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THE COLLAPSE OF THE ANCIENT TEMPLE OF ZEUS AT OLYMPIA REVISITED.

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ABSTRACT

The temple of Zeus at Olympia in the renowned archaeological site of the Olympic Games, in SW Peloponnese, is a typical case of an ancient monument associated with claims of earthquake damage and destruction. The German archaeologists that initially excavated the site and studied the temple debris the last quarter of the 19th century, as well as later and recent investigators, postulate that the Temple although in ruinous condition, was utterly destroyed the 6th century AD by an earthquake. Recent sedimentological investigations suggest that a tsunami may also have contributed to the destruction and the subsequent burial of the temple with silt. The aim of this paper is to examine in a quantitative way the hypothesis that the last standing columns of the Temple of Zeus were overturned by the seismic shaking of a damaging earthquake and if so what was the likely intensity and characteristics of the strong ground motion at the site. On the basis of dynamic analyses of distinct element models of the columns, it is found that even exceptionally strong seismic shaking is unlikely to overturn them. The location of the fallen columns also differ significantly by the patterns revealed by the numerical analyses. On that basis the hypothesis that the columns were intentionally pulled down by ropes pulled by animals during the early Byzantine period, seems more likely and should be investigated more thoroughly.

INTRODUCTION

The general tendency of the scholars that studied the findings of early archaeological excavations and remains of ancient structures (temples, fortifications or palaces) in Greece, to frequently ascribe evidence of destruction to strong earthquakes without scrutiny, has been strongly criticized by later researchers, who emphasize the need to systematically re-examine such hypotheses. The development of modern analytical tools and laboratory techniques in a wide spectrum of scientific fields and the establishment of a consistent archaeoseismological methodology (Guidoboni et al., 2002) to evaluate and cross check the evidence, provide the necessary tools to undertake such endeavors. The benefit of such investigations is twofold: to clarify the conditions of damage and the final abandonment of important architectural complexes of the antiquity, and to provide data to probe into the seismic history of the examined sites with certain implications to our understanding of the regional seismic hazard.

A typical example of such unverified claims for an “archaeological” earthquake is the Temple of Zeus at Olympia. The German archaeologists that initially excavated the site and studied the findings, as well as later investigators, from Dinsmoore (1940) to Younger and Rehac (2009),

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postulate that the Temple has been seriously damaged by strong earthquakes, and subsequently repaired in the mid 4th century B.C. and the 2nd century B.C. and was utterly destroyed by an earthquake the 6th century AD. A number of column drums, which can be observed today by the ordinary visitor of the site to lay on the ground in a domino-like fashion, form the basis of the hypothesis that at least some of the last surviving columns of the temple were overturned by a strong earthquake. Some recent researchers go beyond the traditional explanation and examine the possibility that the sanctuary of Zeus was inundated by a tsunami that reached the site the mid 6th century A.C. (Vott et al., 2011) which toppled (?) the last standing columns. They observe that the remains of the fallen columns (or at least some of them) "float" in high energy sediments probably deposited by the tsunami. The aim of this paper is to examine in a quantitative way the hypothesis that (at least) the last standing columns of the Temple of Zeus were overturned by the seismic shaking of a damaging earthquake and if so what was the likely intensity and characteristics of the strong ground motion.

THE TEMPLE OF ZEUS AT OLYMPIA

The Temple of Zeus was built from 470 to 456 BC within the sanctuary of Zeus at Olympia, under the direction of the Elean architect Libon. It was the largest Temple of the antiquity in the Peloponnese and later (circa 430 B.C.) it housed the renowned chryselephantine statue of Zeus, sculpted by Pheidias (figure 1). The peristyle of the temple consisted by 6 × 13 columns, about 10.43 m high and measured 27.5 × 64.1 m. The temple itself was over 20 m high (figure 1). Within the peristyle were the pronaos (front porch), cella (central room) and opisthodomos (rear porch) built by large limestone blocks. Two rows, each of 7 Doric columns, divided the cella into 3 aisles (see cross section in fig. 1). The platform (crepis), where the temple was standing, is 27.68 m by 64.12 m in size (figure 2) and has 3 unequal steps. The crepis was built on a foundation 2.50 m deep, presumably to reach competent ground. The temple was build by local shelly limestone covered with stucco. It stood at its place for almost a thousand years, saw moments of glory as it was the center of the Olympic festivities and suffered damages induced by natural disasters as well as warfare, invasions and looting.

The 3rd century AD saw the site suffer heavy damage either from earthquakes or man made interventions. The threat of invading tribes (Heruls) in 267 AD led to the erection of rough fortifications with robbed material from the monuments of the sanctuary. Despite the destruction observed in the monuments and the general decline of the sanctuary, the Olympic festival continued to be held until the last Olympiad in 393 AD. Apparently, after the suspension of the games the Temple of Zeus was abandoned and probably destroyed to a large extend around 426 AD following an edict by Theodosius II enforcing the ban on pagan festivals. The nearby workshop of Pheidias was turned into a Basilica and the site was inhabited by a Christian community which prospered during the 5th century AD until Justinian's plague. The two Earthquakes of the mid-6th century (522 and 551) known by historical sources that caused widespread damage to the Peloponnese are held responsible for the temple's complete destruction. Repeated floods of the nearby Kladeos river (Foundoulis et al., 2008), or flooding by a tsunami(es) according to Vott et al., (2011), ensured that the settlement was finally abandoned altogether in the early 6th Century. Over time the site was buried under accumulated alluvial deposits, up to 8 meters deep.

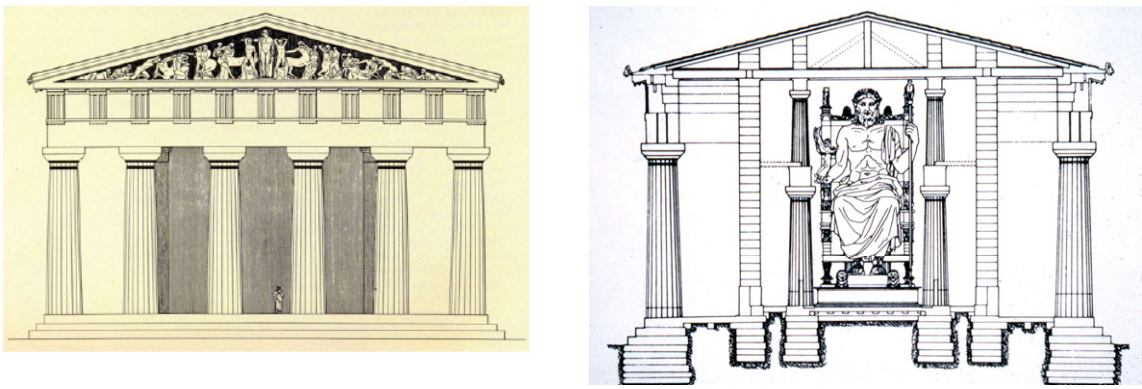


Figure 1 Reconstruction of the West façade of the temple of Zeus and of a cross section

The exact site of ancient Olympia was re-discovered in 1766 by the English antiquarian Richard Chandler. The first excavation of the sanctuary at Olympia was not carried out until 1829, by the French "Expedition Scientifique de Moree" and the first systematic major excavation of Olympia began 50 years later in 1875, by the German archaeological school. During these excavations the temple of Zeus was fully uncovered by the sediments. Many columns of the southern flank were found on the ground in an impressive domino style arrangement of the drums, which was immediately interpreted by the archaeologists to be a result of an earthquake. On the basis of archaeological data they estimated that the final destruction of the temple, which was probably already in ruinous condition, took place in the mid or late sixth century AD. Figure 2 depicts the plan view of the ruins of the temple as found during the archaeological excavations of the last quarter of the 19th century and figures 3 and 4 photographs of the fallen columns during the archaeological excavations and at their present condition.

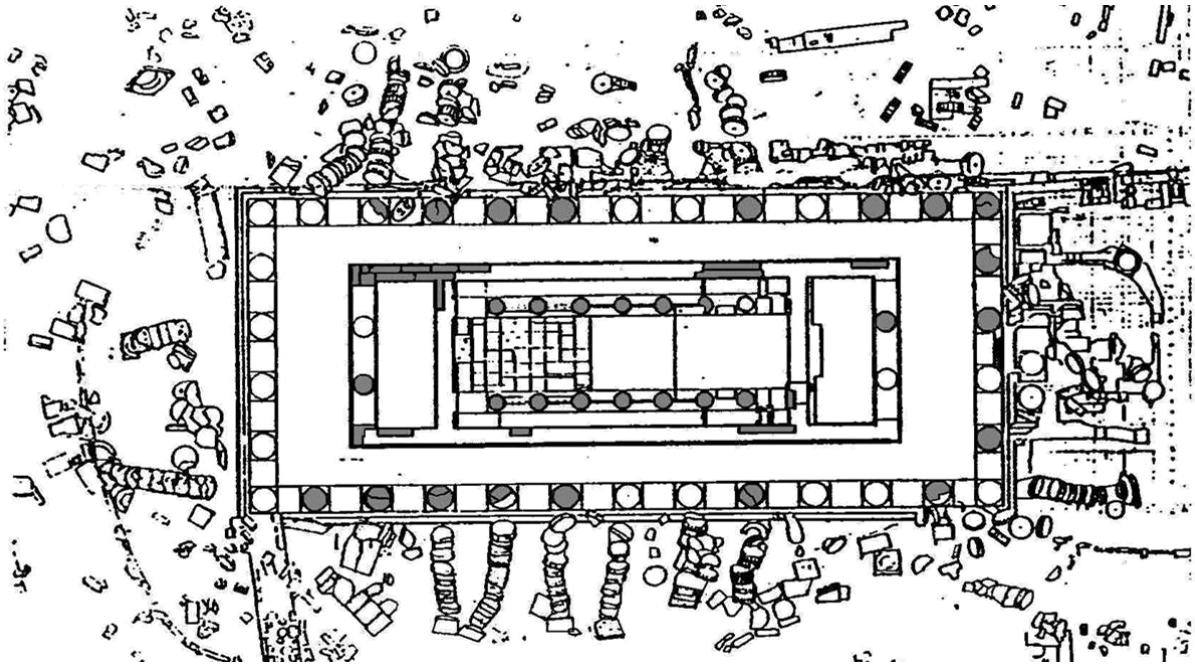


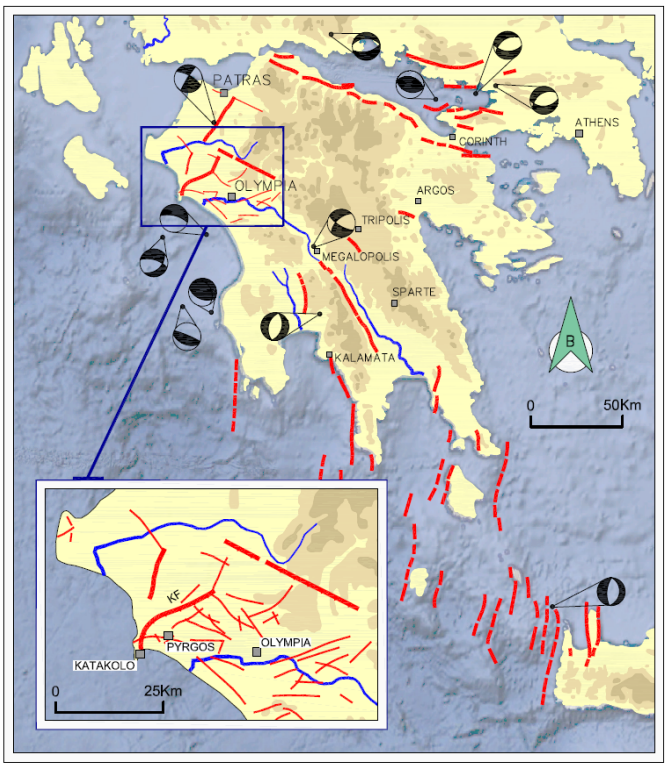
Figure 2. The ruins of the Temple of Zeus as discovered during the excavations of the last quarter of the 19th century undertaken by the German Archaeological School (Curtius and Adler 1892)

Figure 3 The fallen columns of the temple of Zeus as unearthed during the archaeological excavations of the last quarter of the 19th century (Curtius and Adler 1892).

Figure 4 The fallen columns of the temple of Zeus as they are preserved today.

SEISMOTECTONIC SETTING AND POTENTIAL EARTHQUAKE SOURCES

The tectonic activity which controls the seismic hazard in South-Western Greece is dominated by two mechanisms: thrusting along the western part of the Hellenic Arc and extension at the interior of the Arc. The first mechanism is associated with large but infrequent earthquakes, which may have affected the site from a distance, while the latter is associated by more frequent small to medium size events with a potential to affect the site from very short distances. Figure 5 depicts the major tectonic features of the Aegean arc and highlights the regions at the interior of the arc which undergo the most rapid extension, while figure 6 presents the major known active faults of the Peloponnese compiled by Lyon-Caen et al. (1986) and Lekkas et al., (1994). The site of ancient Olympia is situated within the Alphios river tectonic graben, a similar tectonic structure but significantly less active, to the Corinth gulf graben. The Alphios river graben is bounted by E-W and NE-SW trending normal faults. The length of these active faults does not exceed 25-30 km and the expected maximum earthquake magnitudes are limited to 6.0 to 6.4. The inset of figure 6 depicts the location of the Katakolo fault (KF) located at a distance of 12-15 km from the site of ancient Olympia which is the most active tectonic structure at the vicinity of the Olympia site (Lekkas et al., 1993). Offshore to the west lie the Hellenic trench where larger thrust faults are capable of producing stronger earthquakes of magnitude7.0-7.2. These faults are difficult to map and can only be traced by offshore geophysics and microearthquake surveys. Fault plane solutions of earthquakes along the arc as well as in the back arc area are presented on the map of figure 5. Intermediate depth earthquakes also occur on the subducting slab of the African plate underneath the Peloponnese. The 1962 Corinthos earthquake (M=6.8), the 1964 Messenia earthquake (M=6.0), as well as the 2006 Kithira island earthquake (M=6.7) are good examples of such events. The intermediate depth earthquakes are characterized by an attenuation pattern and strong motion frequency content significantly different to the shallower events.



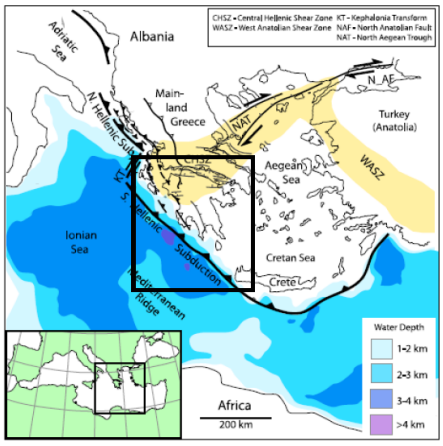


Figure 5. Upper figure: Tectonic setting for the Hellenic subduction zone Thick dark lines with solid barbs indicate active trenches, Orange shading indicate the zones of active oblique extension. (Royden and Papanikolaou 2011)

Figure 6. Left figure: Active faults in the Peloponnese. The selected fault plane solutions depicted in the figure indicate the predominant tectonic stress field of the crust.

The focus of our research is the 6th century A.D. when the temple was completely destroyed and covered by sediments. As mentioned before, there is historical evidence for strong earthquakes that seriously damaged some cities of the Peloponnese during the 6th century A.D., but information is vague and confusing. During this period western Peloponnese is outside the important trade routes of the era and references by travelers and scholars are very scarce. An earthquake that damaged the city

of Corinth in 521 (or 522), (Evangelatou–Notara 1988) is unlikely that had an effect in Olympia. However in 551 (or 552) according to the contemporary annalist Procopius of Caesaria damaging earthquakes occurred in the whole Greece and devastated many Greek towns (Chaeronea, Coroneia, Naupaktos and Patras) and numerous villages in Boeotia, Achaia and the Krissaean Gulf (Gulf of Itea). (Evangelatou–Notara 1987-1988, Guidoboni 1994) The extent of the earthquake damage reported by Procopius, along the entire length of the Corinth Gulf from Patras to Chaeronia, is impressive and it could only be explained by assuming a sequential reactivation of a chain of faults, which bound the southern coast of the Corinth Gulf, (shown in figure 6) occurring within a few weeks or a few months. In this case, the Olympia site would be outside the meisoseismal area of these earthquakes and damages to the temple of Zeus cannot be explained. The destruction of the temple could only be associated with these descriptions in the context of a large intermediate depth earthquake, occurring underneath the Peloponnese or an independent thrust fault event occurring offshore the western coast of the Peloponnese. In any case, the possibility that the temple was stricken by a small local earthquake, which was not associated to the earthquakes reported by Procopius, should also be considered.

On the basis of these considerations, possible earthquake scenarios for the Olympia site are: a) a near field normal fault event with a magnitude 6.0 to 6.4; b) a larger thrust fault earthquake event with a magnitude up to 7.0 to 7.2 but occurring at a longer distance; and c) an intermediate depth earthquake event of a magnitude up to 7.0-7.5 occurring deep underneath the site. Three characteristic strong motion records were selected to represent each of these scenarios: The Kalamata 1986 accelerogramm which was recorded at a close epicentral distance (R=10 km) to the Ms=5.8 normal fault earthquake, and stroke the city of Kalamata, situated 80 km south of Ancient Olympia; the 1979 Montenegro earthquake (Ms=7.2) recorded at the hotel Olympic, represents the thrust fault event, and the peculiar accelerogramm that was recorded at Bucharest during the 1977 Romanian (Vrancea) Earthquake of 1977 (M=7.0) represents the intermediate depth earthquake scenario. The possible seismic scenarios and the selected records are tabulated in table 1.

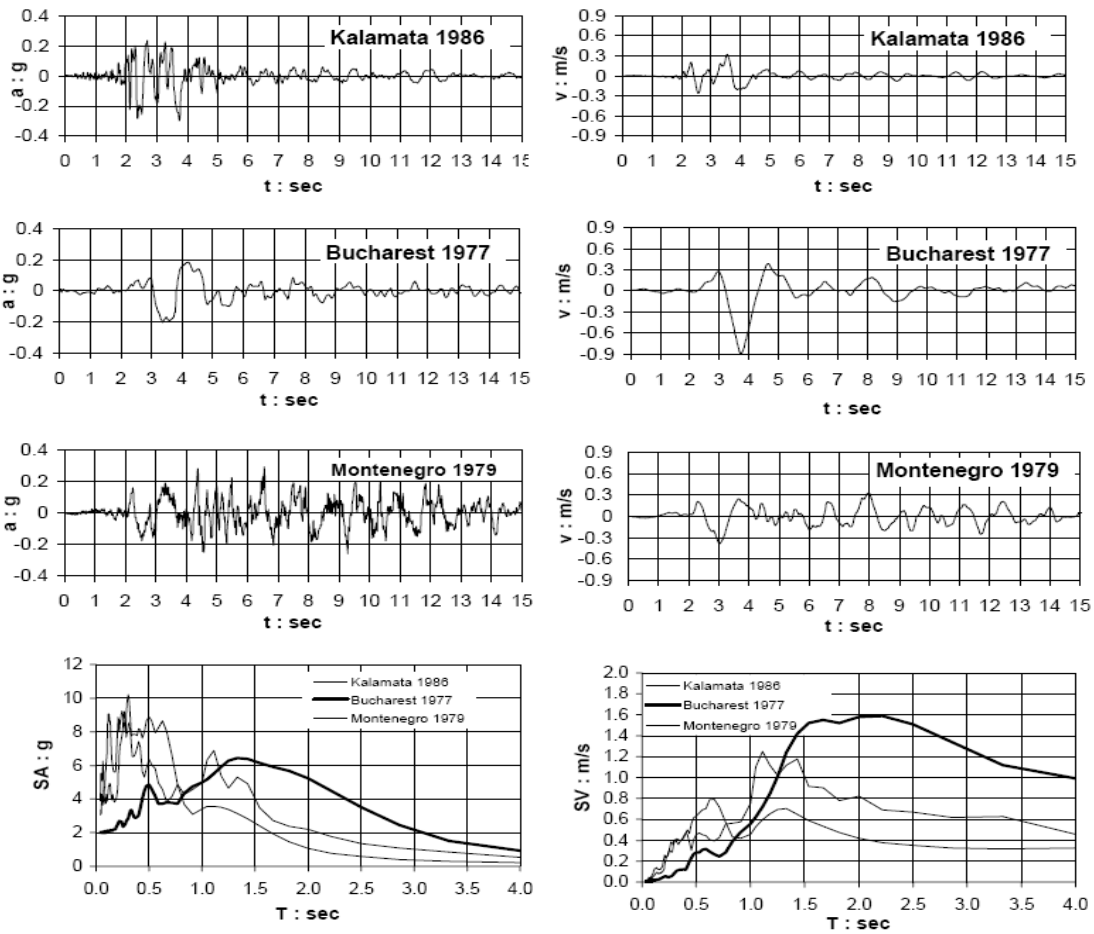


Figure 7. The stronger component of the three records used in the analyses and corresponding response spectra

Table 1 Earthquake scenarios considered and records selected

Earthquake scenarios			Representative Record	
Earthquake magnitude M	Distance from the source (km)	Earthquake mechanism and source depth		
M=6.0-6.4	5-10 km	Normal or Strike Slip Shallow	**Kalamata 1986** (OTE Building) Ms=5.75, R=10 km	**PGA=0.27g** **PGV=32.3 cm/sec**
M=7.0-7.2	30 -50 km	Thrust Shallow	**Montenegro 1979** (Ulcinj-Hotel Olimpic) Ms=7.2, R= 24 km	**PGA=0.29g** **PGV=47.1 cm/sec**
M=7.0-7.5	40-80 km	Thrust Intermediate depth	**Bucharest 1973** (Building Res. Institute) Ms=7.05, R= 161 km	**PGA=0.20g** **PGV=73.1 cm/sec**

We deliberately selected records with a strong impulsive character, attributed to directivity effects, because it is well known from previous studies on the seismic response of ancient columns (e.g. Psycharis et al. 2000) that such structural systems are more vulnerable to long period pulses. The acceleration and velocity time histories of the strongest component of the selected records are presented in Figure 7 along with their response spectra. The earthquake records and the relevant metadata were taken by the Ambraseys et al., (2000) strong motion record collection.

STRUCTURAL RESPONSE

Ancient Greek and Roman Temple columns are constructed by a number of prismatic rock blocks (drums) that lie on top of each other without mortar or any other bonding material. There are only a few exceptional cases of monolithic columns. Under earthquake excitations the column blocks can slide or rock, accumulating permanent dislocations and in extreme cases overturn. Each column of the temple of Zeus was constructed by 14 drums of equal height. The columns were crowned by Doric capitals and on top of them the architrave blocks and entablature slabs were connecting the columns to a continuous colonnade supporting the roof. The typical column of the peristyle of the temple has base diameter 2.21 m and top diameter (below the capital) 1.70 m. The aspect ratio of the typical column of the flanks is H/D=4.73. The size and the proportions of the typical column of the temple of Zeus at Olympia are compared with the columns of other Doric style ancient temples in figure 8. It can be seen that the columns of the temple of Zeus at Olympia are slightly higher than the columns of the Athenian Parthenon and the columns of the temple of Zeus at Nemea, but they are significantly less slender and hence significantly more resistant to earthquake shaking.

The earthquake response of single and multi drum columns is a complicated, highly non linear structural problem. The dynamics of a rocking block were investigated originally by Housner (1963) and subsequently by many other researchers, either by analytical or by numerical methods. Analytical solutions are limited only to the study of the transient response of two dimensional free standing blocks, subjected to trigonometric or other simple pulses (e.g. Makris and Rousos 2000, Jhang and Makris 2001, Dimitrakopoulos & DeJong 2012 and Voyagaki et al. 2013). However these solutions are valuable since they provide insights to the controlling parameters of the response and can provide an approximate estimates of the safety of more complex rocking structures.

In figure 9, on the basis of the safe-unsafe boundaries derived by Jhang and Makris (2001), we compare the safety of the "equivalent single blocks" of all the Doric style columns presented in figure 8, when subjected to a cosine and a sine pulse of a_g=0.5g and T_p=0.8 sec and a_g=0.3g and T_p=1.5 sec. The first case grossly represent the directivity pulse of a small earthquake at short site to source distances and the latter the directivity pulse of a larger earthquake at larger distances. It is observed that the larger columns (Zeus at Olympia, Zeus at Nemea, Athens Parthenon) are less likely to overturn because of their lower p values (where $p=\sqrt{3g/(4R)}$ and $R=\sqrt{b^2+h^2}$ = half diagonal of the block-a measure of its size). Moreover, the relatively small aspect ratio of the columns of the temple of Zeus at Olympia classifies them among the most resistant between the columns shown in figure 8. On the basis of this comparison, under single strong motion pulses of duration longer than 1.5 sec and

amplitude higher than 0.3g, most of the columns shown in figure 8 are likely to overturn if they behaved monolithically.

Despite the valuable insight provided by analytical treatment of the rocking response of rigid blocks, numerical analysis of such systems is more flexible and can handle complex 3 dimensional multi-block columns subjected to real earthquake excitations. The distinct element method in particular, which was selected here for our analyses, has been employed in the past (Psycharis et al. 1998, Psycharis et al. 2000, Psycharis 2007, Psycharis et al. 2013), to simulate the dynamic response of multi-drum column assemblies, with satisfactory results. Although the dynamic response of such systems is very sensitive to initial and boundary conditions, it has been acknowledged that distinct element models do capture the most significant aspects of real dynamic behavior, as compared by observed response during shaking table tests (Papantonopoulos et al. 2002, Papantonopoulos et al. 2009) does not suffer from compromises on reproducing the details of a real life multi block assemblies comprising ancient monuments. In the context of the present investigation, models of a single free standing column as well as a pair of columns coupled by an architrave (limestone slabs) were set up and analyzed by the commercially available distinct element code 3DEC (Itasca Consulting Group). The numerical models presented in figure 10 are used not only as a means to constrain the strong motion level necessary to overturn the columns, but also to investigate the mode of collapse and to predict the final location of the fallen column which can be compared directly to their position in the archaeological site. The modeling methodology and the material model parameters are similar to the ones presented by Psycharis (2007).

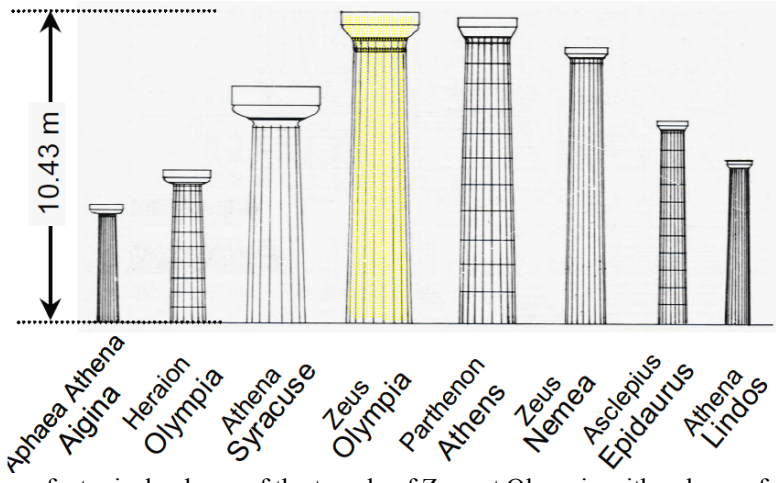


Figure 8. Comparison of a typical column of the temple of Zeus at Olympia with columns from other classical Doric temples (after Müller-Wiener 1988)

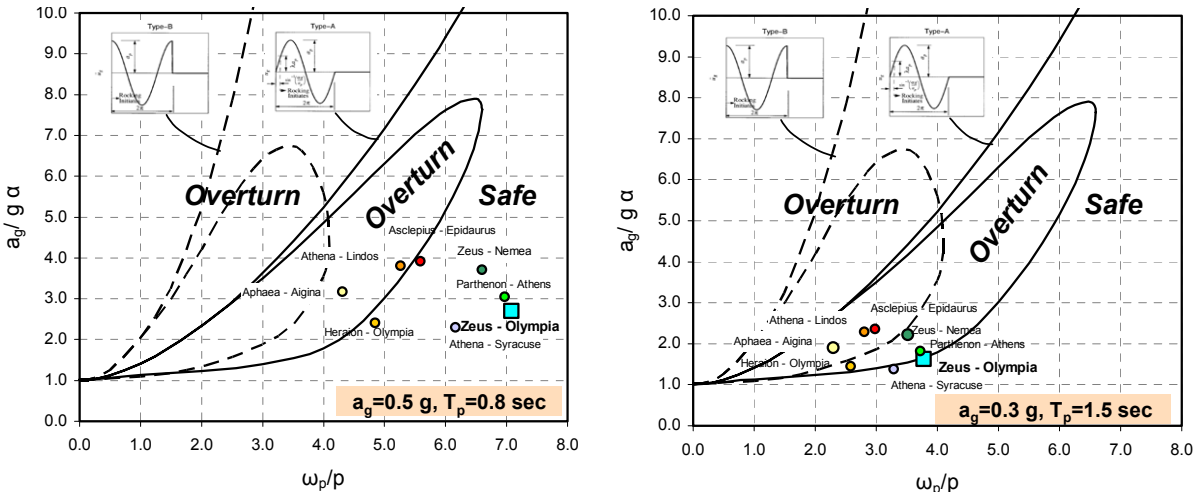


Figure 9. Safety against overturning for cycloidal pulses of single free standing blocks with the aspect ratios of the columns presented in figure 8. **Left chart**: safety margins to a pulse (sine or cosine) with **ag=0.5g and Tp=0.8 sec**. **Right chart** safety margins to a pulse with **ag=0.3g and Tp=1.5 sec**. The excitation amplitude of the cycloidal pulse is normalized to the overturning angle of the block under static conditions $\alpha=\tan^{-1}(b/h)$.

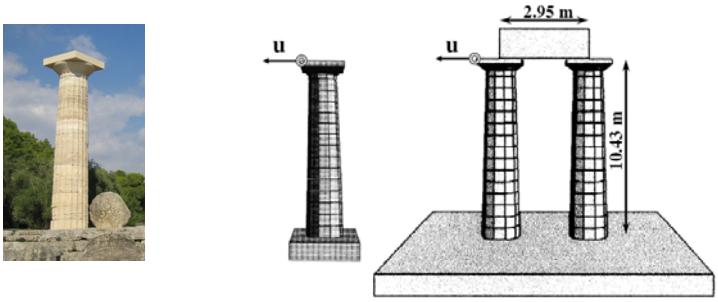


Figure 10. 3DEC single and two-column models used in the analyses. A recently restored column of the temple is shown on the left.

A series of 3-dimensonal dynamic analyses of the single column model, subjected to the earthquake records selected in the previous paragraph, was performed by gradually scaling them up until instability of the column is reached in order to bracket the strong motion intensity necessary to overturn the columns and to study the mode of rocking. Figure 11 summarizes the results of these numerical analyses, in the form of maximum response displacement of the capital versus the peak ground acceleration and peak ground velocity of the excitation. The free standing columns of the temple of Zeus overturn for a peak ground acceleration of 0.24 to 1.20 g, depending on the period of the directivity pulse contained in the record and for a peak ground velocity of 70-130 cm/sec. The peak ground velocity is better correlated to the maximum rotation of the column and is a better indicator of the overturning potential of the record as suggested also by other researchers in the field (Makris and Roussos 2000). The strong motion of a small local earthquake, like the Kalamata 1986 earthquake, is unlikely to overturn a free standing column, since the Kalamata record should be scaled up almost by a factor of 4.5(!) to overturn it. Likewise the Montenegro 1979 record should be scaled up by a factor of 1.8 to overturn a free standing column. On the other hand the Bucharest 1973 record represent a more realistic scenario, since it overturns the column almost without scaling. With respect to the mode of rocking, for all the examined records, the column generally rocks vigorously and looses its upper 5 to 10 drums, but with no exception a number of the lower drums remain in place, as shown in figure 12. It is stressed out at this point that in the archaeological site only the first drum was found in place on the temple platform (crepis). All the other column drums lay in a domino-like fashion aside the temple.

The mode of rocking of a couple of identical columns linked with rigid slabs (representing the architrave blocks) is more complex. The mode of rocking of the system is altered by the addition of the blocks on top of the columns due to the increased inertia. Analytical work presented by Makris and Vassiliou (2013) for a plane trilith rocking frame, shows that the addition of a beam on top of a couple of slender rigid blocks increases their in plane resistance to overturning. In the three dimensional space the induced asymmetry of the system also contribute to the increased dynamic resistance of the system. The two columns do not rock in phase and consequently the top beam starts to rotate in order to follow the asynchronously rocking columns. This mechanism cancels-out some high and medium frequency pulses and consumes energy by friction between the top beam and the columns. The instability of the system occurs with an out-of-plane overturning of one or both columns. The stability thresholds are for the two column model is significantly higher. The Bucharest 1973 record should be scaled up 1.6 times to overturn the two-column model, the Montenegro 1979 record, 2.0 times and the Kalamata record 6.0(!) times. When the strongest component of the accelerogramm is aligned to the colonnade axis the required scaling is even higher. Figures 13 and 14 present the mode of rocking of a two-column model subjected to the Bucharest 1973 and the Montenegro 1979 record. The mode of collapse does not change significantly when we rotate the two components of the record to align the stronger or the weaker one with the colonnade axis. However the stability is found to be significantly higher when the stronger component is parallel to the colonnade axis. In these figures it is also observed that only the upper drums of the columns and the capital fall over while a number of the lower drums remain in place. Figure 14 presents in plan view the likely location of the fallen debris of the two-column model. It is observed that due to the top beam rotation it is more likely the columns to reach the ground at an angle to the colonnade axis and less likely to overturn in a perpendicular direction. However the fallen drum patterns are different to the ones unearthed by the archaeologists during the excavations of the site (compare figure 2 to figure 15).

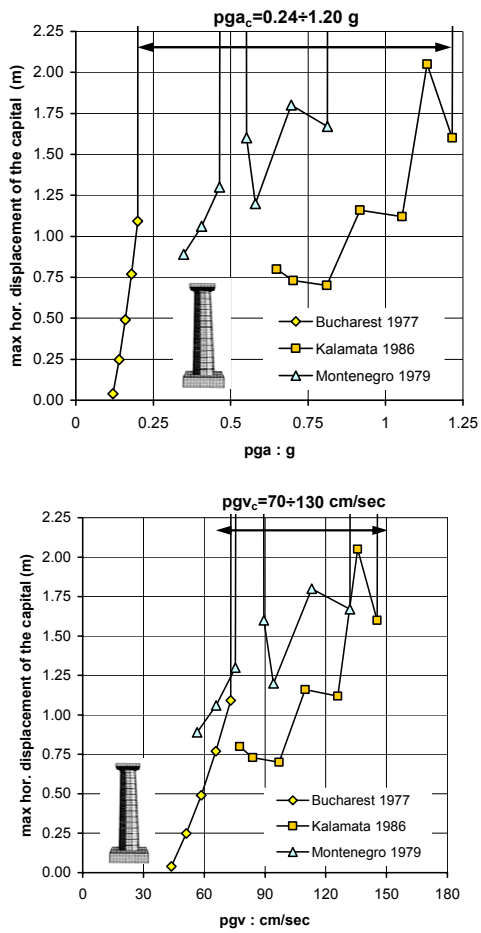


Figure 11. Maximum horizontal displacement registered at the top of a free standing column model versus pga and pgv of the scaled records.

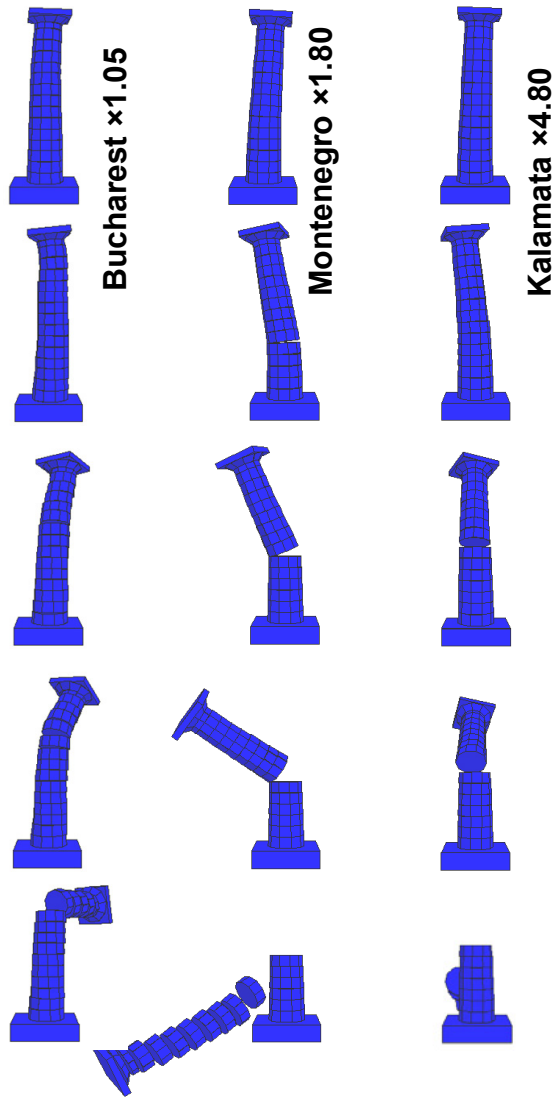


Figure 12.Rocking mode and overturning of a free standing column under the excitation of the three scaled records.

7. DISCUSSION AND CONCLUSIONS

On the basis of the analyses presented previously, it seems that free standing columns or the colonnades of the peristyle of the temple of Zeus at Olympia are significantly resistant to ordinary strong ground motions and they could have toppled only by a strong earthquake shaking containing an exceptionally high amplitude long period pulse(s). Such pulses have been recorded in the near field of large earthquakes (M>6.5) but it is unlikely to be inherent in the strong motion of smaller local earthquakes, like the ones associated with the relatively short length faults mapped in the vicinity of the Olympia site. Intermediate depth earthquakes occurring underneath the Peloponnese or thrust fault events occurring offshore the western coast of Peloponnese are possible and more likely sources of such strong ground motions.

The careful examination of the temple debris poses further questions than provide answers. In all the analyses presented here, when the columns topple more than four of the lower column drums remain in place and only the upper part of the column falls over. This mode of failure revealed by the analyses is clearly not in agreement with the location of the fallen drums found on site.

The radial arrangement of the fallen columns might suggest that either human action led the temple's final destruction, or that the preservation of the roof elements in their place when the

earthquake stroke, produced such a pattern of fallen debris. In figure 2 it can be observed that six of the columns of the southern flank were found overturned straight to the south, while five of the columns of the northern flank have been toppled to the North. Moreover, two of the columns of the western flank are found overturned to the west and one of the columns of the East flank to the east. Not a single column was found overturned towards the interior of the peristyle. It might be postulated that the superstructure elements and the temple roof might pushed the columns in an outward direction and is responsible for this radial arrangement of the fallen columns. But where are the superstructure elements? The cella wall blocks, as well as almost all of the frieze blocks, were never found on site, which means that either before or after the collapse of the temple the debris have been extensively robbed. A reasonable answer is that the blocks that were fit for second use were removed and used probably for other constructions and only the enormous cylindrical column drums, that was difficult to cut or move, were abandoned on site.

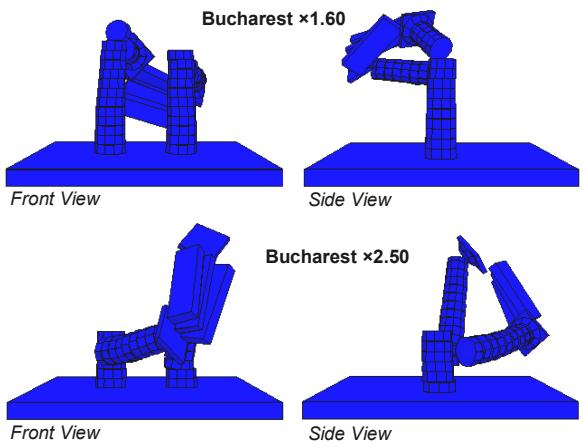


Figure 13. Snapshots of a two-column model subjected to the Bucharest (×1.6) record. The strongest component of the record is applied normal (left) and along (right) the axis of the colonnade

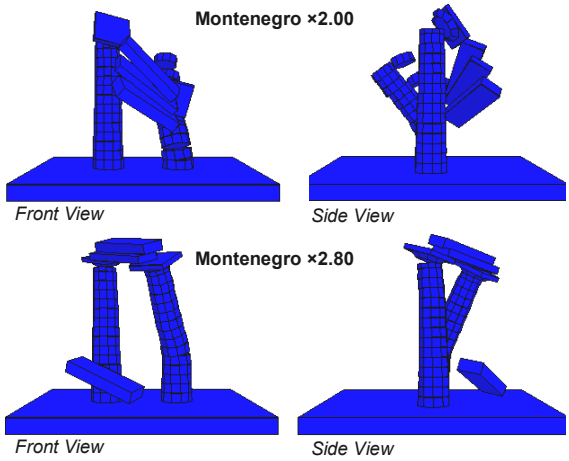


Figure 14. Snapshots of a two-column model subjected to the Bucharest (×1.6) record. The strongest component of the record is applied normal (left) and along (right) the axis of the colonnade.

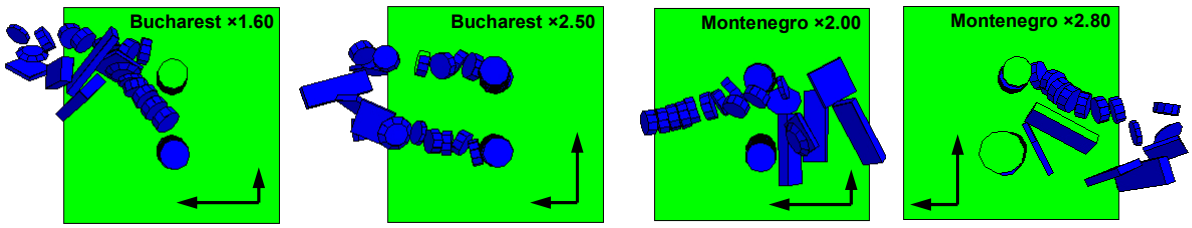


Figure 15. Final position of the collapsed columns for the Bucharest (left) and the Montenegro (right) records (from figures 13 and 14). The long arrow indicates the direction of the strongest component of the record

But if it is not an earthquake that destroyed the temple what were the means and the methods that were used during the early Byzantine period to demolish such structures? Prof. S.Miller, who describes the gradual demolition of the temple of Zeus at Nemea (Miller S. 1986), notices that a simple method to topple the slender (but massive) columns of this temple, was to undermine them either by removing the stylobate blocks or by breaking the bottom drum. A seriously undermined surviving column is a living proof of this practice, also referred as tree-felling technique. A lively description of the methods used for the destruction of ancient temples in the late 4th century A.D. is also provided by Theodoret in his "Ecclesiastical History" (see also Talloen and Vercauteren 2011) where he describes the destruction of the Temple of Zeus at Apamea in Syria by Cynegius, the praetorian prefect of emperor Theodosius I in the East. "An initial attempt was made to pull down the temple but the stone was so hard and the columns so massive, and held together with iron and clamps, that the prefect despaired of pulling them down. Praying for divine assistance, he was visited the next morning by a simple laborer, who suggested that the foundation of three of the columns be undermined and replaced by timber beams, to which he then set fire. When their support had vanished

the columns themselves fell down, and dragged the other twelve with them. The side of the temple which was connected with the columns was dragged down by the violence of their fall, and carried away with them".

By examining the fallen columns of the temple of Zeus, one can also observe that in 18 from the 34 columns of the peristyle the bottom drum (gray shaded in figure 2) was found in place, and that the crepidoma is also intact. Most drums of the fallen columns are also intact and hence we can safely conclude that the undermining technique was definitely not used in Olympia. The other method to overturn the columns is to pull them down by ropes and pack animals (figure 16). Given the size of the columns of the temple of Zeus at Olympia and their low aspect ratio it would be required a significant effort and resources for such an endeavor. Each column weights approximately 80 tons and with a slenderness ratio of 4.73 a horizontal force of 17 tons would be required under static conditions to overturn them. A single column would require at least 16 of the strongest horses and at least 10 strong oxes to apply such a force. The provision of the animals as well as the necessary ropes for such an operation would require a considerable preparation and organization.

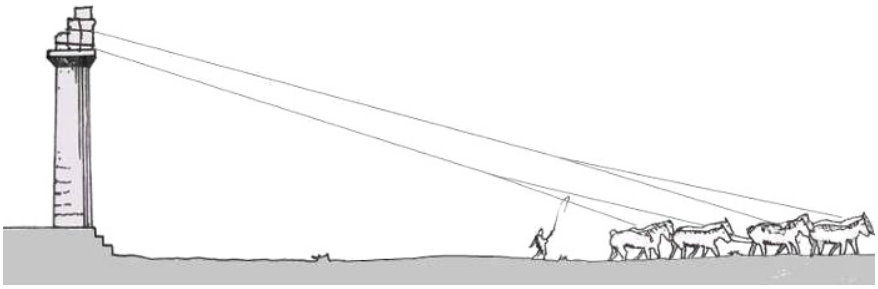


Figure 16. A possible method to pull down the columns using pack animals and ropes.

In conclusion, our analyses highlighted the resistance of columns with the size and proportions of those of the temple of Zeus at Olympia to earthquake shaking and their relative vulnerability to impulsive near fault motions. The toppled columns of the temple could be the imprint of strong motions similar to the Bucharest or the Montenegro records, while smaller earthquakes are unlikely to produce such long period-high velocity pulses able to topple the columns. However the domino like pattern of many columns as well as the radial pattern of some of the columns around the temple is more difficult to explain by considering simple one or two-column models. A more complete structure (with some roof elements) might end up in the ground in a similar manner, but such a model has not been investigated in the present stage of research.

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