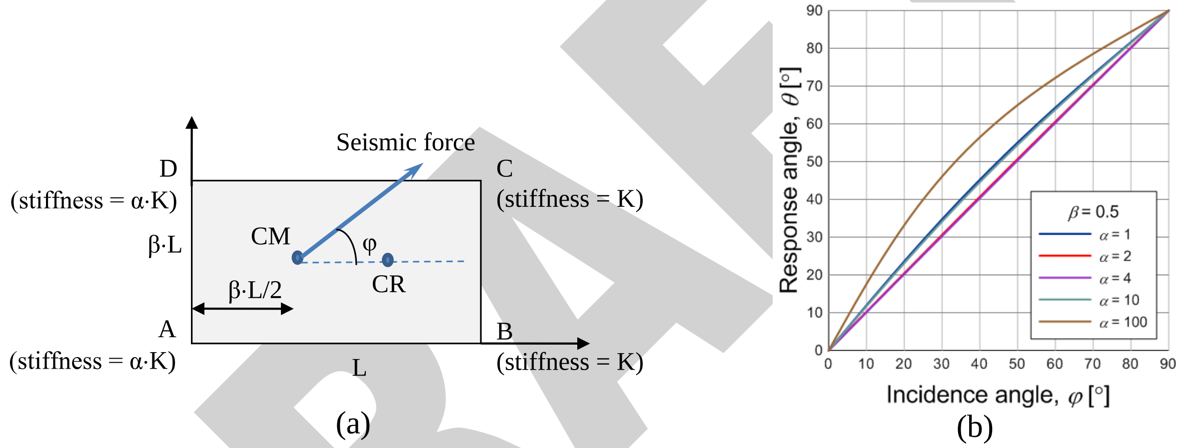


Figure 12. The seismic force acts at a horizontal incidence angle φ with respect to the x-direction causing the C.M. to move in direction θ. The diagrams show the relation between φ and θ for various values of the stiffness ratio α and for $\beta = 0.5$.

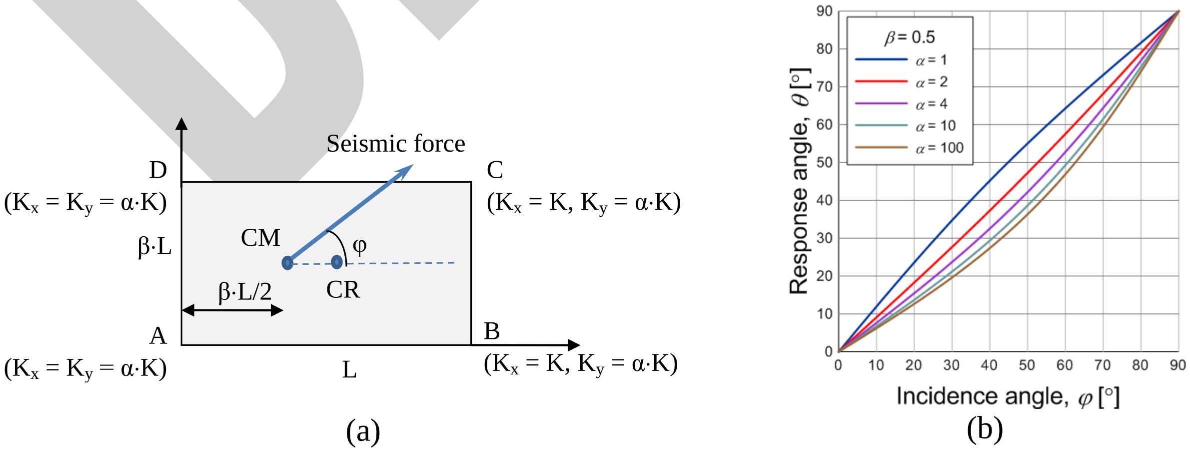


Figure 13. Relation between φ and θ for $\beta = 0.5$ and for various values of the stiffness ratio α with the difference in stiffness applied only in the x-direction.

Back analyses

Numerical model

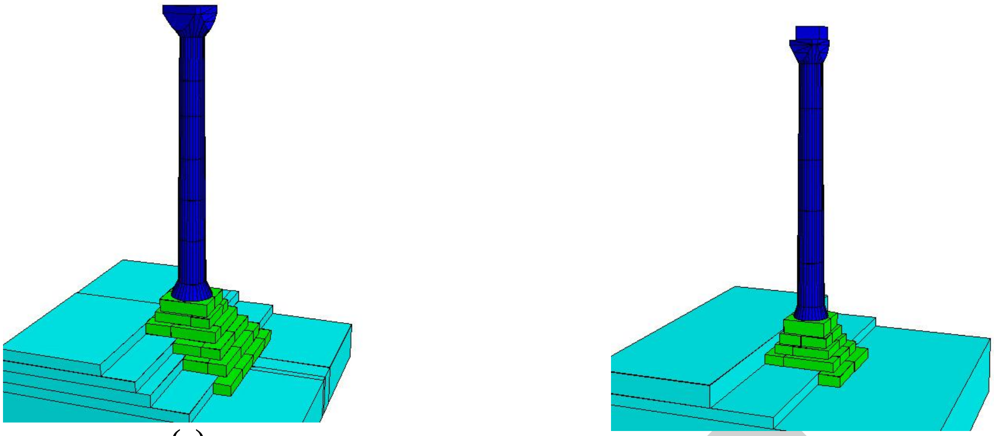
The numerical analyses of the Thrasyllos columns were performed with the code 3DEC of Itasca, Inc., which is based on the Discrete (or Distinct) Element Method (DEM) following the Molecular Dynamics (smooth-contact) approach (**Cundall & Strack 1979**). This method may not be the only choice for the numerical modelling of the seismic response of multidrum columns, but it forms an efficient and validated manner for the study of the dynamic behaviour of such systems as it employs an explicit algorithm for the solution of the equations of motion, taking into account large displacements and rotations. The code 3DEC provides the means to apply the conceptual model of a masonry structure as a system of blocks which may be considered either rigid, or deformable. In the present study only rigid blocks were used, as this was found to be a sufficient approximation and capable to reduce substantially the computing time (**Papantonopoulos *et al.* 2002**). The system deformation is concentrated at the joints (soft-contacts), where frictional sliding and/or complete separation may take place. The efficiency of the method and particularly of 3DEC to capture the seismic response of classical structures has been already examined by juxtaposing the numerical results with experimental data **(Papantonopoulos, *et al*. 2002; Dasiou, *et al*. 2009b).**

A quite important factor for the numerical analysis is the selection of the appropriate constitutive laws that govern the mechanical behaviour of the joints, namely the normal and the shear stiffness, k_n and k_s respectively. Such elastic joints were considered between the drums of the columns, between the columns and the pedestals, between the plinths of the pedestals and between the pedestals and the rock base. The last ones model the flexibility of the ground. In the present paper we made use of a Coulomb-type failure criterion. Notice that the stiffness affects considerably the results of the analysis (**Toumbakari & Psycharis 2010**). The values used in the analysis were calibrated against measurements of ambient and forced vibrations as explained in the ensuing.

No artificial (numerical) damping was introduced to the system during the response to the strong part of the ground motions according to the results of a previous investigation (**Papantonopoulos, *et al*. 2002**). However, significant damping was introduced towards the tail of the response in order to dissipate the free vibrations and calculate the residual displacements.

The numerical models (**Figure 14**) were exact reproductions of the columns, based on the available data (**Zambas *et al*. 2011**). The pedestals, the bases, the drums and the capitals were considered with their actual dimensions, without damage though (except of a parametric investigation that is mentioned in the following), not only because, due to lack of in-situ measurements, the observed damage, deterioration and dislocation of plinths and pedestals could not be quantified and introduced in the response analysis, but also because it is not known when this damage occurred and whether it has affected the current state of the columns, as discussed earlier.

The steel dowels that exist at the joints between the drums were also considered in the numerical models. According to **Zambas *et al*. (2011)**, there are two steel dowels at each joint, of dimensions 7 cm × 14 cm × 1 cm. In the numerical analyses, they were modelled as non-linear shear connectors without tensile strength and with properties: shear stiffness 4.5×10^5 kN/m and yield force in shear 170 kN. These properties correspond to a 12 cm long dowel with 7 cm^2 cross-section, as in the real structure, made of steel with Young's modulus equal to 200 GPa and ultimate strength in shear equal to 240 MPa.



(a) (b)

Figure 14. Numerical models used in the analyses showing difference in pedestals: (a) East column; (b) West column.

It must be noted that, for large rocking angles, it is possible that a shear dowel disengages from the upper drum. In that case, the dowel might not be able to re-insert in the mortise during the reverse of the motion, due to the wobbling and the sliding of the drums, blocking thus the proper sitting of the upper drum. For the Thrasyllos columns, however, the shear dowels are inserted 7 cm in the drums and the amount of rocking predicted by the numerical analyses is not large enough to cause their disengagement, even for strong ground motions. For this reason, the shear connectors were assumed continuously engaged.

In the original structure, dowels existed also between the base of the columns and the plinths. However, these dowels have been removed long time ago, unknown when. The W column shows a displacement at its base in the order of 2.5 cm (**Zambas *et al*. 2011**), which means that the column has been shaken by quite strong ground motions after the removal of the base dowels, or after they have been destroyed during previous earthquakes. For these reasons, the base dowels were not considered in the numerical models.

Calibration of the joint stiffnesses

As mentioned above, an important issue of the numerical analysis of classical columns is the appropriate choice of the joint stiffnesses k_n and k_s. Previous comparisons of numerical results with experimental data (**Papantonopoulos *et* al. 2002; Dasiou *et* al. 2009b**) have shown that for good quality joints among marble drums the normal stiffness k_n is in the order of 10 GPa/m, while k_s is typically set equal to one fifth to one third of k_n. Similar values were obtained from the calibration of the numerical model of the column of the statue of Apollo at the Academy of Athens with ambient vibration measurements (**Ambraseys & Psycharis 2011**). However, for the columns under consideration it is evident that different values of k_n should be used at different parts of the monument, due to the different materials and the observed different degree of damage and deterioration. For this reason, the appropriate values of k_n to be used in the numerical analyses were calibrated by matching the natural periods of the columns that were measured on site from ambient and low-amplitude forced vibration tests (Table 1). It is noted that columns made of drums do not possess natural periods in the classical sense if the shaking is strong enough to produce rocking or sliding. For low-amplitude vibrations, however, they behave like multi-degree of freedom continuous systems and do possess natural modes.

The ambient vibrations of the ground and of the columns were recorded over many hours during day and night, while forced oscillations were generated by physically pushing the top part of the shaft in different directions, in some cases more than once. The response to both ambient and forced vibrations was recorded with sensors placed on the capital and pedestal as well as on the ledge on which the columns are standing and on the floor in the cave below. The recordings were made by Prof. V. Kouskouna and Dr I. Kassaras.

Table 1. Measured natural periods from ambient and forced vibration tests.

Column	First period, T_1 [sec]		Second period, T_2 [sec]	
	Median	Standard deviation	Median	Standard deviation
E	0.69	0.032	0.35	0.016
W	0.74	0.022	0.29	0.004

It is noted that periods T_1 and T_2 are not the fundamental and first harmonic but the predominant periods of oscillation in two different directions, arising from the lack of symmetry of the pedestals. This is evident because their ratio ($T_1/T_2 \sim 2.0$ for the East column and ~ 2.5 for the West column) is much less than the ratio of the first two periods of a bending cantilever beam (equal to 6.3) and even lower than the corresponding ratio for the extreme case of a shear cantilever beam (equal to 3), which of course does not apply to the case of the columns of Thrasyllos.

The difference in the periods in the two principal directions is reasonable due to the inclined foundation, the asymmetric pedestal and, mostly, due to the excessive damage in the southern faces, in which there are gaps formed at the joints that result in longer period T_1 of both columns in the N-S direction. In the E-W direction, the contacts are much better, thus period T_2 is close to the one for intact joints.

The numerical calculation of the natural periods was based on free oscillations of the columns triggered by a sine-impulse of short period and of small amplitude. The natural periods were determined from the peaks of the Fourier spectrum of the response of the capital in the two main horizontal directions. Analyses were performed for various excitation directions; in general, however, excitation in one direction produced spatial motion of the column, therefore, both eigenperiods could be identified from the motion of the capital. In this sense, the direction of the excitation was not important for the determination of the natural periods. The analysis was performed for the E column but the resulted stiffnesses were also applied in the W column.

It was assumed that the second measured period T_2 corresponds to the E-W direction, in which the effect of the pedestal to the response is expected to be small. For this reason, a parametric investigation was initially performed for the East column without the pedestal (**Figure 15**), in order to calibrate the stiffness of the joints between the drums. In this analysis, the normal stiffness at the interface with the rock was assumed: $k_{n,soil}$ = 10 GPa/m, which is a reasonable value for limestone. Note that according to site investigations made in the immediate vicinity of the Monument the material properties of the ledge on which the columns stand are: wave velocities V_s and V_p ranging from 400 to 650 m/sec and 740 to 1500 m/sec respectively and bearing capacity of about 1.0 MPa.

This investigation showed that the most appropriate values for the joints of the column are (**Figure 15**): k_n = 10 GPa/m and k_s = 2 GPa/m, for which the fundamental period of the column is equal to 0.34 sec and practically coincides with the measured period T_2 (equal to 0.35 sec). It is noted that when these values were applied to the full numerical models, including the pedestals, the fundamental periods of both columns matched well the measured periods T_2.

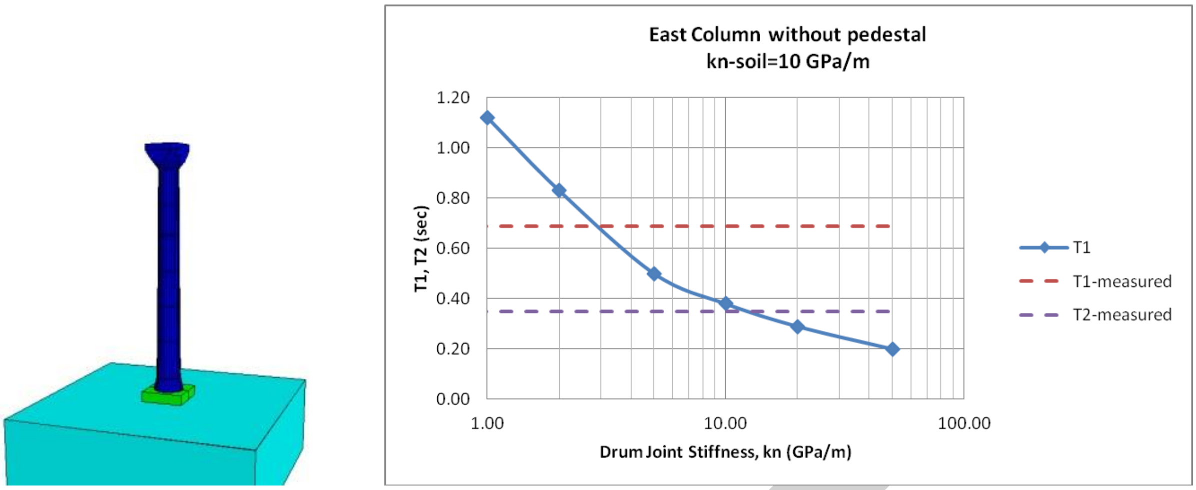


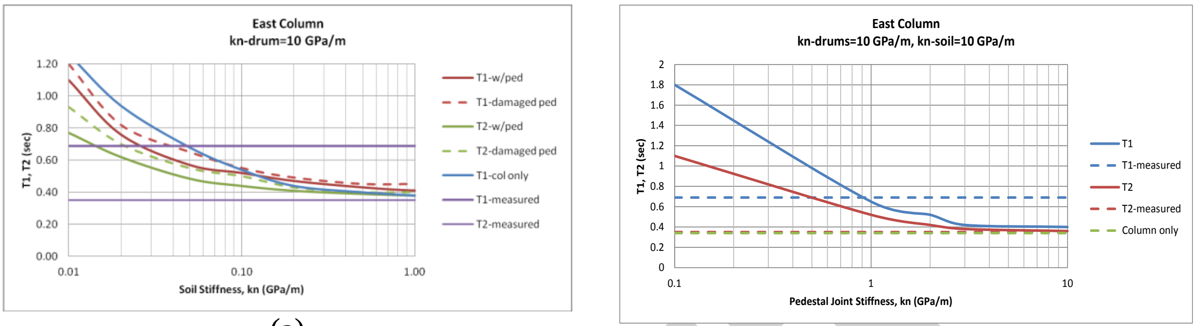
Figure 15. Variation of the calculated fundamental period of vibration of the East column without pedestal vs. the normal joint stiffness of the drums, k_n and comparison with the measured periods.

After the joint properties of the columns were set, an attempt was made to calibrate the joint stiffness of the pedestals, which is difficult to estimate as the slabs are loosely stacked on an irregular limestone foundation. Again, the analysis was performed for the E column only and the criterion was to match the larger measured period, T_1. To do this, one has to consider the 'loose' contacts at several joints of the pedestals and the interface with the ground. Several scenarios were examined, namely:

1. Uniform stiffness $k_{n,ped}$ and $k_{s,ped}$ at all joints of the pedestal and uniform stiffness $k_{n,soil}$ and $k_{s,soil}$ at all contact surfaces with the ground. Several values were considered for these parameters.
2. Much softer contact stiffness at the two bottom layers of the pedestal and at their contact surfaces with the ground. This scenario was aiming at modelling the existing significant deterioration and the increased damage of the plinths of these layers.
3. As in scenario #2 but, additionally, considering reduced stiffness also at the downhill contact area of the square base of the column with the plinths of the pedestal, due to the questionable quality of the contacts in this area.

Indicative plots of the obtained results are presented in **Figure 16.** In all cases examined it was evident that there are two distinct characteristic periods, similarly to what was found during the ambient and forced vibrations measurements. However, it was not possible to match absolutely both measured periods T_1 and T_2. This happened, because, due to the limitations of the code (3DEC), it was not possible to assign joint stiffnesses that were different in the N-S and in the E-W directions, as it seems to be the real situation due to the larger corrosion at the southern side. As a result, "soft" joints could predict well the first period T_1 but overestimated the second period T_2 and "stiff" joints could predict well the period T_2 but underestimated T_1.

As mentioned above, the actual condition of the joints of the pedestals and the drums of the columns is not known, making the numerical reproduction of the real situation of the monument extremely difficult. Therefore, any attempt to quantify some of the damage by refining further the numerical model would be rather underproductive. One should have in mind that, during a strong earthquake, when intense rocking of the drums of the columns occurs, the effect of the damaged plinths should not be so important to the response as it was during ambient vibrations, when it was most probably responsible for the large value of the measured first period T_1. For this reason, in the numerical analyses that were used for the earthquake motions the stiffness at the joints of the pedestal was assumed equal to the stiffness at the joints of the drums while the stiffness at the joints of the pedestal's plinths with the ground was considered one order of magnitude smaller in order to account for the loose contacts. **Table 2** gives the values of the joint parameters that were considered in the analyses for both columns. In the same table, the coefficients of friction that were used are shown. For the Thrasyllos columns we adopted μ_s = 0.70 and μ_k = 0.60 for pre-cut marble surfaces and good quality limestone.



(a) (b)

Figure 16. (a) Variation of periods T_1 (red lines) and T_2 (green lines) of column E with the stiffness at the interface with the ground. Solid lines correspond to $k_{n,ped}$ = 10 GPa/m, equal to the corresponding value at the joints of the drums of the column; dashed lines correspond to reduced joint stiffness at the bottom-front part of the pedestal by 15 to 100 times; (b) Variation of periods T_1 (blue line) and T_2 (red line) of column E with the joint stiffness of the plinths of the pedestal.

Table 2. Joint properties of the numerical models considered in the analyses.

Position	Normal stiffness, k_n (GPa/m)	Tangential stiffness, k_s (GPa/m)	Coefficient of friction	
			Static, μ_s	Kinetic, μ_k
Column	10.0	2.0	0.70	0.60
Pedestal	10.0	2.0	0.70	0.60
Foundation	1.0	0.3	0.70	0.60

Replication of the damaging earthquake

Constraining ground motions to an upper limit earthquake which would simulate the observed damage of the Thrasyllos columns requires the selection of what one may call suitable surrogate ground acceleration time histories that could replicate as closely as possible the time histories of past and perhaps anticipated earthquakes. Records must be chosen from past earthquakes which are associated specifically with the tectonics and seismicity of the region or with earthquakes from other regions of similar tectonics. Among the important characteristics of ground motion time-histories to be used in 3D numerical analyses are their maximum velocity and length of associated period as well as the directivity effects which will be present depending on the proximity of the columns to a potentially active fault.

The choice of which time histories to include and which to exclude in order to constrain ground motions is an important decision in deriving the worst possible ground motions that happened in the past. There is a balance to be struck between being not restrictive enough in the time histories used leading to unreliable results and hence predictions due to errors and uncertainties. And being too restrictive, which leads to a too small set of time histories and hence non-conclusive answer (**Somerville *et al*. 1997; Douglas 2001**).

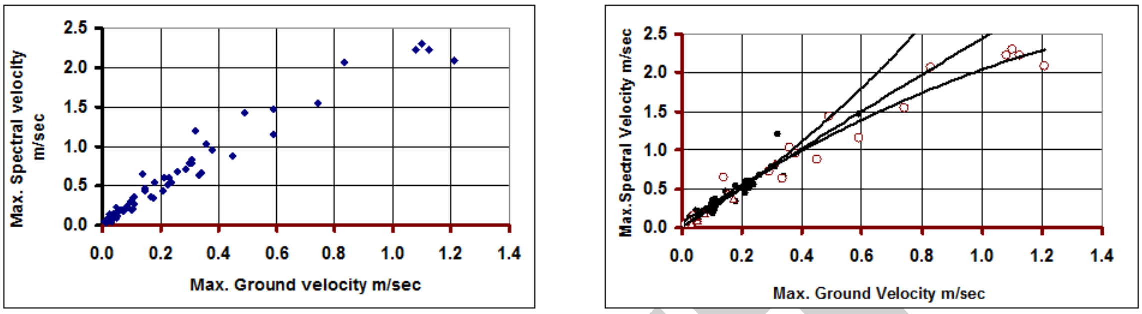
In the case of the Thrasyllos columns there is no evidence for potentially active faults within a radius of at least 10 km. Both the geomorphology and GPS measurements of the regional and the local tectonics of the Basin of Athens show a subdued activity which is confirmed by a steady decrease in N-S extension rate from 12 mm/yr in the western Gulf of Corinth, to 5 mm/yr at the eastern end of the Gulf of Corinth, to about zero in the larger area around the Basin of Athens. The selection of surrogate ground acceleration time histories that could replicate time histories of past events must be extended to include also records consistent with the distribution, attitude and activity of fault-lengths outside the Basin of Athens capable of producing locally damaging events away from the Basin.

For sites close to the causative fault, the ground motions will show pronounced directivity effects in their ground velocities and displacements. These will appear as long-period amplitude pulses linearly related to the seismic moment (**Boatwright & Boore 1982; Somerville *et al*. 1997**). In the near field, the effect of the source mechanism on directivity will be that ground accelerations due to strike-slip faulting will be larger than those due to normal faulting, while ground velocities and displacements will be larger for thrust faulting compared with normal earthquakes. A simple way of expressing the forward-directivity concept is to say that there is roughly a dominant period T_d of the largest-amplitude cycle in the velocity trace (**Bray *et al*. 2004**). If more than one peaks of comparable amplitude exist, then the longest period of the near-fault ground motions affected by forward-directivity is considered and its value may be taken as the period at which 5% damped spectral velocity (*PSV*) peaks. Directivity produces a bell-shaped amplification around T_d **(Shahi and Baker 2011**), while soil effects produce a general amplification of the response spectra.

Turning to the selection of surrogate ground acceleration time histories, these should be shallow from normal faulting. The magnitude scale should be moment magnitude (M_w) implying that only records from moderate and large earthquakes may be used so that only records from earthquakes with $M_w \geq 5.0$ were chosen. The source-to-site distance must be the distance to the surface fault break or to the surface projection of the causative fault. Only records from stations recorded on rock or on upper class A foundation materials, which are as free-field as possible have been chosen. Soil sites of lower than A class, S and L, would strongly enhance ground velocities particularly at large stains. This is important in the numerical analyses, since the duration of ground motion is a function of magnitude and near-surface soil conditions. Duration increases strongly with earthquake magnitude and moderately with source distance as well as with decreasing site shear wave velocity.

The selection of the records that were used in the analyses was made from a list of 75 strong-motion records from the European Strong Motion Data Base, from shallow depth earthquakes of $4\frac{3}{4} < M_w < 7\frac{1}{2}$ recorded at source distances 1 to 90 km, which were used to replicate time histories of past earthquakes, not specifically for the testing of Thrasyllos columns, but also for the testing of the stability of columns in other seismo-tectonic environments. For these records, **Figures 17** show an almost perfect scaling of the maximum spectral velocity at 5% critical damping with the peak ground velocity for different faulting mechanisms. In spite of the fact that the data are not numerous it can be seen that the modelling improves with source mechanism, with spectral values scaling somewhat higher for strike-slip than for normal than thrust fault-breaks.

The analyses were performed for five earthquake excitations, four of which were taken from this sample and are compatible with the regional tectonics and the seismicity of the Basin of Athens, while the fifth one (Syntagma-B) was recorded 25 m below ground level at the underground Metro station at Syntagma, less than 1 km from the monument, during the 1999 earthquake. All three components of each earthquake were used in the analyses. In **Table 3**, the peak ground acceleration (*pga*), the peak ground velocity (*pgv*) and the predominant pulse period (T_d) of the two horizontal components of each ground motion are given. The periods of the predominant directivity pulses were determined from the peaks of the corresponding velocity response spectra for 5% damping (**Rupakhety *et al*. 2011**). This parameter of the seismic excitation is considered important, as it is known that the vulnerability of classical columns increases with the period of the base excitation (**Psycharis *et al*. 2000**) as is also the case for the overturning of a single rocking block (**Zhang & Makris 2001**).



(a) (b)

Figure 17. Scaling of the peak ground velocity with the maximum spectral velocity: (a) all faulting mechanisms; (b) for strike-slip (upper), normal (middle) and thrust (lower) faulting.

It is understood that in using surrogate ground acceleration one must consider the uncertainties inherent in the selection of its characteristics values, as *pga* and *pgv*, which, because of differences in source distance, foundation conditions and mechanism may vary by a factor of two or more. Thus, scaling of the selected records within a reasonable range is legitimate and can cover such differences. In the analyses that are presented herein, the records were scaled up or down step-wise, up to the point where collapse of the columns occurred. For column W, the required scaling was, in general, within a narrow range of accelerations about the adopted surrogate value. For column E, however, large amplifications were required to cause collapse in some cases, which might not be legitimate for the selected records. Large scaling up of the original acceleration creates a fictitious time history, the frequency content and duration of which belong to an earthquake of the selected magnitude while its acceleration belongs to an earthquake of considerably larger magnitude. In this sense, results for large amplifications of the original records can only serve as indications for the assessment of the stability of the columns and should not be used quantitatively but only to estimate the degree of their stability.

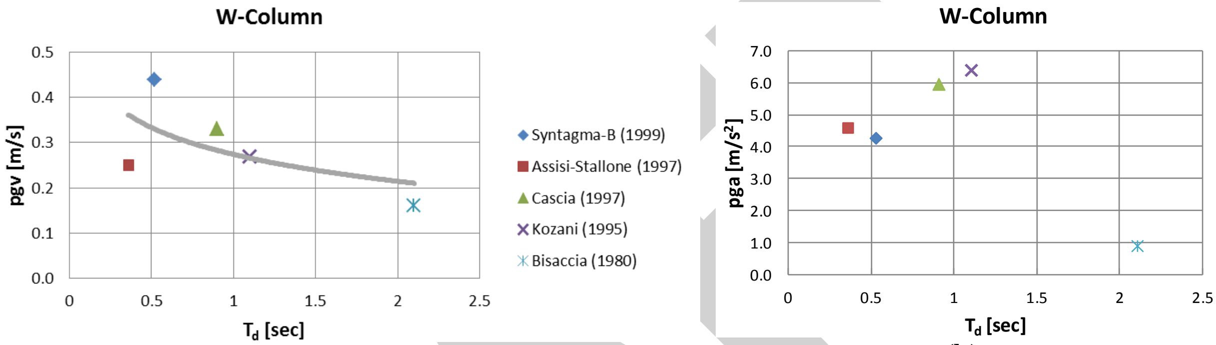
Table 3. Earthquake records considered in the numerical analyses.

Earthquake record	Component Long			Component Trans		
	pga (m/s^2)	*pgv* (m/s)	T_d (sec)	*pga* (m/s^2)	*pgv* (m/s)	T_d (sec)
Syntagma-B (1999)	1.07	0.10	0.89	0.84	0.11	0.52
Assisi-Stallone (1997)	1.84	0.10	0.34	1.64	0.08	0.36
Cascia (1979)	1.42	0.08	0.64	1.99	0.11	0.90
Kozani (1995)	2.13	0.09	1.16	1.38	0.07	1.10
Bisaccia (1980)	0.90	0.16	2.02	0.78	0.15	2.10

And one last point. Precariously balanced rocks have been used to constrain the probable ground motions in a region giving a direct indication of the upper bound on the ground motion of past earthquakes at the rock site (**Anooshepoor *et al*., 2006**). This method provides statistical estimates of the ground motions which have not been exceeded during the life-time of the precarious rocks. In our case this method is not applicable for two reasons: Firstly the number of free standing columns available for observation in a given region is very small, so that a statistical approach is not possible; and secondly that a deterministic estimate of the maximum ground motion responsible for the damage sustained by the columns can be made only from a back analyses of the observed damage.

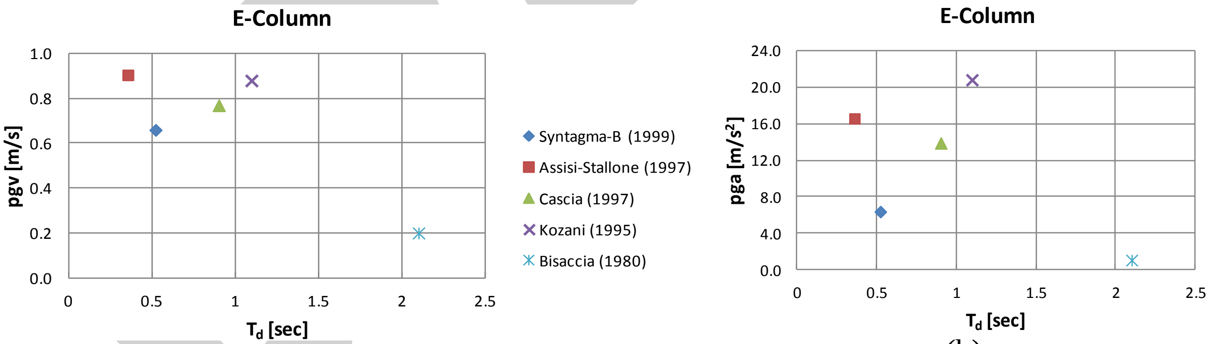
Estimation of the worst-case earthquake

The worst-case earthquake that has not occurred yet in the Basin of Athens can be determined from the maximum earthquake that the columns can sustain without collapse. The *pga*’s and *pgv*’s of the selected records required to bring the columns to collapse are plotted in **Figures 18 and 19**. It is noted that, in most cases, the base excitation was increasing in steps of 50% of the original record, thus it is possible that the columns collapse for ground motion parameters slightly smaller than the ones shown in these figures.



(a) (b)

Figure 18. (a) Minimum *pgv* and (b) minimum *pga* required to bring column W to collapse for the records considered.



(a) (b)

Figure 19. (a) Minimum *pgv* and (b) minimum *pga* required to bring column E to collapse for the records considered.

Table 4. Upper limit of earthquakes’ intensity that does not topple column W.

Earthquake	Amplification	*pga* (m/s^2)	*pgv* (m/s)
Syntagma-B	3.5	3.75	0.39
Assisi-Stallone	2.0	3.68	0.20
Cascia	2.5	4.98	0.28
Kozani	2.5	5.33	0.23
Bisaccia	0.9	0.81	0.14

In general, collapse of column E occurs for significantly stronger ground motion than for column W, thus column W is the critical one to determine the upper limit earthquake. This must be attributed to the smaller size of column W, as it is known that, between two columns of the same slenderness but different size, the smaller one collapses for smaller intensity of the ground excitation than the larger one (**Psycharis *et al.* 2000; Zhang & Makris 2001**). In **Table 4** the worst case earthquakes that could have occurred in Athens are given, based on the fact that column W has not collapsed yet.

Quite large amplifications of all records except Bisaccia are required for the collapse of column E. As mentioned above, large scaling of the original records is not legitimate, thus these results are considered only as proofs that column W would have collapsed under these earthquake motions before column E.

For the Bisaccia record, both columns collapse for small amplification: 1.0 for column W and 1.25 for column E. As shown in **Table 4,** the maximum *pga* and *pgv* of an earthquake with the frequency characteristics of Bisaccia that could have happened in Athens are 0.08 g and 14 cm/sec respectively, i.e. relative small values that correspond to a moderate earthquake. It must be noted that this record contains a pulse with long period T_d = 2.10 sec. Therefore, these results show that earthquakes with such large predominant period are rather improbable that have hit Athens.

It is evident from **Figures 18 and 19** that, between *pga* and *pgv*, the ground velocity is a better intensity measure showing less scattering. It should be noted, however, that there are a number of other parameters that affect the results, which are not examined here, as the magnitude of the earthquake and the distance from the fault.

Maximum level of ground shaking

In general, the maximum level of shaking may be assessed from a back analysis of the observed damage. As reported by **Zambas *et al.* (2011)**, column W is displaced at its base by approximately 25 mm. This dislocation is considerably larger than the one predicted by the numerical model for single application of the ground motions considered. This is shown in **Figure 20**, in which the residual displacement at the base of column W for each earthquake is plotted versus the corresponding *pgv* of the excitation. It is seen that the considered ground motions produce dislocation of the column smaller than 3 mm in most cases, even if they are amplified significantly (but less than what is required to topple the column).

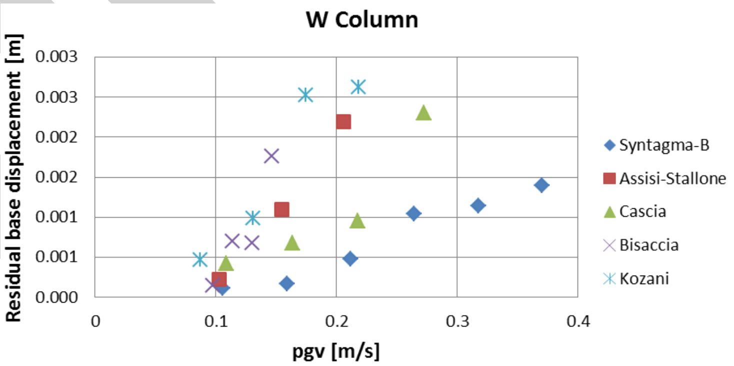
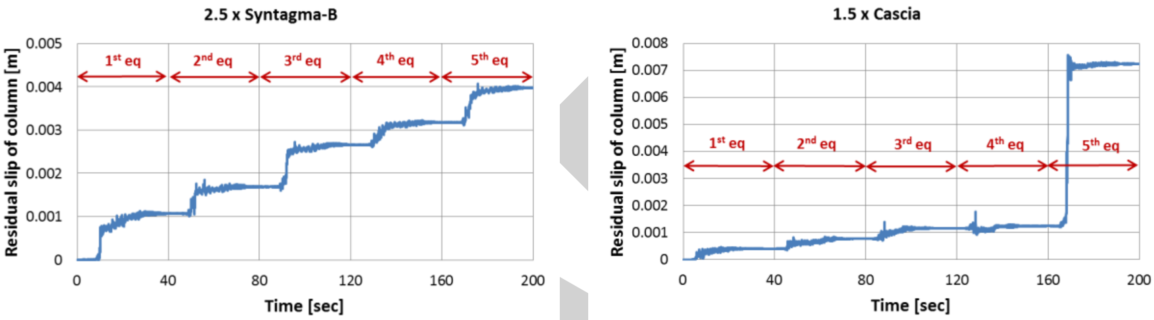


Figure 20. Permanent dislocation at the base of the W Column versus the *pgv* of the ground motion for the earthquakes considered.

However, the present state of the monument is the cumulative result of a number of shocks that had occurred during its life. It is known that the permanent deformation of classical columns increases, in general, with the number of repetitions of the base excitation (**Psycharis 2007**). This is also shown in **Figures 21a&b,** in which the time history of the horizontal displacement at the base of the column is shown for five consecutive applications of the Syntagma-B and the Cascia earthquakes amplified 2.5 times (*pgv* = 0.27 m/s) and 1.5 times (*pgv* = 0.16 m/s) respectively. These ground motions correspond to 70% and 60% respectively of the corresponding worst-case earthquakes of **Table 4**. It is evident that, in general, following earthquakes increase the base dislocation caused by previous ones, while it is possible that the pre-existing deformation of the column causes a large base displacement during a single event, as occurred during the fifth repetition of the Cascia earthquake (**Figure 21b**). Such unexpected slips of the drums were also observed during the shaking table tests on a marble column (**Mouzakis *et al*. 2002**).

It must be noted that the results of **Figures 21** do not represent real earthquake scenarios, as it is not possible that the same earthquake is repeated and consecutive seismic motions have different charcteristics. In this sense, they can be considered as indicative only of the effect of repeated ground excitations that show that the present state of the monument has probably been caused by several seismic motions. Otherwise, the measured deformation cannot be explained by the numerical analysis.



(a) (b)

Figure 21. Time history of the slip at the base of W Column for five consecutive applications of (a) the Synatgma-B record amplified 2.5 times and (b) the Cascia record amplified 1.5 times, showing the increase of the residual dislocation with each repetition of the excitation. Notice the large slip that occurred during the fifth repetition of the Cascia record.

Similarly, the numerical analyses predict small relative dislocations of adjacent drums even for the worst case earthquakes (less than 1 mm), while, according to **Zambas *et al.* (2011),** a much larger dislocation exists at the joint between 2nd and 3rd drum of column E, equal to 15 mm. Again, it is possible that the observed damage is the results of multiple earthquakes.

It is reminded, however, that the analyses were performed considering that iron dowels exist at the joints between drums. It is not known whether the dowels are tightly fixed to the drums, or small displacements are allowed. If these dowels were considered loose in the analyses, then the residual displacements would be different. An example of the effect of the dowels is shown in **Figure 22** where the residual drum dislocations at the joints of column E are shown for the Syntagma record amplified to its limit (3.5 times). If the iron dowels are included in the numerical model the displacements are very small (blue line); however, if the dowels are ignored significant residual dislocations occur with the maximum being equal to 17 mm at the joint between 2nd and 3rd drum (red line), which is close to the measured displacement. Consideration of loose dowels also produces larger dislocations at the base of column W.

These results show that, if the dowels are not tightly connected with the drums, strong ground motions close to the worst-case earthquakes could cause the measured damage. On the other hand, similar damage could also have been caused by two or three smaller earthquakes.

Due to the lack of information on the degree of fixation of the dowels, it is not possible to say which scenario is most probable.

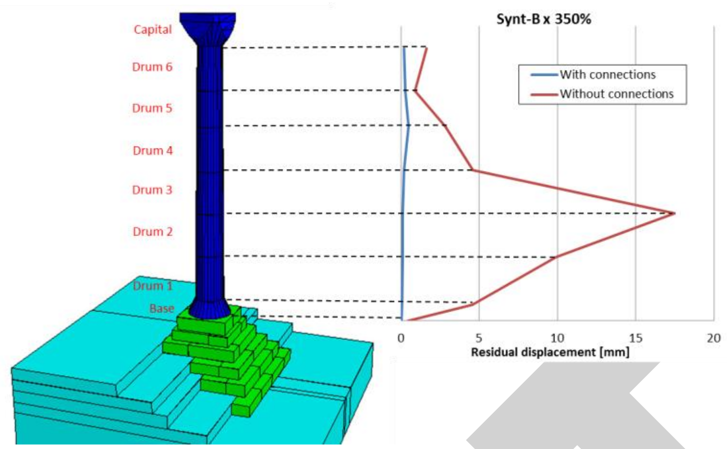


Figure 22. Residual dislocations of column E subjected to Syntagma earthquake amplified 3.5 times. Blue line: with shear dowels at the joints of the drums; red line: without dowels.

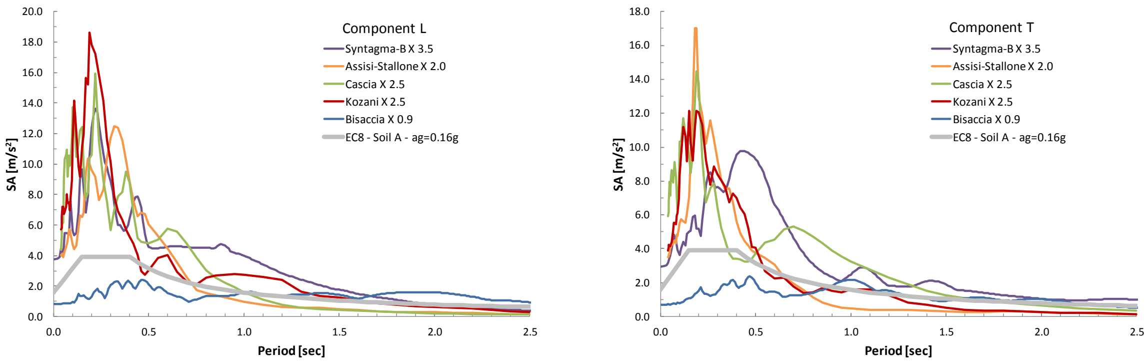
It is worth noting that the earthquake of 1999 was responsible for relative displacements between the stones of the monuments on the Acropolis which were larger than those calculated here. However, those displacements were measured mainly at architrave beams, where much more intensive shaking takes place during earthquakes, especially for corner configurations, than between column drums, as observed during shaking table tests (**Dasiou *et al.* 2009a**). No notable drum dislocations were reported at the monuments on the Acropolis during the 1999 earthquake, which is in accordance with our numerical results that show that stronger than the 1999 event or repeated ground shakings are needed to produce the measured displacements at the columns of Thrasyllos.

Design implementations

According to the seismic code provisions (Greek Annex of Eurocode 8) that apply to the centre of Athens for stiff ground (type A), the ground acceleration for the design of ordinary structures is: a_g = 0.16 g. This value must not be compared with the *pga*'s of the worst-case earthquakes (**Table 4**) because it refers to significantly less return period (this issue is discussed in the ensuing) and corresponds to the effective ground acceleration (*epa*) and not to the peak one (*epa* is generally 1.5 to 2.0 times less than *pga*). For a proper comparison of the worst-case earthquakes with the design earthquake, on must compare related response spectra.

The response spectra of both horizontal components of the five earthquakes considered in the analyses, amplified to the values shown in **Table 4,** are shown in **Figures 23**. In the same figures, the Eurocode 8 (EC 8) elastic response spectrum that applies to Athens (a_g = 0.16 g, ground type A) is shown for comparison**.** These plots show that, with the exception of the Bisaccia record, the worst-case ground motions are quite stronger than the design earthquake of the code.

In **Figure 24** the average spectrum for 5% damping, for both horizontal components of the considered records excluding the Bisaccia record, is compared with the EC 8 spectrum. Again, the amplification shown in **Table 4** was considered for each earthquake. It is interesting to notice that the average spectrum is close to the design spectrum of Eurocode amplified by a factor of two (dashed line) which, in fact is almost the average plus one standard deviation. As noted above, however, the design spectrum of the code is applicable to the design of ordinary structures (belonging to importance class II according to EC 8) and corresponds to mean return period of the seismic action T_R = 475 years, while the average spectrum of the worst-case earthquakes shown in **Figure 24** corresponds to events that probably have not happened yet, i.e. to events of return period at least 2300 years.



(a) (b)

Figure 23. Acceleration response spectra for 5% damping of the earthquakes considered, amplified as in Table 4 compared with the EC 8 spectrum for the centre of Athens: (a) Component Long; (b) Component Trans.

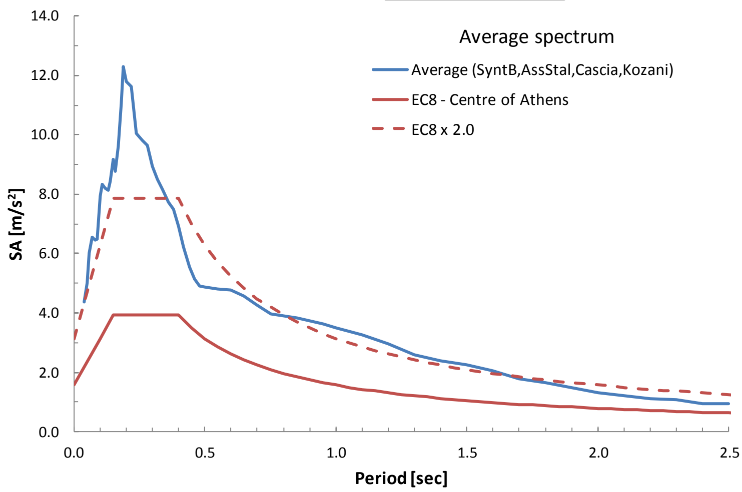


Figure 24. Average acceleration response spectrum for 5% damping of both horizontal components of four earthquakes considered, amplified as in Table 4 compared with the EC 8 spectrum for the centre of Athens.

The return period T_R is related with the probability of exceedance P_R in a period of T_L years with the expression $T_R = -T_L/\ln(1- P_R)$. Thus, the return period of 475 years corresponds to probability of exceedance 10% in 50 years and is associated with importance factor γ_I = 1.0 (coefficient with which the code spectrum is amplified). Similarly, the return period of 2300 years corresponds to probability of exceedance P_R = 2.2% in a period of T_L = 50 years, or to probability of exceedance P_R = 10% in a period of about 250 years.

For a proper comparison of the spectra, one has to increase the code spectrum by a factor γ_I that corresponds to return period T_R = 2300 years. In order to define the appropriate value of γ_I the relation between the intensity of the ground motion and the return period is needed, which depends on the seismicity of each region. As a first approximation, one could use the relations provided in EC8, i.e. either (i) determine the value of the importance factor γ_I to achieve the same probability of exceedance P_R = 10% in T_L = 250 years as in T_{LR} = 50 years, for which the reference seismic action is defined, using the expression $\gamma_I \sim (T_{LR}/T_L)^{-1/k}$; or (ii) determine the value of the importance factor γ_I that needs to multiply the reference seismic action to achieve probability of exceeding the seismic action P_L = 2.2% in T_L = 50 years instead of the reference probability of exceedance P_{LR} = 10% over the same period, using the expression $\gamma_I \sim (P_L/P_{LR})^{-1/k}$. The exponent k depends on seismicity, but is generally of the order of 3. Both approaches give $\gamma_I \sim 1.7$ which means that the average response spectrum of the worst-case earthquakes is about 15% stronger than the corresponding design spectrum for return period 2300 years (**Figure 24**).

It is noted, however, that the worst-case earthquakes are upper limits derived on the basis that the columns are still standing and it is possible that such strong ground motions have not occurred yet in Athens. As mentioned above, the experienced maximum level of ground shaking could not be determined from the observed damage, due to the lack of information on the actual effect of the shear dowels in preventing drum displacements. It is reasonable, however, to assume that the maximum earthquake that has occurred is less than the upper limits shown in **Table 4**, which means that the response spectrum of the code is generally compatible with the assessed long-term seismicity of Athens. In any case, modern structures that have been designed according to the seismic codes can withstand without serious damage seismic motions larger than the ones they have been designed for.

It must be emphasized that the above conclusion on the compatibility of the design provisions with the worst-case earthquakes applies to the historical centre of the city and might not be valid for the whole Basin of Athens, as there are regions in the suburbs that are located close to active faults, where the seismic motion might be significantly increased.

Conclusions

In this paper, the two columns of the Thrasyllos monument on the south flank of the Acropolis of Athens, which have remained free-standing for more than 2300 years, have been used for the assessment of the long-term seismicity of Athens. The results of the historical review, the seismotectonic investigation and the back analyses performed can be summarised as follows:

- Probabilities of exceedance for very long periods of time are beyond mathematical analysis; we can only have recourse to the guidance of common sense, using the observations from regional tectonics and the study of the vulnerability of extant early structures such as the Thrasyllos columns that may confirm these probabilities.
- We find no active faults within a radius of about 10 km from the Acropolis capable of producing damaging earthquakes, while much of the threat comes from earthquakes originating from active faults at greater distances. The seismicity of the past 300 years, for which we have reasonably good macroseismic information, particularly for the last 100 years from good seismological monitoring, confirms for Old Athens a subdued level of seismic activity.
- There is no evidence that Old Athens was ever seriously damaged with loss of life or injuries.
- For the assessment of the long-term seismicity of a region based on the current state of ancient monuments, it is important to separate the damage caused by earthquakes from the one caused by other reasons including cracks due to rusting of dowels and temperature effects that can cause a pre-existing crack to grow. This identification of damage, however, is not always evident, nor is it easy to be included in the numerical models.
- Based on the results of the "Thrasyllos experiment" we concluded that the maximum earthquake that could have happened in Athens during the last 2300 years is unlikely it had

pgv larger than 0.35 m/sec on rock and predominant period in the range 0.5 to 1.2 sec (**Figure 18**).

- More information on the actual effect of the shear dowels in preventing drum displacements (degree of fixation with the dowels) is needed to draw conclusions on the most damaging earthquake based on the present deformed state of the Thrasyllos columns.
- The probable worst-case earthquakes were found to produce response spectra that, in the average, are approximately double the design spectrum of EC 8 for return period 475 years (**Figure 24**). However, taking under consideration that they refer to much longer return period (more than 2300 years), the design spectrum for the Old City of Athens is generally in accordance with the finding of this investigation, being approximately 15% smaller. This conclusion applies to the historical centre of the city and might not be valid for the whole Basin of Athens where there are regions located close to active faults.

Lastly, the conservation of the Thrasyllos columns should aim at preserving their existing condition with a minimum amount of strengthening of their pedestals and the maximum effort to arrest further deterioration and weathering of their stone.

Concerning the seismic hazard of the Basin of Athens we conclude with the statement of the first director of the Observatory of Athens regarding the seismicity of the old city, which says that: ....*Athens having been built on rock and for so many centuries not having suffered from earthquakes the city must be considered immune to such calamities... as for the damage that the city experiences occasionally, much of it must be attributed to the bad construction of its houses ... and as for the magnitude of the damage it suffers, this is always exaggerated by the daily press and by politicians* (**Schmidt 1867a,b**).

All this makes one bound to agree with Professor Korres, who rightly feels that “kindynologia” (paraphrasing catastrophism) has no place in the assessment of the seismic vulnerability of the Acropolis (**Korres 1990**).

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