Ambient vibration experiments at classical and neo-classical columns on the Acropolis and the Academy of Athens, Greece

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Abstract. The seismic history of the centre of Athens may be revealed through the response of its classical and neo-classical columns to ambient noise and earthquake shaking. Detailed ambient vibration surveys in two cases are presented: a) the two choragic columns on the south slope of the Acropolis, above the Monument of Thrasyllos, constructed in the late classical-early Hellenistic era (3rd–1st century B.C.), with an original design and a high constructive quality (13 April – 10 May 2011) b) the statue of Apollo (mid-19th century), on the right side of the Academy of Athens building prostyle, mounted on a column in the Ionian rhythm (5-13 March 2008). In the first (Acropolis) case, ambient noise measurements were performed with seven digital 3-component seismographs at the top and the base of each column, as well as at three nearby reference sites. In addition, forced vibration tests at the top of each column were also conducted. In the second (Academy) case, five instruments of the same type were installed at the base of the column, the base of the statue, with reference sites at the two corners of the Academy building and the garden at the back side of the building. For both cases, the response spectra and amplitude ratios were computed, providing information on the soil-column interaction, as well as the characteristic frequencies of spectral ratios peaks.

Keywords: Ambient vibrations; Columns; Statues; Dynamic Characteristics

1 INTRODUCTION

The vulnerability of historical monuments, such as free standing columns or column-statue systems, is assessed through the record of the past earthquakes they have been subjected to, taking into account that these events have not caused their collapse. In actual fact, a small percentage of such still earthquake witnesses from the classical period remain in the Eastern Mediterranean, due to its high seismicity level. At present, most of these columns or column-statue systems carry the scars of several earthquakes, depending on their age; earthquakes of the instrumental period (1900–today), a number of well documented and parameterized historical earthquakes of the period 1000AD-1899, and historical earthquakes of the period before 1000AD, not always sufficiently recorded in historical sources. In any event, these monuments have survived through a process of natural selection and they represent a small percentage of the total number of columns that existed in earlier times, either as examples of best final design and construction, or of extensive repair after earthquake damage which enhanced their earthquake resistance, or by chance (Ambraseys & Psycharis 2011).

In this paper we present the results of the dynamic characteristics study of two cases of historical monuments:

a. The two choragic marble columns at the southern slope of the Acropolis, above the choragic monument of Thrasyllos (Figure 1a,b) and the theatre of Dionysos, dating most probably between the end of the classical and the beginning of the Hellenistic period, with exceptionally high standards of structural design. Both columns carry triangle shape capitals of Corinthian style, which have acted in
the past as the base of choragic bronze tripods. Their total height (capital+column) is 10.27m for the eastern column and 8.79m for the western. In general, their condition has not changed for nearly 2,000 years, and this may be proven by the preservation of a considerable part of their authentic chromatic printing at the base of their capitals. However, both columns present damage due to bombardments, but also due to strong earthquake shaking, as displacement and rotation of their drums is observed. The 1981, Alkyonides (M<sub>W</sub>6.4) and 1999, Parnitha (M<sub>W</sub>5.9) damaging earthquakes which affected Athens, were found not to have caused any damage or sliding to these columns (Zambas 1982, 1989). The columns were erected on the Upper Cretaceous limestones of the Acropolis, overlying the Athenian schists, just above the choragic monument of Thrasyllos, which is in fact a natural cave inside the rock, with a marble facade.

b. The Pentelic marble column situated in the front right of the Academy of Athens, with the statue of Apollo mounted on it (Figure 1c), being 13.3m high including its capital. The Academy, as well as the columns in front, are founded on rock, i.e. the Athenian schist, above the maximum seasonable water table. The column was erected in 1874, and the statue of 4.1m height was mounted in 1882. Since then, the column/statue system experienced a number of strong earthquakes apparently with no damage. However, the Parnitha 1999 earthquake produced significant sliding and rotation of the statue base, which rests rather loosely on the column, through a system of four small iron pads coated with lead, inserted between the capital and the base of the statue to guarantee its proper leveling (Ambraseys, 2010a, Ambraseys & Psycharis, 2011).

*Figure 1. Top left:* The two classical columns at the slope of the Acropolis, founded on the Acropolis limestones (view from the west). *Top right:* The same columns (view from the south) above the cave of Thrasyllos monument. *Bottom left, right:* The neo-classical column and Apollo statue on the front right side of the Academy of Athens - Photos (Top left and right) by K. Zambas, (Bottom left and right) by N. Ambraseys.
1.1 Multidrum Columns and Column-Statue Systems Response to Ambient and forced vibration tests

Multidrum free-standing columns may be categorised as (a) classical columns that still exist in a state of tolerable preservation, (b) restored classical columns and (c) newly built columns. The response of multidrum columns, with or without a mounted statue, to earthquake strong motions is nonlinear, due to rocking and sliding. Their geometry and structural design strongly influence their dynamic behaviour. On the other hand, such structures behave linearly to ambient vibrations, since the amplitudes of these vibrations are small. In other words, a multidrum column will behave like a monolithic one to earthquake excitation, with characteristic frequencies of oscillation. The sources of such vibrations are different, spatially distributed, mostly unrelated and often continuous, natural or man-made; microtremors, microseisms, and various local random or periodic sources, such as metro vibrations, drilling, etc. Additionally, forced vibration tests on top of the structures are used to produce larger response amplitudes, leading to more prominent excitation of the modes of vibration, with different paths of waves propagating through the structure. The method is usually applied in structural health monitoring and retrofitting. Microtremors and microseisms have been extensively used to study the seismic waves amplification due to local geological or topographic conditions, where a structure is founded.

In ambient vibration tests, the instrumentation comprises of continuously and simultaneously operating seismometers, installed at the base, intermediate and top level of the structure, as well as at nearby reference sites for free field recordings, aiming at a relative comparison of the recorded amplitudes and frequency content, in order to separate the foundation rocking due to soil-structure interaction from the total recorded response. During these experiments, external noise sources and temperature variations are taken into account.

The produced spectral H/V ratios demonstrate a central frequency, which gives the fundamental period of the multidrum column or column/statue system. This, if not due to external sources, is attributed to the transfer function of local soil conditions.

2 CASE STUDIES

2.1 The Thrasyllos Columns at the Slope of the Acropolis

Due to the importance of the site, measurements of ambient vibrations were taken during a long period, for Acropolis standards, with all security measures taken. The experiment aimed at the assessment of the eigenfrequency of vibration and other response parameters, such as the free vibration (i.e. rocking) damping factor and the main directions of oscillation for the two studied columns. Natural ambient vibrations and forced vibrations at the top of both columns were recorded by a total number of 9 sensors (Figure 2) for the period 13 April to 10 May 2011; digital 3-component seismographs Reftek 72A, with Lennartz-3D of 1Hz eigenfrequency and Guralp CMG-40T of 60 sec eigenperiod seismometers.

2.2 The Column and Statue of Apollo in the Academy of Athens

Ambient vibrations were recorded by a network of digital 3-component seismographs Reftek 72A, with Guralp CMG-40T seismometers (Figure 3). The instruments operated continuously on 12-13 March 2008 for a maximum period of 21:25 hours, thus including heavy traffic and working hours, as well as reduced traffic activity at night. The sensors were installed at the base of the column, the base of the statue, at the two front corners of the Academy, in the basement and in open ground, in the
garden of the building (reference point). The existing scaffolding for the repairs to the column and the statue allowed the installation of the sensor at the top.

Figure 2. Top view of the two studied columns and locations of sensors. The picture on the right is a detail of the eastern column top view. – Photos by K. Zambas.

Figure 3. Left: The seismometer at the base of the statue of Apollo. Right: This base rotated and slid to a maximum of 4 cm due to the 1999 Parnitha earthquake – Photos: Left: by I. Kassaras, Right: by N. Ambraseys.

3 DATA ANALYSIS

In both experiments, the collected data were transferred to hard disks and archived, while the software SAC2000 was used for data reduction, signal correction and header assignment. Spectral amplitudes were calculated for the three ground motion parameters (acceleration, velocity, displacement). Finally, the data analysis was performed using the freely distributed GEOPSY software (Geophysical Signal Database for Noise Array Processing), developed in the framework of the European project SESAME (Site EffectS assessment using AMbient Excitations). This algorithm is a java application with a user friendly graphic environment for aplication of various techniques of seismic signal processing.
3.1 The Thrasyllos Columns

In Figure 4, an example of spectral analysis is presented, based on the technique of selecting different signal windows, depending on the STA/LTA ratio.

**Figure 4.** Spectral analysis using the technique of selecting different signal windows. **Left:** ambient vibration record in the N-S component at the capital of the eastern column of 30 min duration and the selected coloured windows of 20 sec duration each. **Right:** the Amplitude spectrum. The thick black line represents the mean value of individual spectra, corresponding to the selected signal windows (coloured lines). The dashed line shows the standard deviation.

The analysis resulted to the evaluation of the predominant frequency of oscillation for the two columns, as well as a secondary one. For the eastern column these frequencies were assigned at 1.3 Hz and 2.9 Hz and for the western at 1.2 Hz and 3.4 Hz, respectively.

Furthermore, during forced vibration tests at the top, both columns performed free vibration with damping. The damping factor was calculated in the two horizontal components (Figure 5), which was found at 2.6% (N-S) and 2.8% (E-W) of critical damping for the eastern column and 2.8% (N-S) and 3% (E-W) for the western.

**Figure 5.** Damping factor for forced vibration of the eastern column in the N-S direction
3.2 The Column and Statue of Apollo

The spectral amplitudes of ground motion parameters (acceleration, velocity, displacement) were calculated using the Fourier analysis procedure and the amplification frequencies and corresponding spectral amplitudes were assessed (Table 1).

H/V spectral ratios were determined for the site in open ground in the garden, in order to evaluate the response of the soil conditions and their possible interaction with the column-statue system. The amplification frequency $f_0=3.5$ Hz ($T_0=0.29$ s) showed that no soil-column interaction takes place, as the corresponding frequency was not observed in the spectra at the top or the base of the column. Therefore, the fundamental period of the column-statue system is $T_0 \approx 30$ s. In addition, the spectral ratios between the top and base of the column were also calculated (Table 1, Figure 6), for the determination of the transfer function of the column. The transfer functions of the column present a peak in the vertical and E-W component at $\sim 1.95$ Hz (0.51 s). Its response in the N-S component is at $\sim 2$ Hz (0.5 s). The observed deviation between the two horizontal components is attributed to the unsymmetrical dimensions of the Apollo statue.

![Figure 6. Spectral ratios at the column (top/bottom) in the N-S component](image)
Table 1. Response frequencies and maximum spectral ratios ($A_0$) (top/base) of the column

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Figure 7. Left: Response spectra of the column-statue system during the night. Components N-S and Z present peaks at 1.5, 1.9 and 2.7 Hz, E-W at 2 Hz. Right: To-scale response spectra of the column-statue system during the entire measurements period (black: Z, green: E-W, red: N-S).

CONCLUSIONS

The purpose of the study is to contribute to the seismic vulnerability assessment of the free standing columns above the Thrasyllos monument at the Acropolis of Athens and the free standing column and statue of the Academy of Athens building, through measurements and analysis for the estimation of their natural periods. The columns studied in this paper present different characteristics, as far as the age, height, construction, state of preservation and foundation materials are concerned. The fundamental periods calculated were found to be around the value of $T_0 \approx 0.3$ s, which are compatible with the properties of the near-surface Athenian limestone, obtained using geophysical methods, which is present at both observation sites.
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