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ORIGINAL ARTICLE

Monumental articulated ancient Greek and Roman columns and temples and earthquakes: archaeological, historical, and engineering approaches

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Abstract Structural analyses indicate that monumental articulated ancient Greek and Roman (MAGR) columns and temples have a very particular seismic response, differing from rigid structures (made with mortar); tall columns in particular, have an excellent seismic performance, favoring anthropogenic effects as causes of their destruction. Archeoseismological studies, on the other hand, provide evidence of seismic damage in MAGR structures. To investigate this apparent conflict, we analyzed the conditions and limitations of structural models, as well as historical and archeological evidence of response of such structures to natural and anthropogenic effects. In addition, we examined two groups of MAGR structures: first, structures damaged or destroyed by known causes, including earthquakes and wind; second, structures damaged by unknown causes, based on comparative damage analyses with emphasis on geotechnical (soil dynamics) effects. This analysis indicates that reports of deliberate destructions of MAGR structures are exaggerated, and in addition, (i) these structures seem safe against earthquakes only if structurally healthy, concerning both their superstructure and foundations; this condition is not always satisfied, and hence, no controversy exists between structural engineering and archeoseismological approaches; (ii) their seismic response is sensitive to small changes of the source- and site-specific parameters; and (iii) no deterministic evidence of absence or of occurrence of critical earthquakes can be derived from their survival or damage, because the latter reflects superimposition of natural and anthropogenic destructive effects, some with apparently similar outcomes, and rarely only single event destructions. These results are important for palaeoseismology (paleoseismology), seismic risk assessment, archaeology (archeology), and restoration of ancient monuments.

Keywords Archaeoseismology (archeoseismology) · Historical seismology · Ancient column · Rocking · Earthquake response · Soil dynamics

> "In this kind of earthquake you may see columns, which had been all but hurled from their bases, rising again to the perpendicular…. ".
> First exaggerated description of rocking of columns during earthquakes by the second-century AD writer Pausanias (vii 24, 10–11).

Highlights

- Structurally healthy monumental articulated Greek and Roman temples and columns tend to withstand earthquakes.
- Seismic and wind-induced damage and toppling of these structures are mostly related to structural and foundations weaknesses.
- There are no controversy between earthquake engineering/archaeoseismological approaches and no deterministic evaluations of causes of damage.

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1 Introduction

Monumental ancient Greek and Roman columns, representing parts of ancient temples (Fig. 1), of road colonnades, or of solitary structures, are among the most impressive elements of the ancient architecture. They also represent structures very particular from the point of view of structural engineering: they correspond to articulated mechanisms, i.e., structural members excellently fitting each other without mortar and standing erect only because of gravity and friction. For this reason, monumental articulated Greek and Roman structures, columns, and temples, thereafter MAGR structures, are structurally very different from modern constructions (Sinopoli 1989; Makris 2014), as well as from other types of ancient and later rigid structures (i.e., made with the use of mortar) which included columns (for example, Pantheon in Rome) which are beyond the scope of this article.

MAGR columns seem fragile (Fig. 1), but they proved stable against earthquakes and other natural hazards, and their use was generalized in the ancient world. Still, only a very small percentage of ancient columns survive in their original position. What caused the collapse of ancient columns, sometimes found in certain excavations lying on the ground in numbers justifying the term "column cemeteries" (Guidoboni et al. 1994; Galli and Molin 2014)? Gradual collapse because of aging and decay? Earthquakes and other natural calamities? Deliberate destructions? A combination of different effects during millennia?

Because of the high quality and durability of materials used (mostly marble) and the nearly perfect geometric design of MAGR columns (Sinopoli 1989), earthquakes and deliberate destructions represent the two main scenarios for the causes of their damage and collapse. However, the role of earthquakes and of deliberate effects in the demise of ancient MAGR temples and columns remains obscure and a matter of debate; this role is currently regarded from two different points of view: the archeoseismological and the structural. Archaeoseismological studies are based on evaluation of historical, archaeological, geological, and occasionally engineering arguments for identification and eventually modeling of possible seismic damage in ancient remains (Stiros 1996; Hancock and Altunel 1997; Galadini et al. 2006). Structural studies, on the contrary, are based on results of computational or experimental simulations of the response of structures to seismic loads.

Based on *archaeoseismological* evidence, there has been recognized seismic damage in various cases of deformed or toppled down columns, including certain MAGR structures (cf. Karcz and Kafri 1978; Stiros 1996; Hancock and Altunel 1997; Guidoboni et al. 2002; Galadini et al. 2006; Bottari et al. 2009; Sintubin 2013; Stiros and Pytharouli 2014; Kazmer 2014). On the other hand, based on results of *structural engineering* studies, MAGR columns are regarded as structures highly resistant to earthquakes (Sinopoli 1989; Konstantinidis and Makris 2005), and their failure is regarded possible only under rather unusual earthquake scenarios. This favors anthropogenic effects as causes of their demise (Alexandris et al. 2014).

Is there a discrepancy between these two apparently different points of view? Under which conditions it is reasonable to regard damaged and toppled down

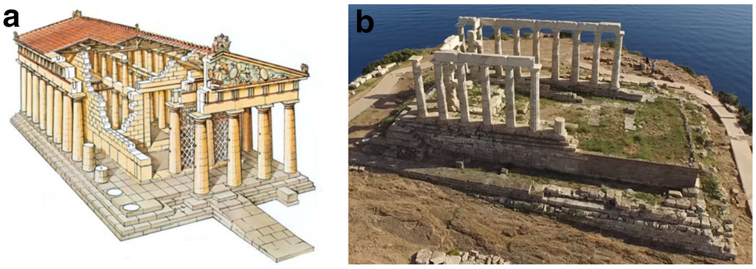

Fig. 1 Representative views of MAGR temples and of their remains. **a** Isometric view of the Aphaia temple in Aigina, an island near Athens (modified by Mansell, source: The Doric Essence, www.mileslewis.net). **b** Remains of the Poseidon temple at Sounion, near Athens. Most of the nine columns of the south (background) colonnade are characterized by drum displacements. The northern (foreground) colonnade is partly restored, along with the western part of the platform. The temple was damaged in antiquity and abandoned, and its cella (central building) and decorative elements were dismantled to be used in other buildings. Collapse of the western part of the temple is assigned to aggravated seismic motion because of damage to the foundations

columns as evidence of past earthquakes, and their occasional preservation as evidence of absence of strong seismic shaking?

Are there any convincing signs ("criteria") of deliberate or of seismic destruction of MAGR columns? Can evidence from MAGR columns be extrapolated to non-MAGR columns and vice versa?

Answering these questions is very important to understand the seismic history of various regions and of specific ancient monuments, as well as to provide constraints on their restoration and preservation. Just to notice that recent earthquakes have damaged recently restored ancient columns (see below, Section 5.1).

The aim of this article is to contribute to an answer to the above questions based on new evidence and on critical review and analysis of historical, archaeological, and engineering data. Some important aspects of this study are (i) the discussion of limitations of deterministic constraints to models of past earthquakes and of limitations and conditions of structural analyses of ancient structures, (ii) a critical evaluation of the evidence for deliberate destructions of ancient structures in various periods, and (iii) the identification and study of two groups of damage in MAGR structures: on one hand, structural failure of known causes (for example, seismic and wind-induced effects), providing some constraints in the history of destruction of MAGR structures; and on the other hand, a group of different types of structural failure of unknown causes, grouped by possible damage conditions and characteristics. Damage in the second group is examined mostly on the grounds of results of the first group (hence, this approach is somewhat reminiscent of supervised learning in digital signal analysis) and especially of geotechnical engineering and of soil dynamics from a qualitative point of view. In fact, geotechnical engineering is likely to represent a missing link in the study of deformation of ancient remains.

A main outcome of this analysis is that the above two apparently different points of view of ancient columns, archaeoseismological and structural engineering, represent in fact the two faces of a single coin: MAGR columns, especially tall ones, are highly resistant to earthquakes, but under certain conditions (for example, lack of structural health, i.e., in cases of structural damage), they may be toppled down by earthquakes. This means that under certain conditions, destroyed MAGR structures may represent indicators of unrecorded or misunderstood palaeoseismic events, but on the condition that alternative explanations are excluded.

2 Architectural style and destruction of MAGR structures

MAGR columns are of different types and dimensions, ranging from simple cylinders a few meters high to elaborate structures more than 10 m, and occasionally up to 40 m high, with different characteristics: massive (several meters wide) to slender cylinders or truncated cones (drum diameter essentially decreasing upwards), simple or with sculpted decorations, monolithic or multiblock, composed of drums standing on top of each other only with gravity (Fig. 1).

From the structural point of view, MAGR columns were of three types: (i) columns integrated in ancient temples, mostly at their façade or perimeter, and other public or private buildings, carrying loads especially from their roofs (Fig. 1a); (ii) series of columns forming colonnades along the two sides of main roads, not infrequently supporting roofs; and (iii) solitary decorative or commemorative monuments.

All these constructions were made of dry-masonry (i.e., without mortar), but in many cases, metal or wooden clamps were embedded among column elements (drums) and wall blocks (Dinsmoor 1975). Such type of structures required a nearly perfect architectural design, structural members perfectly hewn and fitting with neighboring members, as well as building material surviving for long (for example, high-quality limestone or marble). For this reason, even after millennia, the remains of ancient columns and temples are characterized by very sensitive markers of their deformation (occasionally not visible by the naked eye, see Section 3.3), of repairs, and of the style of their collapse (Fig. 2d).

2.1 Early theories for the destruction of MAGR structures

Earthquakes have been vaguely regarded as causes of destruction of ancient temples by some early nineteenth-century travelers. It is worthy to mention that an early hypothesis for the earthquake response of ancient temples had been proposed in the 1870s, probably inspired by eyewitness effects of an earthquake on the Hephaisteion (Theseion) in Athens (see Zambas 1998 and Section 6.3, referring to Pennethorne 1878). The earthquake scenario for collapse of various temples was adopted by various investigators at the end of the nineteenth and the beginning of the twentieth century (see Guidoboni

Fig. 2 Damage and repairs in ancient columns. **a** Offsets in drums in the Hera Temple, Samos Island, Greece. **b** Temple of Zeus, Olympia, drums of columns collapsed in a domino-type pattern. This collapse in Later Antiquity postdates a repair of the temple probably in the second century BC. **c** A well-known case of oriented collapse of columns in the internal part of a basilica at Susita, Galilee, not corresponding to a MAGR structure. Photo by A. Nur, reproduced from the original of the cover of a book with an article of Nur and Ron (1996). **d** Philippeion Temple, Olympia. A notch for metal clamp (marked with arrow) indicates a beam in second use, and restoration in ancient times, possibly after a damaging earthquake

et al. 2002), but till the first decades of the twentieth century, the majority of investigators were favoring the hypothesis of deliberate destructions of ancient Greek and Roman temples. This is because they were inspired by certain ancient texts mentioning for example, damage in temples in the region of Athens during a Persian invasion near circa 480 BC, during a war between Roman and Macedonian armies in 200 BC (for example, Section 4.3.2), or in a regional scale, during the efforts of Christian zealots to eradicate all signs of pagan culture between AD360 and AD450 (see below, Section 4.3.1).

This situation radically changed in 1926, when a M_w 7.4 earthquake in the Aegean Arc produced major damage in central Crete, disrupted the excavations of Arthur Evans in Knossos and inspired his theory for seismic destruction of the Minoan civilization. This theory, at the early stages of modern seismology, and especially the authority of the excavator of Knossos, played a catalyzing role in the study of the causes of structural damage in ancient sites in a broad scale (Stiros 1996). Since then, various investigators claimed a strong influence of earthquakes in the history of monuments and of wide regions. Still, in most cases, earthquakes were simply regarded as *Deus ex machina* to explain damage in buildings, destruction layers in excavations, even societal changes (see Karcz and Kafri 1978; Rapp 1987; Stiros 1996).

Of course, there were exceptions, and reasonable arguments for earthquake occurrence were presented. Concerning ancient columns, Dinsmoor (1941a) assigned dislocations among column drums (such as of Fig. 2d) to seismic effects. In particular, he observed repairs in certain drums for the temple of Zeus at Olympia, long before its final collapse several centuries later (Fig. 2b). His suggestion was that these repairs became necessary because seismic dislocations among drums produced disfiguration of a part of the temple and led to dismantling and restoration of a part of the temple, probably in the second century BC. Similar repairs are clearly observed in other nearby temples in antiquity, for example in the circular Philippeion temple (Fig. 2d). Offsets (sliding) along column drums in the Hephaesteion (Theseion) Temple in Athens, one of the most well-preserved ancient Greek temples, have also been regarded as signs of rocking during strong earthquakes (Fig. 3d) and as evidence that Athens, assumed till then as earthquake free, had been shaken in the past by strong earthquakes (Galanopoulos 1956).

In the last 30 years, with the increase in the volume of publications of archeological studies, with the advent of archeoseismology, as well as with the needs for restoration of ancient monuments, the study of earthquake impacts on ancient columns was intensified. As a result, evidence of potential signs of earthquakes from observations of ancient columns have been discussed for different structural systems and for different tectonic environments, for example, in Rome (Galli and Molin 2014; Galadini et al. 2018); in Sicily (Guidoboni et al. 2002); in Priene (Altunel 1998), Laodikeia (Kumsar et al. 2016), and Hierapolis (Guidoboni et al. 1994, p. 350) in western Turkey; but also in Syria (Kazmer and Major 2015); in Jordan (Sinopoli 1989; Al-Tarazi and Korjenkov 2007; Fandi 2018); and in Baelo Claudia, Spain (Rodríguez-Pascua et al. 2011).

2.2 Characteristic patterns of damage in MAGR columns

In some cases, column damage or failure in isolated structures is observed (for example, sliding of drums of an isolated column as in the Heraion Temple, Samos (Fig. 2a) or displaced drums in columns of the Poseidon temple at Sounion, near Athens (Fig. 1b; Papastamatiou and Psycharis 1993). In other cases, damage seems to represent a site-wide event, for example in Selinunte, Sicily (Guidoboni et al. 2002), or in Baello Claudia, Spain Rodríguez-Pascua et al. 2011).

Damaged and toppled columns are frequently characterized by specific patterns: (i) columns lying parallel to each other ("oriented collapse"), for example, in Laodikeia, western Turkey (Kumsar et al. 2016) and especially at Sussita (Hippos) in Israel (Fig. 2c; Karcz and Kafri 1978; Wechsler et al. 2018); (ii) column drums found in a domino-style arrangement (Fig. 2b); and (iii) colonnades in long sides of temples (usually except for corner columns) toppled in a single direction, but also outwards or inwards of the structure perimeter (Fig. 4). Such failure patterns are clearly not limited to MAGR structures: the Sussita (Hippos) columns (Fig. 2c), for example, supported the roof of a byzantine basilica made with mortar, i.e., of a rigid structure.

The patterns of column collapse have fed scenarios and debates for the causes of structural failure. For example, the direction of collapse of colonnades or of single walls has been correlated with the direction of seismic waves, a kind of seismoscope (for example, Guidoboni et al. 2002; Al-Tarazi and Korjenkov 2007; Schweppe et al. 2017; Fandi 2018), somewhat analogous to the early Chinese seismoscope (Korjenkov and Mazor 1999). In one case, contrasting directions of column toppling along the two sides of a strike-slip fault (Nur and Ron 1996) have been regarded as a parallel to first motion arrivals in focal mechanisms of earthquakes (but also to the pattern of dynamic displacements during the strong motion; Saltogianni et al. 2016).

2.3 Limitations in understanding the causes of column damage

A major problem with MAGR temples and columns is that their overall structure imposes serious limitations in the reconstruction of their post-construction history. Indeed, even for standing structures, repairs in columns and temples can be recognized, mainly from differences in style and material of certain structural or decorative members. Unfortunately, such repairs cannot usually be dated. For example, Fig. 2 d shows architraves (beams) in second use (recognized from marks of metal clamps during first use), clearly indicating repairs of unclear dating (cf. Dinsmoor 1941a). In the case of the Nemesis temple in Ramnous (Rhamnous) near Athens, totally in

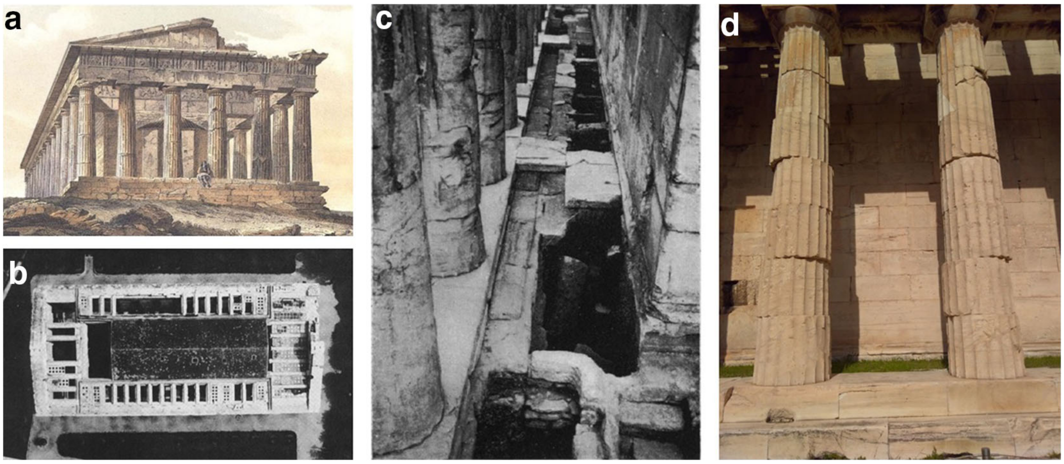

Fig. 3 Hephaisteion (Theseion) Temple in Athens: one of the best-preserved ancient temples exemplifying the architectural style of classical temples. **a** Temple from the east, from an engraving circa 1882. Colonnades (peristyle) surround the cella, modified with later walls (later removed) built to transform the temple into a church. **b** Aerial view of the roof of the temple, upper part points to the north. After Dinsmoor (1976). The cella was covered with a vaulted roof in Medieval times. Mark asymmetry in transversal beams between cella and peristyle, especially between the northern and southern peristyle, producing different coupling. **c** Excavations in the southern peristyle, after Dinsmoor (1941b). Voids are due to medieval to subrecent graves and cover the whole of the temple and of the surrounding area, modifying its structural behavior: because of the voids, the superstructure is built not on a platform, but on walls protruding from the ground. **d** Offsets in drums, mostly confined to the southern colonnade, assigned by Galanopoulos (1956) to an earthquake

ruins before a partial restoration, it is unclear *when* the damage occurred; remains of pottery roof tiles testify to a repair in the Roman period (Miles 1989), but this covers a very broad period. Only in rare cases, direct, stratigraphic evidence of damage is possible; for example, the case of temple C in Selinunte, in which columns were found toppled over houses containing a datable stratigraphic layer (Bottari et al. 2009).

In some cases, a dating of damage is inferred from site-wide correlations (Stiros and Pytharouli 2014),

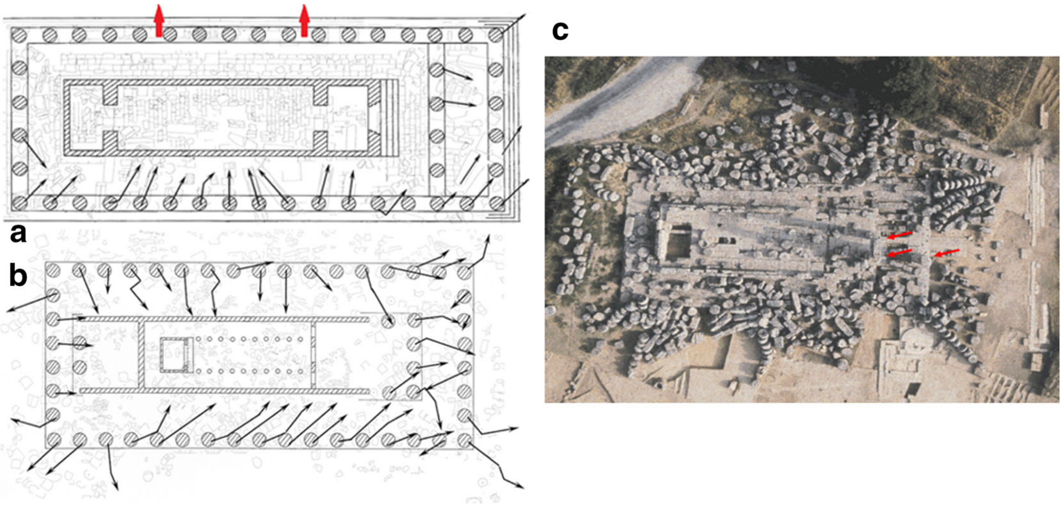

Fig. 4 Different patterns of collapse of the long sides of temple columns: toward a single direction (**a**), Temple C, Selinunte, Sicily; inwards, (**b**), Temple G Selinunte, Sicily; outwards (**c**), Zeus Temple, Nemea, Greece. Thin black arrows in **a** and **b** indicate sense of toppling of columns, and two solid red arrows in **b** indicate inferred sense of toppling of the restored colonnade. In **a** and **b**, corner columns deviate from the mean pattern of toppling, probably because of coupling with transversal colonnades. In **c**, three red arrows indicate the surviving columns (before restoration). Modified from Guidoboni et al. (2002) (**a**, **b**) and Makris and Psychogios (2004) (**c**)

while in other cases, it has been suggested that it is possible to identify the source of sculpted material used in repairs (for example repairs of the Hephaisteion Temple using material from other temples of the wider Athens area; Thompson 1981).

3 Response of columns to earthquakes: structural engineering approach

3.1 Models of seismic performance of MAGR columns

Motivated by the pioneering works of Housner (1963) and Yim et al. (1980), it was Sinopoli (1989) who first explained that MAGR columns consist of elements staying on top of the other only thanks to gravity and friction (articulated), and that are characterized by a specific dynamic behavior: When excited by earthquakes, MAGR columns behave like inverted pendulums and respond by rocking, but their structural members (drums) tend to behave quasi-independently (Fig. 5a, b). This seismic response is very particular, different from that of modern and ancient rigid structures (for example, made with concrete; Fig. 5a); they bear similarities only with bridges with isolators beneath the deck (Makris 2014).

More recent studies confirmed and refined this approach. These last studies were based on different computational approaches (Papastamatiou and Psycharis 1993; Ulm and Piau 1993; Psycharis et al. 2000; Konstantinidis and Makris 2005; Pitilakis and Tavouktsi 2010; Makris and Vassiliou 2014; Papadopoulos and Vintzilaiou 2008; Papaloizou and Komodromos 2009; Ambraseys and Psycharis 2012; Kounadis et al. 2012; Kavvadias et al. 2017; Sarhosis et al. 2019 for a complete review till 1994 see Beskos 1993, 1994) and on shaking table experiments (Manos and Demosthenous 1997; Papantonopoulos et al. 1998; Mouzakis et al. 2002; Drosos and Anastasopoulos 2015). Based on these results, the response of ancient columns to earthquakes can be described with simple words as follows.

If an earthquake exceeds a certain acceleration threshold, an ancient, free-standing monolithic column is forced to oscillate along the vertical axis; this type of motion is described as rocking. During rocking, the column is partly detached from its basis and slightly uplifted, and its motion is characterized by successive impacts of its bottom edges with its base (Fig. 5b). Such impacts are combined with sliding which absorbs some of the kinetic energy (Spanos and Koh 1984; Sinopoli 1989), and lead to transient and permanent offsets such as those of Figs. 2a and 3d and occasionally fracturing of the drums (cf. Pecchioli et al. 2018).

For multiblock columns, rocking impacts and sliding are observed among different drums (blocks), permitting to dissipate energy along several surfaces between column drums (blocks); hence, the probability of overturning is smaller, but at the expense of a remnant morphological disfiguration (offsets along drums as those in Figs. 2a and 3d). Rocking is not a 2D effect, and the direction of sliding among drums differs during each impact (“wobbling”; Stefanou et al. 2011; Burger et al. 2017) and has a rather random character. This means that each new impact-induced dislocation may modify or eliminate previous dislocations during the same or different earthquakes. An implication of this effect is that impact may not occur at a (previously) damaged part of the basal platform or the base of a drum, and even a damaged column may survive a typically destructive earthquake.

The new studies reveal that MAGR columns are characterized by a very particular response to strong seismic shaking, they are not subject to resonance because of their negative stiffness, while gravity tends to counteract their instantaneous tilting and tending to restore their stability (see Makris 2014).

The resistance of a column to seismic motion is influenced by its height, and taller columns seem more stable than shorter column of the same slenderness (ratio between height and width). This apparent paradox is because resistance of a column to seismic overturning (rotational inertia) increases with the square of the column height, whereas the overturning moment increases linearly with the column height. Such scale effect is important to understand that shorter columns are more vulnerable to seismic shaking compared to taller columns of similar slenderness. In addition, heavy beams (architraves) on top of columns tend to increase structural stability (Papaloizou and Komodromos 2009; Makris 2014; Makris and Vassiliou 2014). This apparent paradox is summarized in Fig. 5 c and indicates that the seismic stability of rocking columns increases with their slenderness (ratio of height to width) and with the mass on their top (architrave).

Seismic stability hence requires that the dimensions of columns and of their blocks satisfy certain conditions; surprisingly, this seems to have been understood and respected in most cases by ancient engineers (Sinopoli 1989) cf. Mark and Billington 1989). In contrast, statues

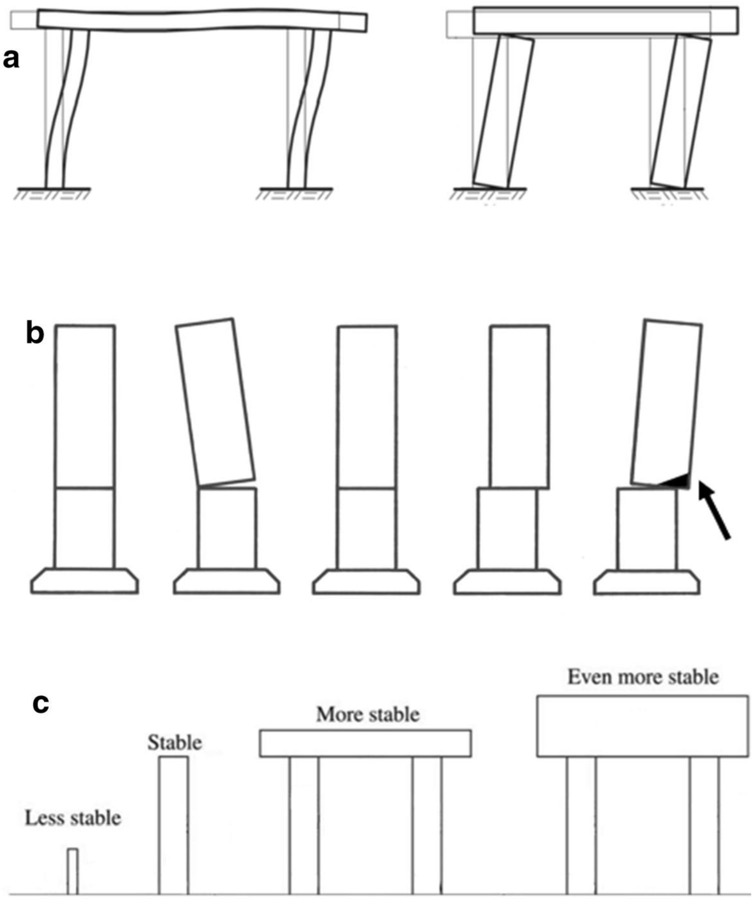

Fig. 5 Pattern dynamic deformation qualitative estimation of seismic performance of MAGR columns. **a** Differences in the response of a typical rigid structure (made with concrete) from that of an articulated structure (mechanism). **b** Response to an earthquake of a multidrum column by rocking. Failure (or missing wedge, marked black) modifies the pattern of oscillation and may lead to failure. **c** The apparent paradox in the seismic performance of MAGR columns: stability increases with the column height and the load of horizontal beams (architraves). **a**, **b** after Makris (2014) and Makris and Vassiliou (2014); **c** modified after Sinopoli (1989)

on top of solitary columns may not satisfy such criteria and hence seem not safe against earthquakes, as historical evidence and modeling indicates (Ambraseys and Psycharis 2011).

For all these reasons, MAGR columns represent structures resistant to earthquakes. In many cases, the components of MAGR structures include metallic or wooden clamps and dowels. Such coupling, however, is weak and does not influence much their overall behavior (Sinopoli 1989; Konstantinidis and Makris 2005).

In addition to MAGR temples containing columns, colonnades, and solitary columns, there existed also MAGR temples probably not containing columns. These last temples were made of well-hewn ashlar blocks without mortar, and structural analysis has shown that they also tend to be highly resistant to earthquakes (Schweppe et al. 2017), but in at least specific cases, there is evidence of seismic collapse (Triolo temple Selinunte, Guidoboni et al. 2002; Bottari et al. 2009).

3.2 Potential for column toppling

The study of the response of columns to earthquakes requires to simulate both structures and the unknown characteristics of the past or future earthquakes. A column or a frame of columns is simulated by an idealized structure defined by certain parameters for a numerical (computational) approach or by a constructed scale model in a shake table experiment. The problem of structure simulation is simpler, but the problem of simulation of the source characteristics of earthquakes is more complicated, because no recordings of the earthquakes which have affected the study column in the past (or will affect it in the future) are available.

To overcome this problem, one or more recent earthquakes recorded in the study area or in other remote areas are selected as input in the analysis (representative earthquakes). In some cases, this study is combined with a sensitivity analysis: one of the adopted earthquake characteristics (for example, peak ground acceleration) is gradually increased, and the (numerical or shake table) experiment is repeated, until the toppling threshold is reached (predicted). In rare cases, synthetic ground motions are computed (Hinzen 2009).

The overall output of the studies cited in the previous paragraph is that the idealized column models resisted to conventional earthquake scenarios, often with dislocations among drums. Toppling was predicted only for earthquake scenarios with rather unusual characteristics (high peak ground accelerations (PGA) and long-period pulses in seismic motions). In some of these scenarios, domino-style collapse of drums of columns or oriented collapse of columns was reproduced (Fig. 6), especially for low frequencies which represent unfavorable cases of earthquakes (Sinopoli 1989; Papaloizou and Komodromos 2009).

3.3 Conditions and limitations in simulations of column response to earthquakes

Structural models of response of columns to earthquakes are subject to certain conditions and limitations.

First, all studies of ancient Greek and Roman columns to earthquakes focus on solitary columns or on two columns coupled with a beam (architrave) on their top; occasionally, only three coupled columns in a line have been examined (Papaloizou and Komodromos 2009). Studies of more than three columns had been made only for the Olympia temple (Ulm and Piau 1993) and for structures which are not directly representative of MAGR columns, a byzantine basilica (Hinzen 2009/2010) and parts of a Roman palace (Nikolić et al. 2019). Whole temples or even parts of temples with more complex arrangements (colonnades in two different directions, etc.) have *not* been examined so far because of their structural complexity. Hence, the seismic response of colonnades forming corners or of whole temples is not covered.

Second, the results of numerical and shake table modeling are valid *only* if certain initial conditions are satisfied: rigid drums, vertical columns, and rigid bases. If some of these conditions are not satisfied, the seismic resistance of the column is obviously reduced and the risk of damage and of collapse is increased. This, for example, can happen if a wedge at the edge of the base of a rocking drum is missing (so that the impact of Fig. 5b cannot be perfect; cf. Pulatsu et al 2017), either because the drum was deliberately undermined, mostly to remove metal clamps between drums, or because of damage during a previous rocking impact. Drums with missing basal wedges are described for the temple of Zeus at Aizanoi in Turkey (Ambraseys 2009) or the Terme del Foro in Ostia near Rome (Pecchioli et al. 2018). In addition, there is evidence that the bases of certain columns are not horizontal and rigid (Fig. 7c).

The practical question is how frequently the above initial conditions were not satisfied. No statistics are available, but there is evidence of frequent deviations from the ideal cases. For example, a laser scan analysis

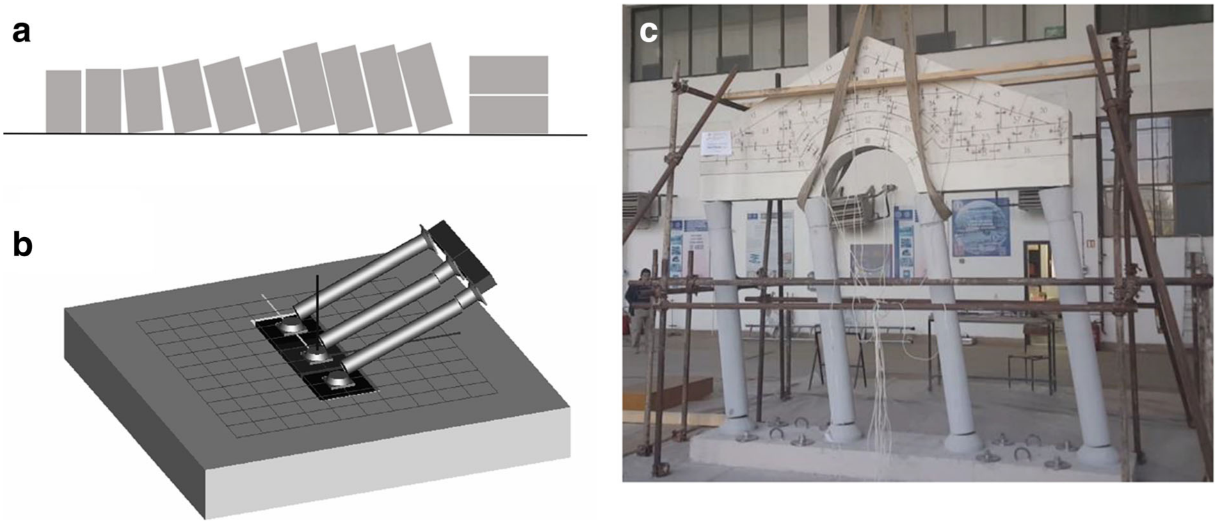

Fig. 6 Predicted characteristic patterns of column collapse in response to earthquakes: **a** domino-type arrangement of drums (computational model, redrafted after Sarhosis et al. 2019) Fig. 18); **b** oriented collapse of columns (computational model, after Hinzen 2009/2010), Fig 14); (**c**): set of columns just before oriented collapse (experimental, after Nikolić et al 2019).

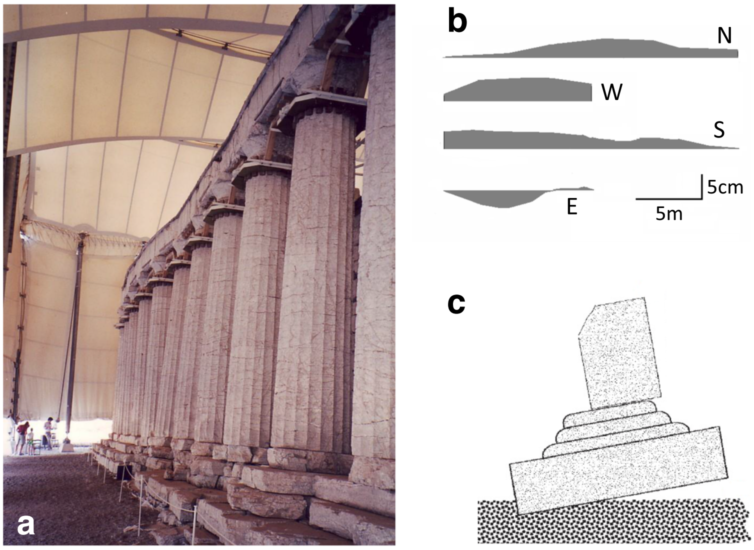

Fig. 7 Deformation of platforms of ancient columns/temples and their impacts. **a** Tilted columns in the Epikoureios Apollo Temple at Bassai (Bassae), Peloponnese, because of deformation of the foundations. Photo taken in the 1980s, during restoration works. Tilting reduces the dynamic resistance of columns. **b** Deformation of the platform of the Nemesis temple, Rhamnous (Ramnous), near Athens, derived from height profiles along its sides (after Miles 1989, Fig. 7). **c** Tilted (plastic) base of a column in Priene (after Altunel 1998). Compare with Fig. 9 a

of one of the surviving columns of the temple of Nemea indicates that its vertical axis is not vertical, as is derived from observations with the naked eye, but it has a bow-type shape with maximum deflection of several centimeters (Georgopoulos et al. 2016). Evidence from Fig. 7 in fact indicates that the platforms of certain temples (Basai, Ramnous, etc.) are not horizontal and rigid.

Third, the response of ancient columns to dynamic effects is a *nondeterministic process* and rather justifies stochastic approaches, which, however, have occasionally only been attempted (Kavvadias et al. 2017). Furthermore, repeated experiments under the same conditions produced different results concerning slippage, damping, and peak amplitude in oscillations (Papantonopoulos et al 1998). These results are in full agreement with the conclusion of Ambraseys (2009) that the seismic response can be described as literally *chaotic and unpredictable process*, because trivial changes in the geometry of a structure or the foundations characteristics or of the strong motion may produce significantly different response (Yim et al. 1980; Hinzen 2009/2010; Ambraseys and Psycharis 2011).

Fourth, engineering modeling of the response of columns to earthquakes is based on selection of specific earthquake scenarios which are assumed to have hit in the past (or are expected to hit a specific area in the future) and then predict their impact on a study structure. In some cases, the value of a certain variable of the selected earthquake scenario (for example, PGA) is gradually increased and checked until damage/toppling occurs (predicted). This approach is fine for linear systems, but ancient columns represent highly nonlinear, multivariable systems and this approach may not be conclusive. For example, column collapse may be predicted if the value of a certain variable of the earthquake scenario (peak ground acceleration, etc.) is *highly* increased. However, a similar result may be obtained if instead of one, two other variables are moderately only modified (see Sarhosis et al. 2019). This indicates that failure of columns can be predicted not only for extreme, but for more ordinary earthquake scenarios.

Fifth, the rocking response of columns is very sensitive to details of the seismic ground motion (Yim et al. 1980) and seismic motions show considerable variability because of variability of local ground conditions (Douglas et al. 2015). This indicates that geotechnical effects should be included in the simulations of seismic response of ancient columns, especially local amplification of the ground motion and soil–structure interaction (SSI) effects. The reason is that MAGR temples and columns are usually built in selected sites with conditions favoring amplification of strong motions, for example, faulting (Stewart and Piccardi 2017), local topography and soil aggravation effects, and directivity effects (cf. Assimaki et al. 2005; Rodriguez-Marek and Bray 2006; Garini et al. 2017). Still, despite their importance (Kamai and Hatzor 2008) such effects are usually ignored. This point is discussed in Section 6.

4 Damage to columns and temples: archaeoseismological evidence

4.1 Perception of the response of columns to earthquakes in antiquity

The only ancient text with an explicit description of the response of ancient columns to earthquakes is by Pausanias (vii 24, 10–11), partly cited in the overhead.

> In this kind of earthquake you may see columns, which had been all but hurled from their bases, rising again to the perpendicular…. and walls which had cracked closing up again, beams, dislocated by the shock, go back to their places ….The second kind of earthquake brings destruction to anything liable to it, …. The most destructive kind of earthquake …. shakes up buildings their foundations …. leaves no trace on the ground that men ever dwelt there.

Pausanias seems to describe the rocking of columns, in agreement with engineering views, though with some exaggeration, probably inspired by oscillations of plants by wind. Seismic tilting of column can be of the order of few degrees only, but this was probably enough to be noticed, especially in comparison with nearby bulky, rigid structures and because of the sliding among drums accompanying rocking.

Rocking as an instantaneous effect is attributed by Pausanias to his first type of earthquakes, i.e., to a certain level of strong motion, which produces also transient openings along joints between hewn blocks in walls (see below, Fig. 8d showing permanent openings).

Pausanias' description of rocking is consistent with modern structural engineering (see Section 3), and there seems to exist recent eyewitness observations of such rocking (cf. Miller 2000). Pausanias' information is probably conveyed from eyewitness reports and discussions with ancient engineers during his visits to numerous earthquake-prone regions, but his description and earthquake classification have been ignored (for an exception, Dinsmoor 1941a). The probable explanation is that column rocking was only recently understood, so that

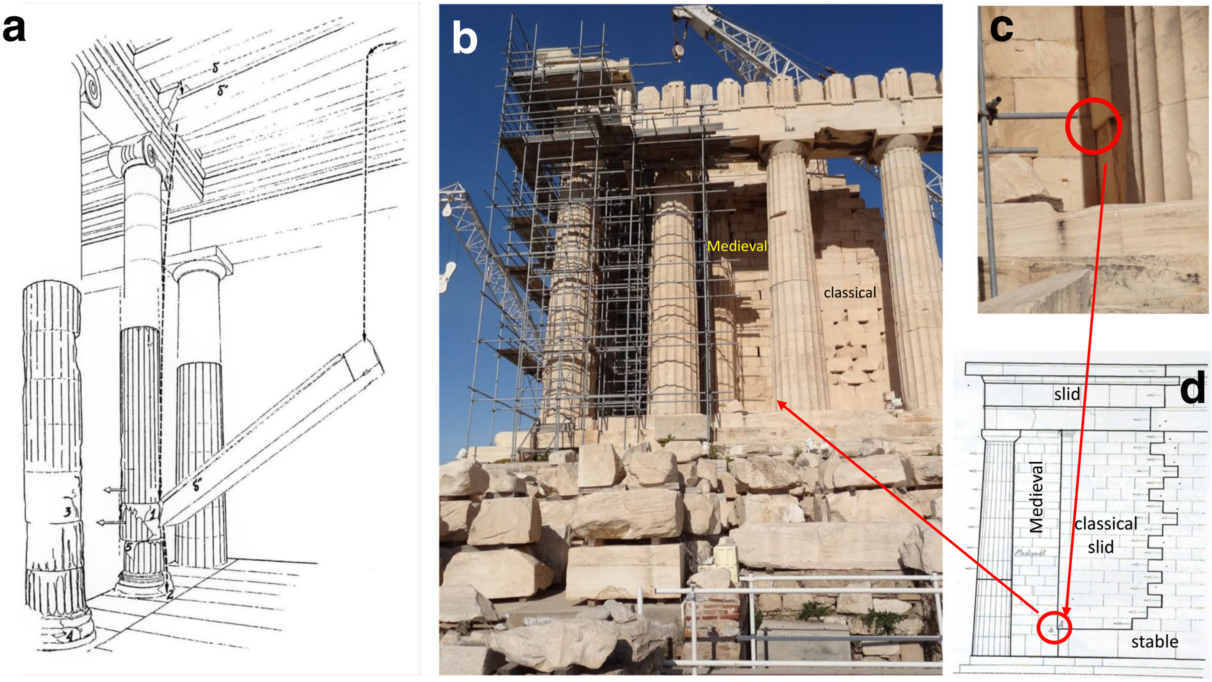

Fig. 8 Seismic and secondary damage in the Acropolis of Athens (after Korres 1996). **a** A diagram to illustrate how a marble beam fell from the top of the Propylaea during an explosion circa 1640, hit a column leaving on it marks of the impact, and caused drum dislocations. **b**–**d** Displacement of the west part of the south wall of the cella of Parthenon above the lower row of domes, possibly combined with sliding among drums of the nearby columns (marked by arrows). This displacement was assigned to the 1689 explosion. However, the blocks of a Medieval staircase were adapted to the protruding, displaced block (**b**, **c**), indicating an event before the advent of explosives, conspicuously a seismic effect before 1204

Pausanias' report appeared awkward. Furthermore, the description of rocking was overshadowed by a following glossy description of a 500-year-old, at that time, legend for the loss of a town by an earthquake.

Following Pausanias' description, it may be speculated that since it was known that strong earthquakes tend to instantaneously open joints among hewn blocks, metal clamps connecting them were introduced as a countermeasure to seismic deformation. A parallel for static effects and wind effects in later cathedrals is discussed by Mark and Billington (1989).

4.2 Literary and inscriptional evidence of damage to columns in antiquity

Explicit written information on seismic damage to ancient columns is extremely poor. The available information, mined from the catalog of historical earthquakes by Guidoboni et al. (1994), is summarized in the Appendix.

Among the reports of seismic repairs/destructions, very few specify collapses of columns during earthquakes: An earthquake in AD557 is reported to have toppled down a solitary commemorative column in Constantinople. Another earthquake shortly before AD80, possibly related to the Vesuvius eruption, destroyed a specific type of temple, a rectangular building with a line of four columns in its main façade ("prostyle"). Furthermore, from the analysis of various historical sources, Ambraseys and Psycharis (2011) noticed that statues standing on typical Roman columns in Constantinople were reported to have been toppled down during strong historical earthquakes. Column bases (pedestrals), on the contrary, seem not to have suffered any damage.

A question arising is to which degree ancient reports on damage in ancient columns are reliable. An answer to this problem is beyond the scope of this article, but two selected case studies are useful to be discussed: a reliable and a biased report of seismic collapse of ancient columns. They are selected because they both correspond to a period of political and religious stability, during which deliberate destructions can be discarded.

4.2.1 Reliable report for seismic partial collapse of the Adrian's temple in Cyzikus in AD160–161

An earthquake in circa AD160/161, probably related to the North Anatolian Fault, is reported to have destroyed the so-called Emperor Adrian's temple in Cyzicus, near the coast of the Sea of Marmara (Turkey). This temple was described as the largest classical temple ever built, one of the wonders of later antiquity, with columns about 20 m high. The information was conveyed by several authors, especially Dio Cassius (E*pit 70.4)* who was living in the region in the second/third century and hence is likely to report first-hand information. Excavation evidence in combination with an illustrated fifteenth-century report confirmed the partial destruction of the temple before 1431. The only error found in the ancient texts is that the temple was composed of multidrum and not of monolithic columns. Thirty-one of these columns had survived till 1431, but then they were gradually destroyed to be used as building material (Burrell 2002/2003). Hence, at least the report of Dio Cassius seems reliable and seems to testify to a partial seismic destruction of Cyzikus temple during a period for which no evidence of deliberate destructions exists (*Pax Romana*).

4.2.2 Biased evidence for seismic collapse of a colonnade in Apamea, Syria, in AD115

The town of Apamea, Syria, was notorious for a 2-km-long road colonnade, perhaps the longest in the Roman world. Certain modern authors *argue* that ancient texts report destruction of an early phase of this colonnade by the AD115 earthquake, and this assumption is usually regarded by other investigators as an example of column destruction by earthquakes. However, a more careful examination of the ancient sources (for references, see Guidoboni et al. 1994) indicates that the ancient texts mention damage by this specific earthquake only in Antioch (modern Antakya, SW Turkey) and the surrounding area, and no specific reference is made to Apamea, about 100 km away (cf. Balty 1988). Hence, although the Antioch earthquake may have produced some damage in distant areas, there is no literal or archeological evidence for damage in Apamea.

This is a nice example of the "circular process" described by Ambraseys (1971, 2009): archeological *interpretations* (or *assumptions*) are regarded as *factual evidence* and then this "evidence" is adopted in seismic catalogs, occasionally as original literary evidence.

4.3 The problem of anthropogenic destructions in ancient temples

Apart from earthquakes, military operations and other anthropogenic interventions represent for various investigators another *Deus ex machina* to explain destructions and abandonment of ancient sites from the prehistoric till modern times (Stiros 1996).

Destructions related to human activities are due to various reasons: (i) religious reasons, (ii) wars and invasions before the advent of explosives, (iii) bombing and explosions, (iv) looting to obtain building material, and (vi) remodeling of sites and towns.

4.3.1 Destructions due to religious conflicts

Modern experience clearly indicates that during religious conflicts, various buildings are damaged or fully destroyed. In fact, the period approximately between AD360 and AD450 was marked by a struggle between the old pagan and the new Christian religion. This struggle occasionally got the form of a government-directed war against the ancient cult and included decrees ordering the demolition of ancient pagan shrines and banning of related activities (Hunt 1993; Busine 2013). However, to which degree these decrees were adopted in a regional scale is not known.

In very few cases, however, there are explicit reports for eradication of pagan monuments. A text by Theodoret of Cyrrhus (*Ecclesiastical History 5.22*), written in circa AD450, describes organized efforts to demolish the Temple of Zeus Belos in Apamea, Syria, in circa AD390. This text highlights the difficulties to demolish ancient columns overpassing their resistance and describes techniques to undermine their bases in order to facilitate their demolishment: replacement of parts of the column bases by wood to be burnt, leading to a combination of static and dynamic column instability and collapse. Still, the Theodoret text mixes a report for deliberate destruction of temples with miracles. Hence, it should be regarded with much care, as an expression of propaganda highlighting the difficulties in the struggle against paganism (Busine 2013).

Even if in certain eastern provinces pagan shrines were demolished by Christian zealots, generalization of this practice to the entire territory of the Roman Empire is not justified especially since the pagan religion survived for centuries (Brown 1998). But even if it is unconditionally accepted, it cannot be explained why ancient columns, especially in important pagan cult centers, remained standing next to Christian basilicas. A characteristic example is the three columns standing at the Nemea temple of Zeus (NE Peloponnese). Such impressive remains, overshadowing a Christian shrine (see Miller 2014), should have been eliminated if the emperor's directives were taken word-by-word. Furthermore, it is unclear why ancient zealots and looters selected the rough way to destroy temples, pulling them down with the use of tens of oxen, etc. as postulated by Alexandris et al. (2014), and did not adopt simpler and more efficient ways, i.e., undermining their lowermost drums or foundations or using explosives in later periods, as has been the case with one column from the Olympieion temple in Athens, destroyed to produce lime in the mid-18thcentury.

4.3.2 Destructions during wars and invasions before the advent of explosives

There is no doubt that wars and invasions in antiquity were responsible for major structural damage. The problem, however, is the *scale* of the destruction and the *potential* for such large-scale destruction. Clearly, there are known cases of full eradication of towns, for example of Thebes (in modern Central Greece) by Alexander the Great and of Carthage (in modern Tunis) and of Corinth in Greece in 146BC by Romans, but these are very special cases of political punishment of rebel or resisting towns by an organized effort, and at least in the case of Corinth, the reports of destruction seem exaggerated (Gebhard and Dickie 2003). Another example is Athens, which was nearly totally ruined during the Persian occupation in circa 480 BC, making necessary the full reconstruction of temples (e.g., Thompson 1981). Typically, invaders were limited to destruction of walling systems, looting, damaging, and conflagration of key buildings, even of ordinary houses. Before the advent of explosives, highly laborious and long-lasting efforts were necessary to fully destroy ancient temples and other important public buildings, and this was most likely beyond their destruction potential.

This is a point indeed noticed by Di Vita (1990) for Libya. Generalized destructions (including toppled down columns) in circa AD365 in several coastal towns of Libya have been assigned to an invasion by Asturians, a camel-riding tribe. This tribe, however, by no means could not have the potential and motivation for generalized destruction of solid buildings at town-wide scale. Destruction should have been limited to cultivations, key parts of aqueducts, statues and main decorative elements, and certain buildings after their looting. For this reason, an earthquake was proposed as the likely explanation of the observed destructions in coastal Libya in circa AD365 (Di Vita 1990).

This is not an isolated example. Collapse of columns of the façade of a Roman building at Patras, Greece, was usually assigned to vandalism by invading Goths who attacked several towns in Greece at the end of the third century AD. However, the Patras event seems to correlate to town-wide scale destruction, which is not easy to be explained as vandalism. As is derived from historical sources, the remnants of the Goth invaders, pursued by the Roman Army, could only have been anxious to find boats to cross the Patras (Rion) straits in the Gulf of Corinth and escape to the mainland; hence, they could not have the potential of generalized demolition of the numerous well-built houses of the town; this would require an organized and long-lasting effort (Stiros and Pytharouli 2014).

Two other cases highlight the problem of potential for major destructions: first, damage in temples and the flourishing town of Selinous in Sicily during its seizure by Carthaginians in 409 BC. An appeal to early war machines and elephants is made to explain the siege of the town, but such siege techniques were introduced two centuries later. In addition, no signs of burning of temples at this period exist (Guidoboni et al. 2002). Second is the possibility of serious damage to certain temples in the east part of Attica during the Macedonian–Roman War in 200 BC. A text by Livy, a Roman author, reports that Philip V, because of its rage after his unsuccessful effort to capture Athens, "… *ordered the temples of the gods* … *in all the demes* (small satellite towns of Athens) … *to be torn down and burned* ..." From this report, certain authors assume that the Macedonian Army was responsible for the observed damage in temples in Athens and the whole of its territory (Attica), especially at the east side of Attica (for example, the Poseidon temple in Sounion and the Nemesis temple at Ramnous; see Thompson 1981; Miles 1989; Paga and Miles 2016). However, evidence from the Hephaisteion temple, in the center of Athens, indicates that damage was mainly confined to decorative parts and the roof (Thompson 1981), while signs of fire, typically used for destruction in antiquity, are not evident in most temples assumed to have been damaged.

In fact, after a conflagration, a characteristic destruction of the marble (calcination) is expected. A characteristic is that the high intensity of the damage is the floor (fire) and that it is decreasing upwards. In the remains of the temple of Ramnous, on the contrary, damage was more intense in the upper part of the east side of the temple (Miles 1989, p. 235), indicating a dynamic effect. A possibility is that Livy, based on other Roman sources, was exaggerating the actions of the enemy (Macedonian Army), perhaps in an expression of propaganda to support further Roman intervention to Greece, which was totally occupied about 50 years later.

4.3.3 Damage due to bombs and explosions

Explosions and bombing are regarded as causes of destruction of ancient temples mainly because of an explosion in the Acropolis of Athens during the 1687 Venetian invasion to Athens, occupied by the Ottoman. This explosion ruined Parthenon, well-preserved till then, because it had been converted to a Christian temple at a very early stage.

The 1687 explosion was assumed responsible also for sliding to the west of the SW part of the cella of this monument along a horizontal joint above the first row of hewn blocks, leaving openings between certain vertical joints (Fig. 8d). However, Korres (1996) noticed that a medieval wall, built at the SW corner of the cella in circa AD1200 and still preserved, was designed to accommodate the protruding (slid) blocks of the cella (Fig. 8b–d). Hence, the sliding of the blocks of the cella by a few centimeters and probably the offsets in nearby columns originate from an event before 1200, conspicuously an earthquake.

The 1687 explosion had a broad influence among scholars and the population for centuries, and damage in various other sites and monuments was assigned to explosions and bombs. An example is a fourth-century BC circular tower very close to the NW coast in Ikaria Island, Aegean Sea, officially assumed of low seismicity. Damage in this tower, made of hewn marble blocks, was manifested by the collapse or the ruinous situation of its upper parts and by opening of vertical joints among hewn blocks because of sliding of certain blocks along horizontal joints (Zambas 2009). This damage was assigned to looting for metal among hewn blocks and especially to an explosion and to bombing from boats, mainly in the framework of training of the ship crews for naval battles; this was because of the prominent position of the tower near the coast. However, a recent study for the restoration of this tower indicated that there were no metal connections between the blocks of this tower, and no evidence of bombing (impacts on marble blocks) nor of an explosion was found (Zambas 2009). Another study found that the tower stands above a fossil shoreline uplifted by an earthquake at circa AD950–1150; hence, structural damage in the tower is related to very high accelerations of a previously unrecognized near-field paleoseismic event (Stiros et al. 2011).

In circa 1640, the Athens Acropolis was marked by another, less well-known explosion which damaged Propylaea (the entrance building to the Acropolis). Damage included partial collapse of the roof, supported by heavy (9–10 t) marble beams (Tanoulas 1987). The impact of the fallen beam on the Propylaea columns produced shattering of the drum marble and offsets of several centimeters along the column drums (Korres 1996), as is schematically explained in Fig. 8 a. This case highlights the difference between a primary effect (explosion) and a secondary effect (impact of a free-falling block and sliding of a drum; Korres 1996).

At the south flank of the Athenian Acropolis, there exist two solitary classical columns bearing clear signs of bullets and bombs. Such impacts have produced some disfiguration in the drums, but not structural damage (Zambas et al. 2011).

Impacts of bullets and explosions in the Acropolis permit to conclude that bullets and bombs have the potential to produce minor structural damage in columns. Even the impact of free-falling heavy marble beams produced moderate localized damage, shattering of the rock and offsets of a few centimeters only.

4.3.4 Damage due to looting

Ancient temples and columns, especially in abandoned sites, were systematically subject to looting in different periods for various reasons:

(i) Looting to obtain metal clamps which were precious in antiquity and were found between hewn blocks or between column drums (Fig. 9a). In this last case, if the damage was important, it would have serious impacts on the stability of the columns (undermined column bases, critical during rocking impacts).

(ii) Looting to remove hewn blocks to be used as building material, as well as smaller, especially monolithic columns to be used in later buildings (basilicas, etc.). Therefore, the remains of cella in most temples, if any, are poor, but columns and fallen drums are to a higher degree preserved.

(iii) Looting to obtain specific decorative elements, either to be used in other temples (cf. Thompson 1981), or in later periods by collectors.

(iv) Looting to produce lime from marble; in this case, no signs of fallen columns are preserved. Because of the resistance of columns to oscillations, their collapse would be relatively easy only if their bases or lowermost drum was undermined, mostly through fracturing and wedge removal (cf. Zambas et al. 2011), as is the case with forest lumberjacking. Such signs are therefore diagnostic of damage caused by looting.

4.3.5 Remodeling of sites and towns

Remodeling of sites and towns was a practice well-known in antiquity and included temples which represented main signs of prosperity and identity of ancient towns. In fact, for most of the ancient temples, there have been identified different phases of construction, some corresponding to full remodeling. In many cases, such changes were at least partly imposed by natural calamities or deliberate destructions in different periods. In some cases, partial remodeling of the plan of towns was imposed by security reasons, for example construction of new fortifications, dismantling ancient remains (cf. Barrett and Vickers 1975), or even cleaning the ground near the walls. Just to notice the plan of the first king of modern Greece to build his palace on the Acropolis, among the ancient remains in the 1830s; luckily, this plan which would have led to major destruction in classic monuments was abandoned mostly because of technical problems (Penrose 1897).

At structure scale, architectural changes in ancient temples or their remains were imposed due to changes in their use, for example to transform pagan temples to churches (for example, Parthenon and Hephaisteion in Athens), military buildings (armories, Parthenon during the 1687 siege, see Section 4.3.3), or even humble houses (for example, temple C in Selinunte; Bottari et al. 2009). In such cases, fireplaces may have been constructed next to ancient remains, with impacts on the marble remains reminiscent of explosions, etc.

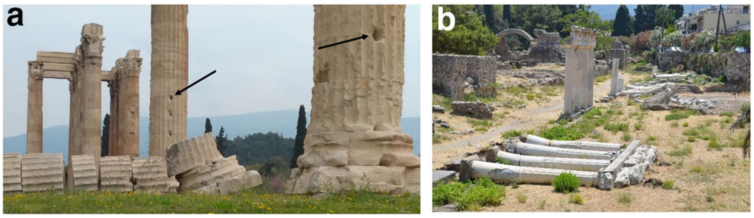

Fig. 9 Recent collapses of classical columns of known causes. **a** Olympieion Temple, Athens, column collapsed in 1852 during a storm, because of oscillations produced by a wind gust and the effect of plastic foundations (derived from the tilted base). The two adjacent columns survived wind-induced rocking, highlighting the nondeterministic character of behavior of ancient MAGR structures. **b** Colonnades in Kos Island collapsed during the 2017 Mw6.5 Bodrum-Kos earthquake. The colonnades were restored in the 1930s and recently

4.4 Decay due to nongeological environmental effects

Although MAGR structures were made with high-quality rocks and superb craftsmanship, they were subject to gradual deterioration from various causes, including atmospheric and biological effects. Deterioration is more severe along contacts of drums and along rock discontinuities (cemented breccia, joints, and fractures) with obvious implications in the static and dynamic stability of the columns (Fig. 10a).

A rather ignored environmental factor affecting the stability of ancient remains is plant growth. Roots of small plants or even tree trunks may highly influence structures, because they intrude in small openings and

Fig. 10 Effects of plants in the structural stability of ancient monuments. **a** Poor condition of the base of one of the three surviving columns of the Nemea Temple, assigned to root action before the excavation of the lower part of the column (Hill 1966) or to unsuccessful efforts at undermining the column (Miller 1986) (after Makris and Psychogios 2004 and Miller 1986). **b** Plants in the superstructure of the east façade of Hephaisteion Temple in 1882, enlarged top right part of Fig. 3 a. **c** The roots of an inclined pine tree represented a threat for the eleventh-century church of the Kaisariani Monastery in Athens. **d**, **e** Marble block tilted because of intrusion of roots of a fig tree in the fence wall of the nineteenth-century hospital of Mesolongi, Greece. If these roots were removed, tilting might have been misinterpreted as a seismic effect

then tend to expand them. This affects both superstructure and especially foundations (or parts during burial; cf. Hill 1966). Penrose (1897) mentions plants at the upper parts of Parthenon, while the engraving of 1882 in Fig. 10 b shows plants also at the upper part of Hephaisteion. Tensile stresses or torsion by root plants may have contributed in the decay of various structures, as exemplified in Fig. 10 d and e. Such plant-induced deformations (block tilting, extrusion, etc.) are frequently misinterpreted as indicators of earthquakes.

Just to notice that the damaged, western part of the Poseidon temple in Sounion near Athens was inaccessible to investigators till circa 1900 because of plant overgrowth (Paga and Miles 2016).

5 Recent damage in columns from known causes

A systematic study led to the following group of cases of damage in MAGR structures, produced by known effects.

5.1 Drums of ancient columns offset during recent earthquakes

The 1981 Gulf of Corinth seismic sequence produced much damage in Athens, at an epicentral distance of about 70 km (Papazachos and Papazachou 1997). During the first main event of magnitude M_s 6.7, an offset of 1 cm in certain columns of the Parthenon has been observed. On the contrary, during the second, M_s 6.4 main event of this sequence, with very similar fault characteristics, no offset in the Parthenon was noticed (Korres 1996). However, even if this second event was of the same magnitude with the first one, no similar effects were expected because of the nondeterministic character of impacts of earthquakes.

During the same earthquake sequence, small offsets were observed also in two solitary columns on the south flanks of the Acropolis (Zambas et al. 2011).

Important to notice that the 1894 Atalandi earthquake produced minor damage in Parthenon (toppling of a few fissured parts of the superstructure), but this minor damage had a catalyzing role in the first restoration of the Acropolis (see Penrose 1897).

The 1999 M_s 5.9 Athens earthquake caused rotation of the base of a statue standing on a tall, slender column, a nineteenth-century imitation of an ancient construction in the center of the city. On the contrary, a second nearby quasi-similar column with a statue on the top suffered no damage (Ambraseys and Psycharis 2011). Finally, Papazachos and Papazachou (1997) report that during the highly destructive 1858 Corinth earthquake some of the still standing capitals and architraves of the Apollo temple were rotated and fissured. This is one of the earliest temples (built in circa 560BC), made of relatively short (about 7m high) monolithic columns.

5.2 Toppling of restored columns during earthquakes

The 1970 M_s 7.1 Gediz earthquake, West Turkey, caused the collapse of two columns of the first-century BC temple of Zeus at Aizani, at an epicentral distance of about 20 km. These were among the three columns which had been restored about 10 years earlier (Ambraseys 2009).

The 2017, M_w 6.5 Bodrum-Kos earthquake, in the SE part of the Aegean Sea, caused the collapse of three out of four lines of columns in the Hellenistic Gymnasium of Kos Town. Fallen colonnades had been restored in the 1930s (using mortar, so they did not correspond to MAGR structures), and some years before 2017, and at least two of them are characterized by an oriented collapse normal to their strike (Fig. 9b; Psycharis and Tampaflas 2017).

5.3 Column collapse because of aeroelastic effects

On 30 September/14–15 October 1852, a thunderstorm hit the wider Athens area with catastrophic results of unprecedented scale. During this storm, one of the 13 surviving at that time 17-m-high columns of the first-century AD Zeus temple (Olympieion) in Athens was toppled down (Fig. 9a). Two adjacent, identical, solitary columns exposed to the same conditions suffered no damage from this storm, except perhaps for minor offset in the westernmost column (Fig. 9a, right side). Although this storm event and especially the fall of the column are well documented, especially because of a resolution of the Parliament to restore the fallen column (which, however, was not attempted so far), no details of the 1852 storm are known. However, since there exist no signs of thunderbolt on the fallen drums, the likely explanation is dynamic loading by gusts in combination with static wind loading. The mechanism of wind-induced effects on ancient or traditional slender structures has been rarely only examined (Ural and Firat 2015), but it should be complicated (Ayati et al. 2019). However, the foundations weakness must have played a significant role in the Olympieion column collapse, as evidenced by the tilted base of the fallen column (Fig. 9a).

At least two other cases of damage in temples have been assigned to wind effects. Possibly influenced from the collapse of the Olympieion column, V. Stais, an early twentieth-century excavator of the Sounion temple, proposed that wind effects or earthquakes are responsible for slip (offset) among column drums observed in the columns of the Sounion Temple near Athens (for references, see Paga and Miles 2016, Papastamatiou and Psycharis 1993). In fact, this temple is located at the edge of a 60-m-high plateau, next to a steep cliff at a promontory notorious for its strong winds which are amplified in the temple area. Damage to a temple in Selinous (Sicily) was also assigned to a wind-induced sandstorm (see Guidoboni et al. 2002).

6 Comparative investigation of damage in ancient columns due to unknown causes

In this section, we investigate whether damage of unknown causes of a second group of ancient structures share some common characteristics, especially local geotechnical characteristics, and hence, their comparative analysis, in combination with the results of Section 5, may provide some clues for the unknown causes of their damage.

6.1 Soil dynamics effects

Soil dynamics theory indicates that seismic shaking may be locally amplified (or attenuated) because of local conditions (aggravation of seismic motion because of topography and of local soil conditions; cf. Assimaki et al. 2005). Hence, strong differences in the damage pattern of neighboring, similar structures can be explained in terms of local amplification of seismic waves.

Colona Traiana and Colona Antonina in Rome are two spectacular examples. These nearly similar columns, about 40 m high and roughly of the same age, are found in the center of Rome, about 700 m apart from each other and were conspicuously influenced by the same effects. However, Colona Antonina is marked by an offset among drums, assigned to earthquake rocking (Sinopoli 1989), while Colona Traiana is not. A main difference between the two columns is that Colona Antonina is situated on a layer (pocket) of recent sediments; this leads to local amplification of seismic waves by a factor of 20, and this may explain their different response to seismic shocks and their different state of preservation (Funiciello et al. 1992). A modern parallel is offered by the Mexico City earthquakes (Nikolaou et al. 2018). Weak foundations conditions (unconsolidated deposits in a former lagoon) may also be the reason for amplification of seismic motion and characteristic offsets among drums in the surviving column of the Heraion temple, built in ca 560BC in Samos Island, Greece (Fig 2a). A possibility is that the causative strong motion was associated with coastal uplifts observed in the north coast of the island, about 25km away, testifying to earthquakes which occurred after the construction of the temple (Stiros et al 2000).

Soil dynamics effects may have been critical for the damage of several temples in Selinunte. Reflection profiles by Balia (1992) indicate that the ancient site is located on an about 10-m-thick layer of argillaceous sands with lenses of friable calcarenite on top of a 10–30-m-thick layer of clay overlaying basement rocks. Especially depending on rain conditions, this unfavorable geotechnical background may have highly aggravated strong motions, especially in specific sites leading to building collapses (for example, the Triolo Temple; Guidoboni et al. 2002; Bottari et al. 2009).

6.2 Foundations failure

Two basic requirements for seismic resistance of columns are a vertical main axis and a rigid base (Section 3.3); hence, tilting drastically reduces their antiseismic performance (Papastamatiou and Psycharis 1993; Papadopoulos and Vintzilaiou 2008). This is exemplified in the case of the Epikourios (Epikoureios) Apollo temple at Basai (Vasai, Bassae, Phigalia, SW Greece), built in the fifth century BC, representing one of the best-preserved ancient Greek temples, mainly because it is located in a remote, abandoned mountainous area.

Two types of damage characterize this temple: displacements between column drums, assigned to earthquakes (Papastamatiou and Psycharis 1993), and tilting of columns (Fig. 7a). Tilting is related to differential settlement of foundations up to 7.5 cm, mostly because of gradual consolidation or underground erosion of a clay layer between bedrock and temple foundations (Andronopoulos et al. 1988). A causative relationship between platform deformation and tilted columns on one hand and seismic response of the temple is likely.

Deformation of the foundation platform (differential settlements) characterizes several other temples (for example, Fig. 7b). It must be noticed that foundation deformation corresponds to the deviation of the existing platform ("crepis") surface from its original smooth, domal shape, constructed for esthetic and practical reasons (drainage of rainwater; Korres 1994; Zambas 1998).

In addition to deformation at platform scale, failure of foundations (nonrigid foundations) of isolated columns has also been observed, as for example in Fig. 7 c or Fig. 9 a.

In all these cases, the seismic performance of columns is expected to have been highly reduced.

6.3 Soil–structure interaction and soil dynamics effects at microscale

In certain standing temples, damage correlates with the foundation pattern and may testify to soil–structure interaction effects at a microscale (single structure scale).

Poseidon temple at Sounion (70 km SE of Athens) The Sounion temple was constructed in marble, after the Persian War, at the end of the fifth century BC, succeeding an older (archaic) temple. The fifth-century temple was in ruins at least since the Roman times, and in fact, it is suggested that parts of its roof have been used for repairs of temples in central Athens relatively shortly after its reconstruction (see Plommer 1950 and Paga and Miles 2016 for references). Drum dislocations are observed in many of the surviving nine columns of the seaward, south colonnade (see Papastamatiou and Psycharis 1993). Although a 1881 photo by H. Belle (easily available in the internet) shows drum offsets in most of the columns of this south colonnade, the possibility some of the offsets to reflect nineteenth-century restoration cannot be ruled out (for evidence of interventions, see for example, www.ascsa.net, Thompson image 1606).

At its west side, the temple platform, an extension of the platform of an older (Archaic) temple, is thicker and was found damaged and characterized by plant overgrowth. The present situation shown in Fig. 1 b is a result of twentieth-century restoration; before the nineteenth century interventions, only nine columns were standing in the southern (background) colonnade and four forming a corner (two along the external colonnade and two in an inner one) in the northern (foreground) colonnade.

The causes of the demise of the temple are not specifically discussed by various investigators (see the review by Plommer 1950). However, there were no signs found of undermining of the existing ancient columns nor signs of fire to justify generalized destruction by the invading Macedonian Army in 200 BC (cf. Section 4.3.2; Thompson 1981; Miles 1989). Some of the missing columns have slid down the slope, and some have been moved to museums abroad. It would be peculiar if any deliberate destruction was limited to the western part of the platform.

The platform collapse is likely to have been affected by gravity sliding. However, ordinary gravity sliding cannot explain displacements among drums in surviving columns.

An earthquake or wind effects have been proposed as causes of the damage of this temple by V. Stais, an early twentieth-century investigator (for references, see Paga and Miles 2016), but wind load effects can influence only the superstructure of the temple, not its foundations.

Hence, a reasonable scenario is that an earthquake produced drum offsets in the southeast part of the temple and damaged the west (thicker) part of the artificial temple foundations (Fig. 1b), which in their turn, amplified rocking of the superstructure, found in nonrigid bases, and this combination led to partial collapse of the temple (especially its western part) during classical times. Perhaps some of the columns in the west part of the temple were toppled later, because of static inefficiency, amplified by expanding plants (see Section 4.4). The rectangular marble blocks of the cella and the decorative elements were removed, while gradually some parts of the western part of the colonnade fell and slid downhill, and only parts of the eastern part of the temple, on stronger foundations survived till modern times, though with some offsets among drums.

Parthenon The southern part of Parthenon is built above an older temple, on a monumental platform. The inner structure of these foundations is unknown (see Bundgaard 1976), and although they seem solid, there is evidence of local subsidence of up to 2 cm in their southern part, where their thickness exceeds 10 m (Zambas 1998). Preliminary analysis of strong motion data indicates that the foundations of the Parthenon lead to reduced strong motion relative to the background rock (Egglezos et al. 2013) but to amplification of seismic motions in the south colonnade (which is marked by offset columns) relative to the north colonnade (which is essentially free of offset columns). The amplification factor is of the order of 5 for high frequencies (Cauzzi et al. 2015), and this may have led to weakening of foundations, especially in their thicker part. Hence, weakening of the south, thickest side foundations correlates with displaced drums in columns and displacement of a part of the cella (see Fig. 8) and may indicate a causative relationship (aggravated motion).

Hephaesteion Temple (Theseion), Athens This temple was built at the end of the fifth century BC and was transformed into a church in the early Christian times (Fig. 3) and, for this reason, is among the best-preserved temples of the ancient Greek world. Offset drums in columns, mostly along the southern colonnade (Fig. 3d), are shown in mid-eighteenth-century engravings and have been assigned to earthquakes by early seismologists (Galanopoulos 1956 citing Kritikos but without providing additional details). This association was, however, questioned by Ambraseys (2009), mainly because of lack of documentation of the earthquake scenario.

The temple is built on soft limestones forming a hill. The original rock surface was leveled and a system of foundation walls corresponding to the cella and to the surrounding columns was constructed, coupled with cross walls to form the temple platform.

The temple was probably damaged during the Roman–Macedonian War in 200 BC, but damage should have been limited to secondary (decorative) parts and parts of the roof, which was repaired probably using material from the Sounion temple (Thompson 1981). Later modifications in the superstructure included a medieval vaulted roof and removal of cross walls and of roof-supporting columns inside and next to the cella. In addition, there were excavated trenches inside and around the temple to host medieval and later graves. These trenches disturbed foundation walls and left voids. In addition, the foundations had been left exposed for centuries, before they were buried again in the 1930s. These extraordinary conditions permitted excavations in the temple foundations (which are not possible in other temples; for an exception, see Sinopoli 1989) and which revealed dislocation of certain foundation blocks (Dinsmoor 1941b; Zambas 1998). It was also found that the temple platform is characterized by settlements of a few centimeters (Zambas 1998).

Apart from missing roof beams, mostly from the northern side (Fig. 3b), damage is observed also in the superstructure, mostly fractures in the cella walls and slippage of column drums, especially in the northern and southern colonnade. This damage was assigned to settlement of the temple platform by Zambas (1998). This author also noticed that Penrose (1851) regarded these damages as an effect of loading from the medieval vault (thrusting) and of earthquakes, while Pennethorne (1878) favored the earthquake scenario; the latter was inspired by an earthquake which occurred during his study. Hence, Pennethorne (1878) and Penrose (1851) are the likely sources of the earthquake scenario of Galanopoulos (1956).

Combining all this evidence, it is possible to suggest that modifications in the superstructure and the foundations have influenced the two structural systems forming the temple, colonnades (peristyle), and cella. The two systems became unevenly coupled, with a high contrast between the northern side (relatively strong coupling) and the southern side (relatively weak coupling), and this tends to produce uneven soil–structure interaction and soil dynamic effects at microscale, amplified by the exposure and weakening of the foundations for centuries. In addition, the overall system of foundations and superstructure was lying on a weakened platform exposed to a level much higher than the designed one and, hence, was subject to soil dynamic effects. A possibility is that the 1705 earthquake has contributed in some of the Hephasteion structural damage, because it occurred during the period of weakened and exposed temple foundations. This poorly known earthquake indeed produced collapse of a large part of the Acropolis east ramparts (Korres 1996), and hence, it is likely that it was associated with relatively long-period seismic waves, to which the temple is typically vulnerable.

6.4 Correlations between nearby structures

In some cases, only isolated signs of column damage exist (for example, the single column at the temple of Hera at Samos; Fig. 2a), while in other cases, there is available evidence of destruction in a site-wide scale (for example, Baelo Claudia in Spain; Rodríguez-Pascua et al. 2011). Under certain conditions, and although earthquake damage is usually highly selective, evidence of site-wide destruction permits to extrapolate evidence of seismic or other destruction from one structure to another.

This is perhaps the case of the Selinunte temples, in which a systematic examination and correlation of damage, mostly assigned to earthquakes, was presented by Guidoboni et al. (see Fig. 4), but the dating of earthquakes, inferred to have destroyed them, is not clear. Two among these temples (temple C and Triolo) provide clear evidence of two different seismic events, the latter one correlating with remodeling of a fourth-century basilica, at Agrigento, not far away from Selinunte. As noticed in Section 6.1, the geologic background of Selinunte may explain the amplification of strong motion and simultaneous collapse of nearby temples.

7 Discussion

So far, there existed two apparently contrasting views concerning the destruction of MAGR temples and columns: an archaeoseismological approach favoring, under certain conditions, earthquake scenarios, and a structural approach highlighting their good seismic performance and hence excluding the possibility of seismic damage and favoring the alternative of deliberate destructions. This (apparent?) controversy should be viewed in correlation with the geotechnical background of structures, a point broadly ignored so far, as well as in the light of the evidence and of the arguments presented above.

Results can be summarized in three points. *First*, the hypothesis that the destruction of MAGR structures in a regional scale is only due to anthropogenic effects, especially between AD360 and 450 is not justifiable because there exists evidence of seismic destructions during periods excluding such a possibility (*Pax Romana*; Section 4.2). On the other hand, deliberate destructions should have left some signs in the ruins, while survival of pagan remains next to Christian churches (for example at Nemea) and in certain key towns excludes the possibility of generalized, successful effort at eradication of any signs of pagan culture between AD360 and 450.

Second, the history of demise of MAGR temples can be described as a long sequence of superimposed and interplaying destructive events, usually of different causes, both natural (including earthquakes) and anthropogenic, some with quasi-similar impacts on the ancient structures. In addition, cases of total, single-event collapses of temples seem rather rare.

Third, the response of MAGR structures to dynamic effects is a stochastic, highly selective, if not chaotic effect, mainly because of various factors determining the behavior of each structure. This is evident in the case of the three identical adjacent MAGR column, only one of which was toppled down during a storm in 1852 (Fig. 9a).

Hence, possibilities of seismic destruction of MAGR structures cannot be ruled out, and the questions arising are under which conditions these structures are (were) vulnerable to earthquakes, which are the characteristics of damaging earthquakes and why their occurrence is possible.

7.1 Survival of ancient remains and possibility of damaging earthquakes

A common argument against the occurrence of strong destructive earthquakes above a certain threshold in a certain area is the survival of certain ancient buildings (cf. Psycharis 2007). However, as has been emphasized by Ambraseys (1971), the survival of a small percentage of ancient structures of a certain type is a result of a *process of natural selection and of chance* and not indicative of absence of earthquakes with characteristics critical for the specific type of buildings.

Furthermore, because of superior craftmanship and of favorable local conditions, surviving buildings may not be directly representative of the population of structures which have been constructed in the past. In addition, evidence from a single structure is not decisive because the response of rigid blocks to seismic shocks is not deterministic and small details control the final output (Yim et al. 1980). For example, the 1856 earthquake leveled Herakleion (Crete) and destroyed all Venetian (sixteenth–seventeenth century) buildings with very few exceptions (Papazachos and Papazachou 1997). These surviving buildings do not testify to absence of earthquakes to which these buildings are vulnerable. Similarly, to the eyes of modern visitor, a few ancient buildings which survived the 1963 Skopje earthquake are not a sign that no 1963-type earthquake affected this city. Hence, the common argument “since a certain recent earthquake produced no damage to a specific structure, this structure (and eventually all other similar structures) is (are) not vulnerable to earthquakes” is not valid.

Another argument derived from this study is that if the wind caused the collapse of a tall, slender MAGR column (Section 5.3), it is not reasonable to a priori exclude the possibility of seismic collapses.

7.2 Underlying conditions of seismic damage: structural health

As analyzed in Section 3.3, modeled resistance of MAGR structures to earthquakes is not unconditional, and it assumes that structures *satisfy two initial conditions*: structural integrity and preserved geometry (structural health of the superstructure; cf. Pulatsu et al 2017), and rigid foundations (structural health of the foundations; cf. Papantonopoulos 1997).

Evidence presented above clearly indicates that both these conditions were not always satisfied. In many cases, various members of MAGR structures seem not to correspond to the necessary level of structural health concerning both their superstructure and foundations. This can be due either to constructional vicissitudes, or more frequently to structural deterioration (loss of structural integrity due to fissuring or decay or rock, tilting of articulated columns, weakened, nonrigid foundations; cf. the case of the Sounion Temple, Section 6.3). Such conditions obviously make structures vulnerable to earthquakes and they can even explain toppling of columns during storms (Fig. 9a).

7.3 Underlying conditions of seismic damage: undetected/underestimated earthquakes

Even in regions covered with long inhabitation and cultural history, the record of earthquakes derived from historical and archeological data is far from complete, and this is reflected in some discordance between predictions of earthquake catalogs and occurrence of earthquakes.

For example, some decades ago, central Aegean was considered as an aseismic area, but it was hit in 1956 by a magnitude 7.6 earthquake, the largest earthquake in the wider region during the twentieth century (Papazachos and Papazachou 1997). Till 1995, the wider Kozani-Grevena area in northern Greece was regarded as an aseismic region, but it was hit by an unexpected M6.6 earthquake, which in fact was a repeat of another ignored major earthquake in circa 1700 (Stiros 1998). SW Greece mainland was considered as an area of low seismicity, and for this reason, a magnitude M6.5 earthquake in 1966 was explained as a result of seismicity induced by the early phase of filling of a rather remote dam reservoir (Stiros and Pytharouli 2018). Such unpredicted or misinterpreted events are only one side of the problem of completeness of earthquake catalogs in Greece and many other areas, and they do not reflect isolated effects. For example, the 2017.11.12 M_w 7.3 earthquake in the Iran–Iraq border was a surprise event in a region classified as aseismic. The earthquakes which hit New Zealand in the last years were also a surprise in this aspect in a broad scale (cf. Bradley and Cubrinovski 2011).

In this framework, the argument of Galanopoulos (1956) that displaced drums in the Hephasteion temple (Fig. 3d) originate from a strong unidentified earthquake and indicate increased seismic risk in Athens, till then regarded as earthquake safe, should be seen. His prediction was somewhat confirmed by the 1981 seismic sequence which produced much damage in a town-wide scale and offsets in columns of the Acropolis (see Section 5.1), as well as by the 1999, M5.9 earthquake which produced extensive damage, high death toll, and extraordinary peak ground accelerations (> 0.5 g; Bouckovalas et al. 2002).

Hence, in combination with the arguments of Section 7.1, no deterministic constraints in the seismic history of certain areas are justifiable, while missed or poorly recorded/misinterpreted seismic events cannot be ruled out. These events are likely to have certain characteristics, the combination of which is likely to lead to earthquake cases unfavorable for MAGR structures (see Section 3.3, fourth argument).

(i) *Underestimated magnitude of earthquakes*. This point was discussed above and is clearly not directly related to damage, though high magnitude earthquakes favor long-period waves to which MAGR structures are vulnerable.

(ii) *Expected maximum PGA*. Earthquake scenarios usually accept maximum PGA of the order of 0.2–0.4 g. However, in Greece, several relatively moderate (M_w 5.9–6.4) recent seismic sequences produced max PGA between 0.52 and 0.74 g

(Lekidis et al. 1999; Bouckovalas et al. 2002; Theodoulidis et al. 2015) which at first hand appear unrealistic. In at least one of these cases, the earthquake was characterized by a potential of overturning slender structures such as obelisks (Bradley and Cubrinovski 2011; Gazetas et al. 2012), and perhaps slender ancient remains. Just to notice that Psycharis and Tampaflas (2017) argued that the collapse of restored columns in Kos in 2017 was due to an earthquake with characteristics (PGA) highly exceeding the typically adopted characteristics.

(iii) *Earthquakes with pulses.* There is growing evidence that high velocity pulses may characterize certain near-fault motions, and such pulses have higher damage potential than conventional (nonimpulsive) earthquakes (Mavroeidis et al. 2004; Makris and Vassiliou 2011).

(iv) *Near-fault, quasi-unidirectional persistent displacements.* Recent evidence from high-rate GPS data permitted to recognize that near the fault, even rather moderate earthquakes, are characterized not by a typical oscillation, but by an essentially unidirectional displacement of tens of centimeters, lasting up to several seconds, in the direction of the permanent seismic slip (Avallone et al. 2011; Saltogianni et al. 2016) and broadly correspond to long-period pulses. Such persistent motions, either horizontal or vertical, may be visualized as a structure laying on a rag which is pulled toward a specific direction.

The above discussion covers an upper threshold of earthquakes in a certain region. There is also a lower threshold, concerning the source characteristics of earthquakes which is a requirement for seismic damage. This point is critical because the archaeological literature is full of examples of uncritical association of damage in various structures with earthquakes inferred from literary or sources. In most of these cases, the historical information for earthquakes is too vague, and archaeologists do not take into consideration that earthquakes can be destructive *only* within certain influence zones. The latter depend on the source characteristics of the earthquakes (to some degree reflected in isoseismal curves bounding areas affected by seismic shaking and of destructive effects above certain thresholds), on lithology and topography, as well as on the type of structures. This is, however, a point beyond the limits of this study.

7.4 Structural characteristics of surviving columns

Theoretical predictions summarized in Section 3.1 indicate that the resistance of a column to seismic motion is influenced by a scale effect, so that taller columns are more stable than shorter columns of the same slenderness (ratio between height and width), and multiblock columns seem more stable against earthquakes relatively to monolithic columns.

Such arguments are reasonable, but they cannot be readily confirmed by analysis of MAGR structures surviving in standing position (i.e., excluding recent restorations). This is because the number of surviving structures is small, their geographic distribution is uneven, and in their majority, they correspond to slender and tall columns. Clearly, a change from monolithic to multiblock structures is observed in many areas, for example in Selinous (Selinounte) in Sicily (Sinopoli 1989). In an area of high seismicity, relatively short (about 7 m high), low slenderness (of the order of 4) monolithic columns of the Apollo Temple built in ca. 550 BC survive in the archeological site of ancient Corinth, southern Greece. In the nearby site of Nemea, of lower seismicity, the surviving columns of the temple of Zeus, built about 200 years later, are much higher (of the order of 10 m), with higher slenderness (of the order of 6).

In view of these difficulties, the survival of taller columns is certainly in favor of the theoretical predictions, but in the absence of additional evidence, they may also be taken to indicate better seismic performance, chance, empirical development of anti-seismic construction techniques, technological improvements imposed by practical limitations (nonavailability or difficulty in extraction and transportation of huge monolithic columns) combined with a tendency (“fashion”) for more impressive structures, or even later structures, not exposed to specific destructive events.

8 Damage scenarios

Evidence summarized above indicates that earthquakes (and wind) have left their traces on certain MAGR structures. These traces are in the form of dislocation along column drums or of opening of joints in temple walls, and under certain conditions, in the form of toppling of certain structural parts.

Although articulated structures share common characteristics in their response to dynamic loads, the response of a solitary column or of an independent colonnade is different from that of whole temples, or even in coupled colonnades, and this may explain the different orientations of corner columns in Fig. 4. Scenarios for collapse of solitary columns and for colonnades have been proposed by various investigators (see Section 3.1) and include even cases of oriented collapse (Fig. 2). The response of structurally complex structures, especially of whole temples, on the contrary, is poorly known and apparently highly complex, mainly because of coupling between transversal colonnades, roof, and cella (Figs. 1a and 3b).

This means that in an intact temple with strong roof (high coupling), it is rather difficult for a column or a colonnade to topple down toward the inner part of the temple (see Fig. 1a). Hence, toppling of columns outwards of the temple is not a surprise or an a priori evidence of deliberate destruction. On the other hand, toppling of columns toward the internal part of the temple (Fig. 4b) may indicate no coupling or weak coupling between columns, roof, and cella through the roof (i.e., a temple without roof, or even with dismantled cella), or very particular conditions (cf. instability of foundations during seismic excitation, for example in the case of Selinunte, see above).

This leads to the following likely scenario: After a destructive event, including an earthquake which took advantage of a structural deficiency, a temple was abandoned because of damage beyond repair for the socio-economic conditions of the period. Its platform was perhaps used as foundations for humble houses, while its precious parts, decorative elements, and well-hewn blocks were removed to be used in other structures, temples, houses, and fortifications (e.g., Barrett and Vickers 1975; Guidoboni et al. 2002). For this reason, certain columns or colonnades resisting to earthquakes and other destructive effects were left standing (for example in Sounion, Fig. 1a), and their response to earthquakes is described by the existing structural models. Later, because of demand for limestone or marble, all or some of the surviving columns disappeared.

9 Toward diagnostic criteria of causes of damage

It would be quite useful to propose certain criteria to recognize the causes of damage. However, the complexity and the selective, nearly chaotic pattern of response to MAGR structures to earthquakes (Section 3.3) *do not permit deterministic criteria* to identify or discard the scenario of seismic and/or deliberate destructions. For this reason, certain *indicative and conditional criteria* can only be proposed, the significance of which increases with the number of different criteria met for a single structure or with site-wide correlations (cf. Stiros 1996).

Under these conditions, the following can be proposed:

(i) Damage and failure of MAGR structures should not be a priori regarded as a single, ON/OFF effect, but as superimposition of various effects, some playing catalyzing role for more recent events, leading to an overall complicated output.

(ii) The output of a certain effect or of a sequence of certain effects may be similar to those of other effects, and for this reason, different possible scenarios should be examined (for example, for the toppling of a column such as that of Fig. 9a), taking into consideration their uncertainty. These alternative scenarios should be tested using all the available historical, archeological, and engineering evidence.

(iii) Absence of basic conditions necessary to ensure the high seismic performance of MAGR structures (structural health of the superstructure and of the foundations, especially absence of background conditions leading to aggravation of seismic motions) indicates that seismic damage cannot be discarded.

(iv) Survival of certain columns of an ancient temple, not converted to a Christian temple, provides evidence of absence of successful and organized efforts to fully eradicate signs of the pagan cult in a certain inhabitation center (but not in remote and nonvisited areas) and not an a priori evidence of absence of earthquakes critical for this structure (see Section 7.1).

(v) Because ancient people were strictly adopting the rule of minimum energy/effort, they were adopting techniques to facilitate their destruction work (for example, to undermine columns in analogy to techniques used in lumberjacking). Hence, the absence of signs of undermining of the bases and/or of the lowermost drums in MAGR columns (as well as absence of signs of conflagration) weakens arguments for deliberate destructions.

10 Conclusions and implications

MAGR structures are articulated mechanisms with structural behavior different from those of rigid structures (i.e., those made with concrete). They seem very fragile, but on the contrary, they are characterized by a particular behavior and high resistance to earthquakes and other dynamic effects such as wind, probably to some degree known in antiquity. This is a main reason why some of them, usually among the tallest ones, survived for about 2000 to 2500 years.

However, MAGR temples and columns are safe against earthquakes only if they are structurally healthy, concerning both their structure and foundations. If structurally deficient, they were vulnerable to earthquakes.

In most cases, the destruction of MAGR structures was a long, gradual, and complex process, influenced by various natural and anthropogenic effects. For this reason, no direct (deterministic) association between toppling pattern and earthquakes, or the known earthquake occurrence and characteristics in a certain area, is a priori justified.

The results of this study are useful for seismology in general (palaeoseismology and seismic risk assessment) and for the study and restoration of ancient remains, although differences in the structural pattern do not permit to extrapolate results from MAGR to rigid structures and vice versa.

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Appendix

Literary sources and inscriptions reporting seismic effects on MAGR temples and columns

Source: Guidoboni et al. (1994)

c. 27 BC, Tralles, modern Turkey, collapsed gymnasium, i.e. a structure usually having columns (Strabo 12.8.18).

76 BC, Rieti, Italy, temples were shaken, and various structures were collapsed (Julius Obsequens 59).

c. AD47, Antioch, Turkey, three temples were torn apart (Malalas 246).

c. AD47, Samos, two inscriptions commemorating the rebuilding by emperor Claudius of two temples, destroyed by aging and earthquakes.

AD51 Rome, restoration of a shrine built a few years earlier. Restoration commemorated by a damaged inscription correlates with the AD51 earthquake.

AD69–79 Corinth, inscription commemorating repairs in three temples destroyed by earthquakes and the passage of time.

AD80, Nola, near Naples, Italy, inscription commemorating the restoration of a temple with four columns in its front, destroyed by an earthquake (perhaps related to the famous eruption of Vesuvius in AD79).

AD142/144, Lindus, Rhodes, rebuilding of the sanctuary of Asclepius destroyed by an earthquake.

AD160/161? Cyzicus, in the Sea of Marmara, Turkey, a gigantic temple collapsed during an earthquake (Dio Casius, 70.4). Excavations and other evidence summarized in the text is broadly consistent with the report and testify to partial collapse of a temple with columns over 20m high.

AD358, Nicomedia (Izmit, Turkey), destruction of temples by earthquakes and fire

Before AD374, Reggio Calabria, Italy, restoration of baths destroyed by an earthquake and restoration of a basilica adding a portico with columns, inscription.

AD458, Antioch, Syria, destruction of the Nympeum and of its porticos, Evagrius 2.12.

AD477/480, Constantinople, Theophanes 125–126, churches and porticos collapsed during earthquake.

AD554–558, Cos island, Aegean Sea, practically the whole city was reduced to a gigantic heap of ruble, littered with stones and fragments of broken pillars and beams (Agathias 2.16, 1–6).

AD557, Constantinople. During a destructive earthquake, the churches of St Stratonicus and of St Callinicus at Rhegium collapsed, as did the porphyry column which stood in front of the palace of Jucundianae. It fell with the stele on top, and penetrated 8 feet in to ground; the column of emperor Arcadius also fell down (Theophanes, 231).

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