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ESTIMATION OF SEISMIC RESPONSE OF HISTORICAL AND MONUMENTAL SITES USING MICROTREMORS: A CASE STUDY IN THE ANCIENT APTERA, CHANIA, (GREECE)

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ABSTRACT

Main purpose of the present study is to investigate the dynamic characteristics of the remainings at the ancient city of Aptera (Chania) and identify the main damage mechanism, in order to evaluate the risk of structure damage or collapse in case of future events using microtremor recordings.

Our study focuses on the application of HVSR method (Horizontal to Vertical Spectral Ratio) to microtremor measurements carried out in specific sites.

Registrations have been performed by means of a tridirectional sensor Lennartz 3D-Lite (1 natural Hz frequency), connected with a 24-bit digital acquisition unit. A set of 10 time series of 800 second each, sampled at 125 Hz was recorded in several sites. The selected time windows of each time series were corrected for the base line and for anomalous trends, tapered with a cosine function to the first and last 5% of the signal, and band pass filtered from 0.5 to 20 Hz with cut off frequencies at 0.3 and 22 Hz. The same procedure performed for all sites and components and finally the H/V spectral ratios were computed. Most of the sites present significant amplification peaks in frequency around 2 Hz.

Finally, electrical resistivity tomography was carried out. The extracted results clearly show a very complex subsurface geometry indicated by the presence of large-scale voids, which may possibly correspond to ancient reservoirs.

In the present work we confirm that the archaeological site of Aptera in Chania consists of a very complex subsurface structure and that the results obtained by HVSR method and by resistivity method are very well correlated.

1 INTRODUCTION

Preservation of historical and monumental buildings all around the world and decreasing their risk against earthquakes is a matter of great importance. To this end, concerning monumental heritage, its architectural value and uniqueness calls for a detailed vulnerability assessment. Greece is seismically very active and has large number of monuments, important part of our cultural heritage, which could be affected by strong earthquakes. It is well known that damage caused by earthquakes strongly depend on the dynamic characteristics of structures as well as on the site amplification of seismic waves. As a result an investigation on their seismic response should be conducted before any repair or reinforcement.

Since historical monuments are not suitable for sophisticated analysis and laboratory testing and all works should be carried out directly on the buildings, the appropriate method should be selected very carefully. Considering this, the microtremor method is applied, which additionally among other time consuming and expensive approaches is the easiest and cheapest way to understand the structural behavior without causing any harm to the structure. In a short period of time it provides the necessary information about predominant frequencies, amplification factors (vulnerable points and modal shapes) and vibration characteristics of structures at different frequencies. Moreover, estimation of the characteristics of surface layers is done since microtremor spectral characteristics are associated with local geological structure, especially with the density and thickness of surface layers (Nakamura 1989, 1996, 1997, 2000, Nakamura et al., 1995, Mucciarelli et al., 2001, Diagourtas et al., 2001).

1.1 Basic theoretical aspects

It has, in general, been observed, that damage associated with the occurrence of earth tremors is the result, not only of the magnitude of the earthquake and its epicentral distance, but also of local site effects caused by the topography and geology of the site. These local effects are frequency dependent. The reaction of the local geological conditions to the incoming seismic energy is known as the “site response”.

During the last 30 years, various techniques have been studied to assess site effects: numerical models, the standard spectral ratio method and the H/V spectral ratios method. The last one, initially proposed by Nogoshi and Igarashi (1971), and updated by Nakamura (1989, 2000), uses one single station. It is very quick to implement and at a low cost. Its principle consists in recording the ambient vibrations of the ground during a period of time and in calculating the spectral ratio of the horizontal component over the vertical component. As shown by numerous authors the resulting curve generally shows a peak at the resonance frequency of the site.

Nogoshi and Igarashi (1971) showed the relationship of the H/V spectral ratio to the ellipticity curve of Rayleigh wave, and took advantage of the coincidence between the lowest frequency maximum of this curve with the fundamental resonance frequency, to use it as an indicator of the underground structure (Bard, 1998). The interpretation is based on the assumption that noise predominantly consists of surface waves.

This technique has been updated by Nakamura (1989, 2000). Its assumptions are in contradiction with the preceding arguments. In short, he considers that noise is composed of body waves and surface waves among which are Rayleigh waves. These ones alter the information brought by the reflected SH waves, which are, according to him, predominant to explain the presence of the resonance peak. In this sense, the spectral division is designed to get rid of the effects of Rayleigh waves in the horizontal components. In this way the resulting H/V spectral ratio highlights the resonance frequency of the sites and their corresponding level of amplification as well.

For sake of brevity, we will not report here a detailed discussion on the method. Bard (1998) and Mucciarelli et al. (2001) report critical reviews. Main purpose of the present study is to investigate the dynamic characteristics of the remainings at the ancient city of Aptera (Chania) and identify the main damage mechanism, in order to evaluate the risk of structure damage or collapse in case of future events using microtremor recordings (i.e. low-amplitude oscillations of ground surface produced by natural sources or by anthropogenic noise). It is worthwhile to notice that there is no previous seismic study carried out in the area.

2 DESCRIPTION OF THE STUDY AREA

The area investigated (ancient Aptera) is located in the north-western part of Crete Island, Greece, 15 Km from the city of Chania, near the village Megala Horafia on a hill above the bay of Souda (230m). Figure 1 gives the geological setting of Crete.

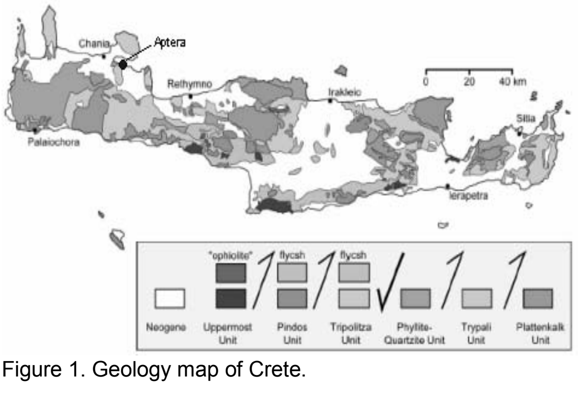


Figure 1. Geology map of Crete.

Founded in the 7th century BC, Aptera was one of the largest and most important city states in Western Crete. It continued to be an important city during the Roman and first Byzantine periods and was continuously inhabited until an earthquake destroyed it in the 7th century AD. The description of this destructive earthquake reported in the historical data suggests the existence of site effects in the area. In the historical period the town was fortified with a wall, which is still visible in many places. Above the fortified acropolis are the ruins of huge vaulted cisterns and other public constructions of the Roman and Early Byzantine periods. A small two-aisled Hellenistic temple has been excavated and part of the Roman Bouleuterion.

Furthermore, there is no detailed geological survey available for the area. It is reported that the territory of Aptera consists of many faults. From the preliminary geological survey, it is concluded that the area of Aptera is characterized by limestones (Tripolis zone, Triassic-Cretaceous). These limestones are compact, white-grey to bluish, microcrystalline to aphanitic usually with rudist fragments, sometimes breccias, at places dolomitizited, strongly karstified. They may include lower members of Jurassic to Triassic age.

3 MICROTREMOR MEASUREMENTS AND ANALYSIS

Detailed microtremor measurements were performed at selected sites in the area of ancient Aptera (Chania-Crete). Their distribution is as homogeneous as possible over the whole area. By taking records both in ground and structures, analyzing and interpreting them, vulnerability specifications can be made. The sites where microtremor measurements recorded are presented in figure 12.

3.1 Microtremor Measurements

Registrations have been performed by means of a tridirectional sensor Lennartz 3D-Lite (1 natural Hz frequency), connected with a 24-bit digital acquisition unit. The sensor has identical characteristics on all three axes; thus working on ratios it is possible to consider a reasonable range below the fundamental frequency, as demonstrated in Giampiccolo *et al.* [2001]. Important care was taken to avoid problems that may arise during in situ measurements such as asphalt coverings that may induce spurious peak of noticeable amplitude, environmental factors and anthropogenic transient noise.

3.2 Data Analysis

At each locality, site responses have been computed by collecting six to twenty-five microtremor registrations, each lasting 60 s, sampled at 125 Hz. The selected time windows of each time series were corrected for the base line and for anomalous trends, tapered with a cosine function to the first and last 5% of the signal, and band bass filtered from 0.5 to 20 Hz with cut off frequencies at 0.3 and 22 Hz, selected in order to preserve energy and avoid spurious maxima due to unrealistic low vertical spectra (Castro et al., 1990). The arithmetic average of all horizontal-to-vertical ratios represents the HVSR site amplification function. The same procedure performed for all sites and components and finally the H/V spectra were computed. Details and limits about the methodology are given in Mucciarelli (1998).

3.3 Results

HVSR of ground level in the Bipartite Temple (site 3) is given in figure 2. It can be followed that the fundamental frequency is 1.93 Hz and the amplification is A=2.5±0.4. In the North-East direction at about 3 m far there was another measurement, whose HVSR resulted in a peak frequency around 2.18 Hz. The amplification of the fundamental frequency is A=2.1±0.3 (see figure3).
Then, in the same N-E direction and in a distance less than 10 m there was another measurement at the Doric Temple (site 7). As shown in figure 4 the transfer function has two dominant peaks, the first one at 12.2 Hz and the second one at 5.84 Hz.

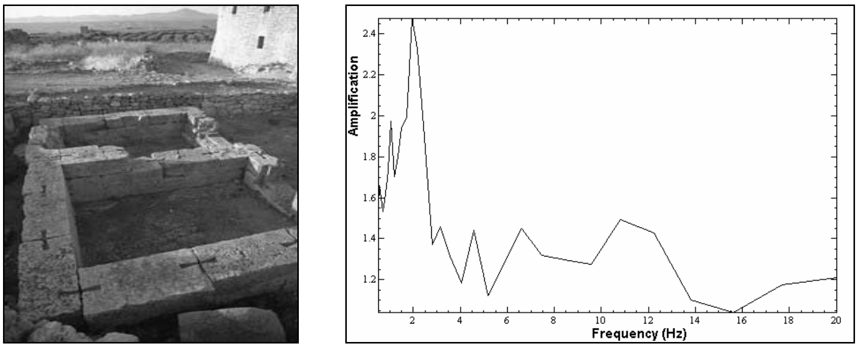


Figure 2. HVSR curve at Bipartite Temple (site 3 on the map).

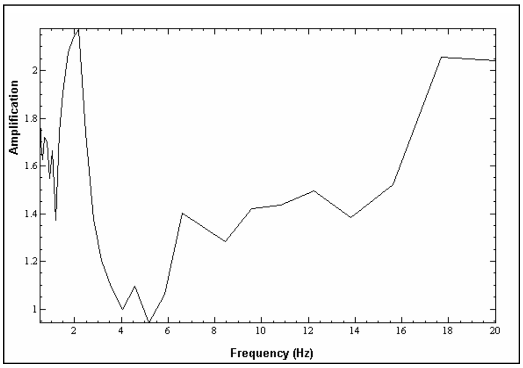


Figure 3. HVSR curves at about 3m away from the Bipartite Temple.

Comparing the HVSR curve derived from the site near the Bipartite Temple in the N-E dimension (figure 3) and the HVSR curve derived from the Bipartite Temple (figure 2), is observed: (i) a minor shift of the fundamental frequency towards lower values (from 2.18 to 1.93Hz) and (ii) a decrease of the spectral amplification, especially in the high-frequency range (at the high frequency 17.6Hz the amplification decreases from 2±0.2 to 1.1±0.1).

Microtremor measurement has been performed at the Doric Temple, which lies at about less than 13m away from the Bipartite Temple (figure 4). The HVSR technique at the Doric Temple indicates two sharp peaks. The amplification in the frequency of 12.2Hz is 3.3. A second amplified frequency is observed at 5.8Hz with amplification 2. By comparing the spectral shape of HVSR curves (figures 2,3 and 4) it is obvious that a high variation exists. This high variation possibly reflects to a very complex subsurface geometry and to large-scale heterogeneities. In order to verify the validity of the above observations (complex subsurface geometry, large-scale heterogeneities) resulted from HVSR curves electrical resistivity tomography has also been performed at this specific area.

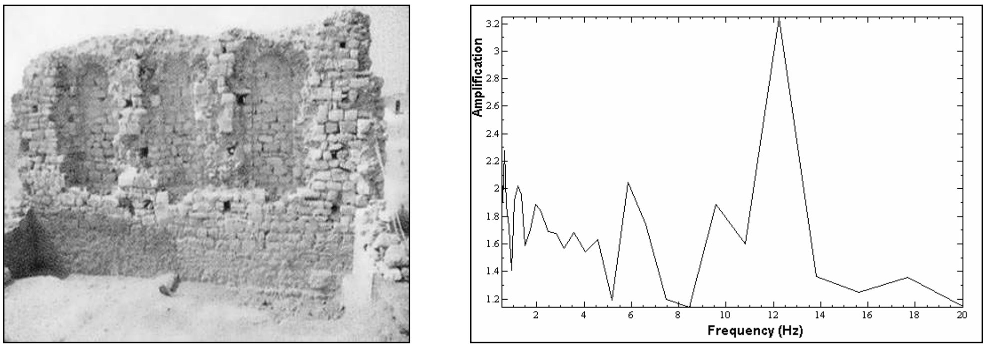


Figure 4. HVSR at site 7 (Doric Temple), at about less than 13 m away from site 3.

The HVSR technique using microtremor measurements has also been performed to identify the building fundamental frequencies of oscillations and to examine the possible coincidence of foundation soil frequency and building frequency (see Mucciarelli et al., 2001). The specific construction typologies as well as the structural properties of Monastery of St. John the Baptist (frames, infill frames, straining beams, bearing walls, building stiffness, mass distribution, e.t.c) were not available. Since no construction technologies were available the estimation of the dynamic seismic response of the Monastery cannot have the complexity and the richness of information of a detailed study. However, the main result expected by the HVSR technique is the determination of the fundamental frequency of the investigated building and of its foundation soil, to put in evidence resonance phenomena capable of compromising the building stability during an earthquake. In such a way HVSR technique represents a preliminary evaluation of St. John the Baptist Monastery's seismic stability. Microtremor measurements have been performed at the soil foundation, on the veranda (points 1,4,7) and at different points of the first floor of the building (points 2,5,8).

The dynamic characteristics of the Monastery of St. John the Baptist result as follows:

1. Predominant frequency and amplification factor of the ground level are respectively 1.93 Hz and 1.9 ±0.3.
2. On the veranda, along a longitudinal transect from the northern to the southern part along the first floor (points 1, 4, 7) the value of fundamental frequency is 7.5 Hz and the corresponding amplification levels are 13, 4.3, 5.8, respectively. Point 1 corresponds to the northern part, point 4 in the central part and point 7 to the southern part of the veranda. It is interesting to notice the existence of a stairway at the southern part of the veranda (point 7,figure 5).
3. Inside the building, along a longitudinal transect from the northern (point 2) to the southern part (point 8), the spectral ratios exhibit a resonant peak at about 7.5 Hz and the amplification factor lies between the values 2.4 and 3.6. It can been seen that at the southern side (point 8) the amplification ratio has the main fundamental peak at 7.5Hz, at the northern side (point 2) at 11Hz, and in the central part (point 5) of the whole structure of the Monastrery the fundamental frequency has the same value as the southern, 7.5Hz. The amplification values at points 8,2 and 5 are 3.6, 2.5, and 2.4 respectively. Microtremor measurements at points 8,2 performed at the same distant from the south and north side of the building.

We note that the HVSR curves suggest that the resonance frequency of the building does not coincidence with the fundamental frequency of the soil foundation. The result extracted from HVSR technique is that the monastery of John the Baptist does not resonate at periods near the period of the soil resonance, which implies that it may not be susceptible to failure during strong ground motion. In the longitudinal transect the northern part of the Monastery (point 2 in figure 5) presents different main period to the southern part (point 8 in figure 5). Consequently, we can speculate that the dynamic behaviour of the southern side is not similar to the northern. Moreover, comparing the HVSR curves derived from the Monastery soil foundation (point 9 in figure 5) with the HVSR curves at the first floor (points 2, 5, 8) it is important to notice that the amplification level increases with height. A similar result is observed by Gallipoli et al., 2004.

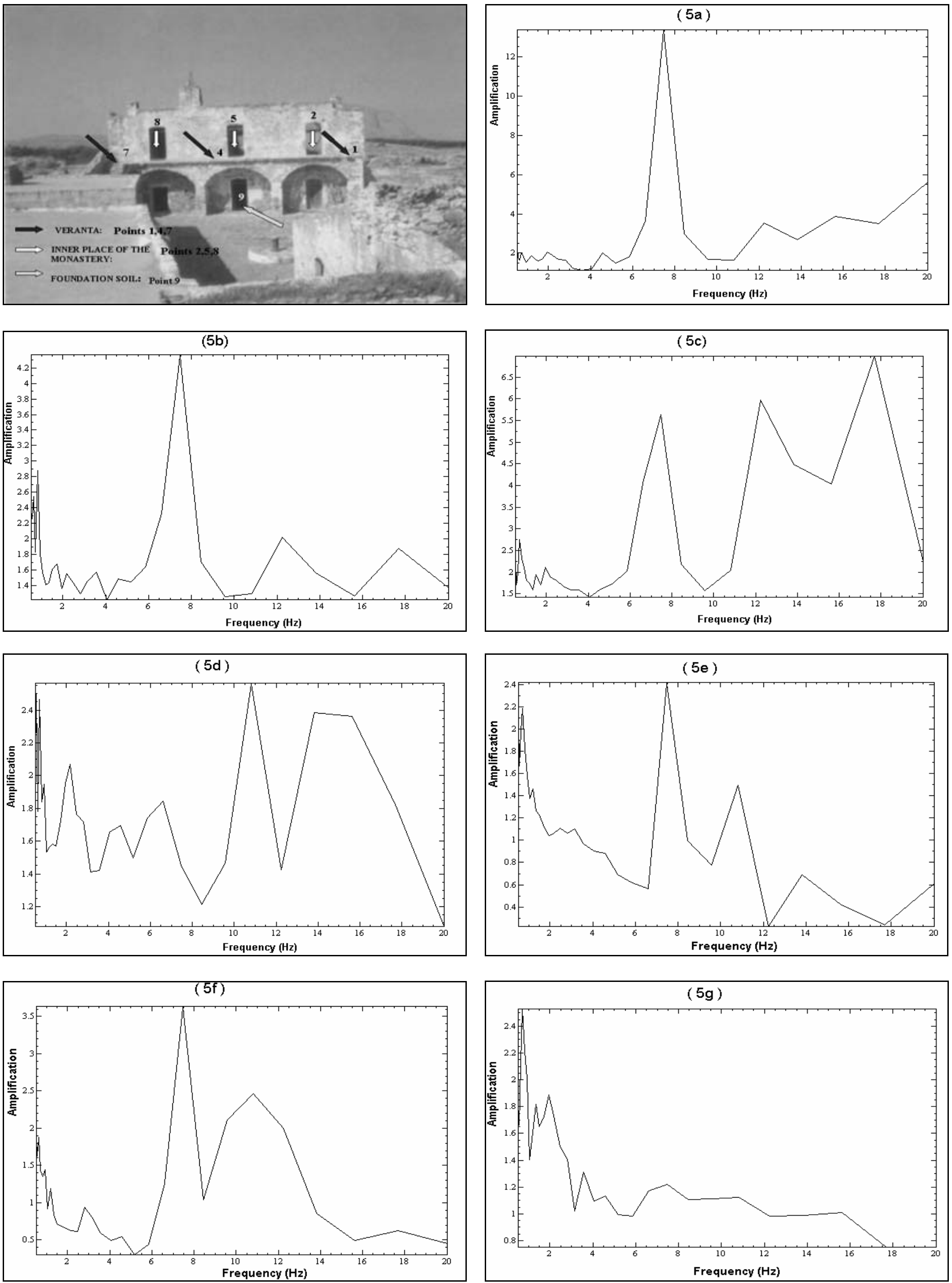


Figure 5. Location of measurements at soil foundation and at the 1st floor (veranda and inner place) (Monastery St. John the Baptist). HVSR results for each measurement. (5a) In the north part of the veranta (point 1), (5b) on the center (point 4), (5c) In the south part of the veranta (point 7), (5d) In the north part of the inner place (point 2), (5e) In the central part of the inner place (point 5), (5f) In the south part of the inner place (point 8), (5g) HVSR curve at the foundation soil.

Figures 7 and 8 demonstrate the HVSR in the Byzantine Buildings and Roman Bath. The distant between these two sites is 15m. We can observe a similarity between these two HVSR curves, not only in terms of the fundamental frequency and amplification, but also in the whole shape. Both spectra show a well-defined peak at 1.93 Hz and the amplification level is also the same. As it is seen from the figures 7,8 the amplification at the Byzantine Building is 2.4 ± 0.4 and at Roman Bath is 2.4±0.3. This cultural terrain is not characterised by a complex subsurface geometry and lateral discontinuities, in contrasts to the Doric Temple.

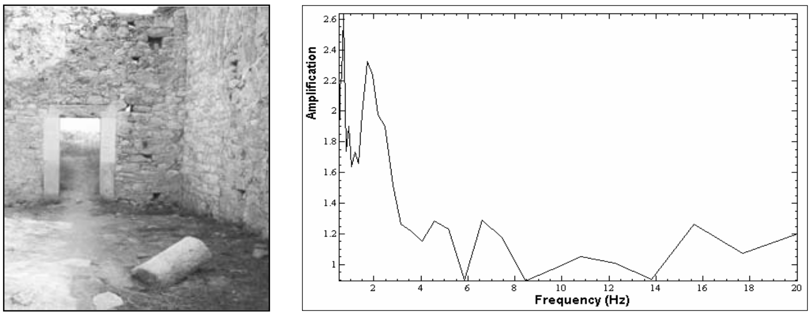


Figure 7. HVSR at site 9 (Byzantine Building).

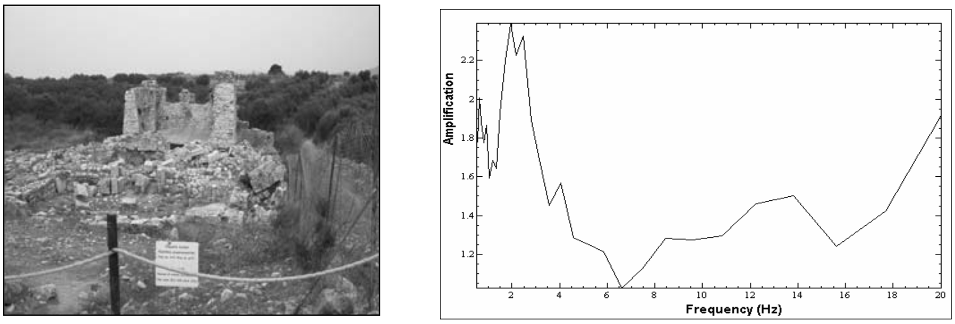
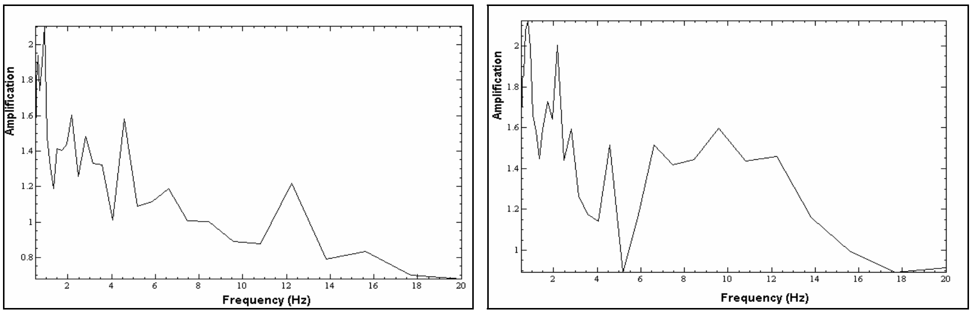


Figure 8. HVSR at site 9 (Roman Bath).

We proceed to the estimation of site amplification close to Roman Reservoirs (see fig. Three arched vaults (figure 9) enclose a huge cistern that held water to feed the Roman baths that cover the site. One can enter the cistern system through a small doorway to view the central chambers. We had three measurements, one for each chamber. All spectral ratios exhibit the resonant peak at 2.18 Hz. The amplification level for the central chamber is 1.8±0.2 and for the two neighboring 1.7±0.2.



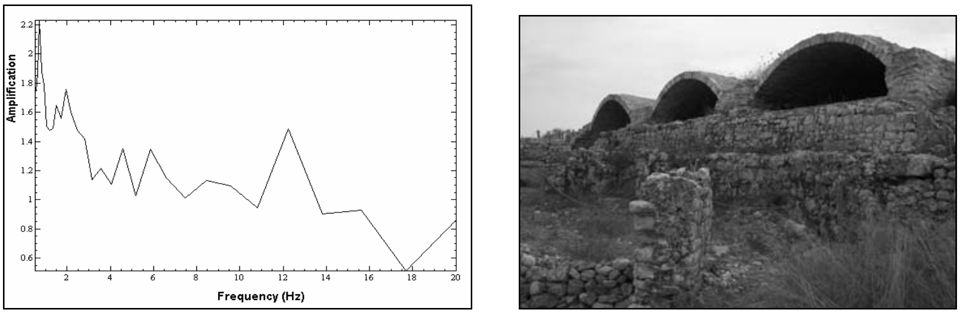


Figure 9. HVSR inside to Roman Reservoirs.

Below Aptera there is a Turkish fortress built in 1872 called Itzendin, once a prison. Figure 10 shows the location of five microtremor measurements, one out of the fortress, two inside it and two more in the arches, as well as the HVSR's in each site. The dynamic characteristics of the place result as follows:

1. Predominant frequency and amplification factor outside the castle are respectively f=2.18 Hz and the amplification level is 2.5±0.5.
2. In the 1st arch we observe two amplified frequency peaks 1.33 and 12.2 Hz. The amplification of the first amplified frequency is 2.1±0.5 and the amplification of the second amplified frequency is 1.6±0.1. In the 2nd arch in the vicinity of the 1st arc) the predominant frequency is 2.18 Hz and the amplification of the fundamental frequency is 1.9±0.3 (figure 10).
3. In the interior space of the castle the spectral ratios exhibit again two resonant peaks one at 3.16Hz and the second at 12.22 Hz. The amplification of the fundamental frequency (3.16 Hz) is 1.7±0.5, while the amplification of the second amplified frequency (12.2Hz) is 1.4±0.2. In 3 m distance the analysis of microtremor measurement resulted in two peaks 1.18 and 12.22 Hz. The amplification of the fundamental frequency (1.18Hz) is 2.2±0.5 and the amplification of the second amplified frequency is 1.9 ±0.3.

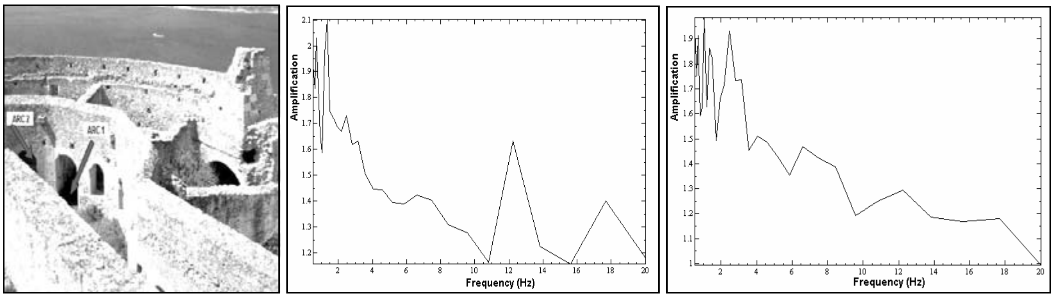


Figure 10. HVSR curves at the arches of Itzendin Fortress.

4 APPLIED GEOPHYSICAL INVESTIGATION: ELECTRICAL RESISTIVITY TOMOGRAPHY

Finally, in order to have a first hint about the presence of lateral variations in the sub-soil structure and verify the validity of HVSR method electrical resistivity tomography was carried out in those sites where apparently similar geological conditions produce significantly different HVSR's. This geophysical investigation will provide information in order to establish the relation between the local geological structures and the observed amplification effects in the aforementioned sites.

The survey was performed along the axis of the undefined anomaly of the subsoil (Doric Temple). The instrument used was an IRIS multi-electrode system (48 channels), and the data were processed using RES2INV. The inter-electrode spacing was 4 m and the total length was 188 m.

Results extracted from electrical tomography (figure 11) clearly show a very complex subsurface geometry indicated by the presence of large-scale voids, which may possibly correspond to ancient reservoirs. More concretely, we were able to identify two geophysically heterogeneous structures within the same geological unit (inside the limestones) through the determination of different values of resistivity. Lateral variations of resistivity and a void 16 m width appear at about 10 m depth and a second one 12 m width at 8.5 m depth. The distance between these two voids is about 30 m, whereas the depth to bedrock is not known. According to historical data there are a lot of underground cisterns in the area, which could induce strong amplifications.

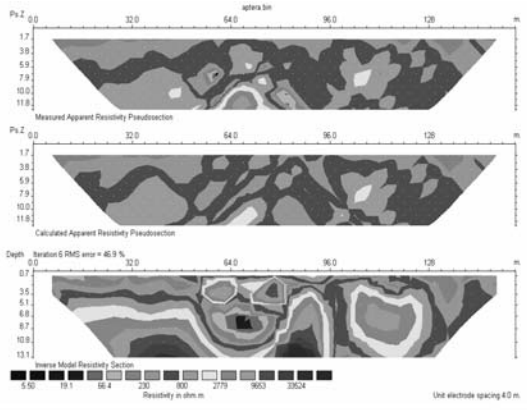


Figure 11. Electrical resistivity tomography

5 DISCUSSION AND CONCLUSIONS

This study focused on a mapping of site response functions using microtremor recordings. The HVSR technique, using microtremor recordings, is used to empirically estimate the site response functions in 8 selected sites in the archaeological site of Aptera. The microtremor measurements yield a series of parameters that can be used to estimate the expected ground motion during an earthquake. The key elements for seismic hazard scenarios are maps of the predominant frequency and maximum relative amplification of ground motion. The frequency of each peak is related to the thickness and velocity of seismic waves of the surface layers. The amplitude of each peak is related mainly to the impedance contrast between the near surface structure and the underlying bedrock. From HVSR curves it is obvious that most of the sites exhibit significant amplification in the frequency range of 1.93-2.18 Hz except of the Doric Temple and Itzendin Fortress, where reliable amplification peaks are observed at high frequencies (12.2 Hz). We propose a preliminary map (figure 12), created on the basis of measurement data, which shows the fundamental frequency across the area and reflects the fundamental characteristics of possible site effects.

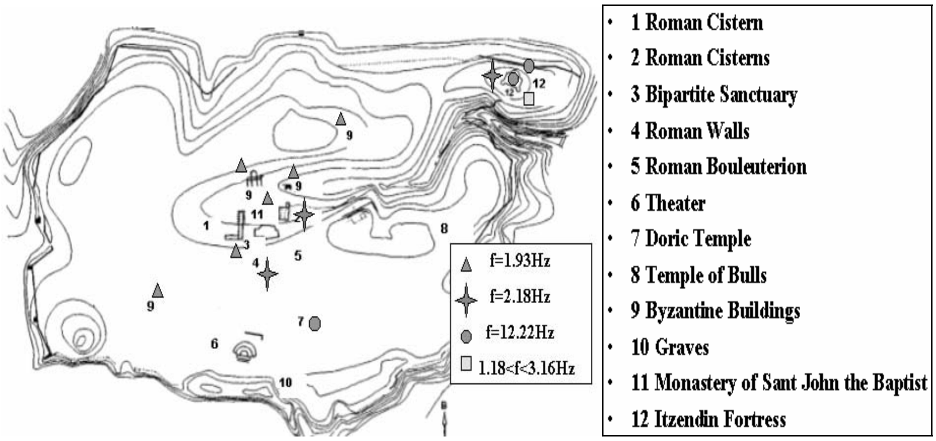


Figure 12. Locations of sites where microtremor measurements were performed and distribution of the fundamental frequency for ancient Aptera estimated from HVSR.

We observe that similar geological conditions produce significantly different spectral shapes. The general behavior of the amplitude response with frequency is not stable but shows a high lateral variation. That possibly suggests the presence of a very complex subsurface geometry, small-scale heterogeneities and possible variation in the thickness of the near-surface layers that probably smooth the amplification curves in such a way that the determination of specific resonance modes becomes very difficult. Thus, we strongly recommend a denser grid of site measurements and additional geophysical investigation. In order to verify the results obtained from HVSR curves a resistivity survey was therefore made on a sector of Doric Temple. Results extracted from electrical tomography clearly show a very complex subsurface geometry indicated by the presence of large-scale voids. We infer that the results obtained from the HVSR technique are very well correlated with the results extracted from the resistivity tomography.

From the results, microtremor method is proved to be a useful tool for this type of preparatory study in highly seismic active areas, since it gives easily and in short time all the needed information for preliminary damage estimation. In regions of unknown basement morphology, such a procedure may be a way to quickly obtain a general idea of the subsurface structure.

Acknowledgements

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