ABSTRACT

Historical buildings are important structures and their preservation and restoration is a vital issue worldwide. A crucial step before interventions is the definition of potential hazards and the monument’s vulnerability estimation. The Kapnikarea chapel is one of the most important and popular Byzantine monuments in Athens and dates back to the 11th century. In 1994, construction of the Athens underground Metro system began, with the tunnels passing underneath Kapnikarea foundations. During excavations, sounds of the approaching underground activities (heavy drilling and hydraulic hammer equipment) were heard in the interior of the chapel, and several failures were observed inside the church. Additional reasons reduced the structure’s rigidity are deterioration in time and past severe earthquakes. Towards the restoration planning of the monument, the University of Athens together with the Hellenic Ministry of Culture and Tourism, assigned to our research group the task to investigate the fundamental frequencies of the monument and of its soil foundation in order to determine resonance phenomena capable of compromising building stability during an earthquake. For this purpose, we conducted a microtremor survey. Ambient noise measurements were taken for 87 points located both on the ground and the chapel. Using the HVSR technique we determined the response of the ground, the monument’s predominant frequency and the spatial variations of the peak frequencies on the monument. Based on the experimental observations we discuss the possibility that differentiations are due to the structural members’ particularity and/or health.
It is well known that the vulnerability of a building strongly depends on its dynamic characteristics. As a result, an investigation of their seismic response should be conducted before any restoration action. The H/V Spectral Ratio (HVSR) technique [6] is typically used for the experimental vulnerability investigation of ground and structures since it can delineate the predominant frequency and the amplification characteristics of both. Recently, the microtremor HVSR method has become a popular approach mainly because of low cost and limited equipment requirements. Microtremor, or ambient noise, exists anywhere and its measurement can be conducted relatively fast. Furthermore, since no artificial vibration sources are required, there is no possibility to damage the investigated objects. It is consequently a useful method which can be applied for the investigation of structures of inestimable value, like the monuments of cultural heritage.

Ambient noise HVSR method has been successfully applied worldwide for the vulnerability estimation of a variety of cultural heritage structures [2, 5, 7 and 8]. The motivation of the present study is to investigate the dynamic characteristics of the Kapnikarea church, a monument of Byzantine architecture, located in the historic centre of Athens (figure 1). The region in which the church of Kapnikarea is built, is one of the most popular sightseeing sites in Athens, attracting thousands of visitors every year. It is an architecturally complex monument, composed by the original church, as well as some secondary structures which were added at latter times to enlarge the building. Kapnikarea belongs to the cross-in-square, four-column type, that was created and widely used during the Middle Byzantine period [1]. Stylistic analysis reveals that it was built at the middle of 11th c. and in particular between the years of 1050 and 1075 (construction phase I). According to legend, it was built over an ancient Greek pagan temple dedicated to the worship of a female goddess, possibly Athena or Demeter, or on the ruins of another Early Byzantine church, which was erected by the Empress Eudokia (AD 460). The presence of a well in its interior is a probable witness of some earlier building. Additional parts were constructed during the 12th century (construction phase II). A domed chapel was added to the north side and a portico to the western one. Interventions to the chapel were made between the years 1931–1986, which may be defined as the post-construction period (phase III).

Figure 1: The Kapnikarea chapel in the center of Athens

Nowadays the church belongs to the University of Athens for the practice of the students of Theology. Recently, serious concern arose about the stability of the church, threatened perhaps by the construction and operation of the new Athens Metropolitan subway, the construction of which
started in April 1994. The section Monastiraki – Syntagma of line 3, passing beneath Kapnikarea, was one of the most difficult parts of the project. The extended archaeological surveys delayed the beginning and the completion of the work. The existence of important buildings above, led to the improvement of the initial drilling method. It must also be noted that the earthquake of 1999 provoked hair line cracks on the keys of the domes. In April 2003, the trains started running in this section. The subway crosses Kapnikarea along an E–W direction at about 17m of depth. The geological conditions (figure 2) beneath the chapel from surface to the tunnel top are alluvium, low resistance Metasandstones/Metasiltstones, medium resistance Metasandstones/Metasiltstones [3].

![Soil Profile beneath Kapnikarea](image)

**Figure 2**: Soil Profile beneath Kapnikarea [3].

During the tunnel construction, sounds of the approaching underground activities (heavy drilling and hydraulic hammer equipment) were heard in its interior when the cap of the well was removed and various small scale masonry fractures and failures were observed [N. Stratigeas, personal communication]. Although the deformations measured on the church by the Metro Operation Company were within the limits predicted by the design, there were suspicions that the construction of the tunnel decreased the stability of the sensitive structure, which is furthermore affected by the metro operation. A small scale microtremor survey which our research group conducted in 2003 showed an impact to ground and structure velocity of the order 30% at almost all peak frequencies during the metro operational hours (figure 3).

In order to assist in the planning of forthcoming restoration interventions the University of Athens, assigned to our research group the task of studying in detail the dynamic and other characteristics of Kapnikarea, such as the predominant frequency the church vibrates at and where is the centre and direction of this movement and to detect possible hidden damaged parts. For this purpose we performed dense microtremor measurements, applied spectral analysis and the HVSR method (or QTS, Quasi-Transfer Spectra). In this paper we present preliminary results of the implemented analysis.
**EXPERIMENTAL**

**Description of the survey**

The field survey took place between 12 and 20 November 2009. The acquisition equipment comprises of four 24-bits 3 channel digital data-loggers of REFTEK-72a type, connected to 3 component Lennartz sensors of 1Hz natural frequency, GPS for timing and a palm PC (figure 4). Microtremor measurements were carried out at several selected points on the ground, the monument windows and roof (figure 5). In order to reach the roof of the temple and install sensors, a mobile scaffolding was installed by the Hellenic Ministry of Culture and Tourism. To overcome the roof inclination and to level the sensors as required solid gypsum bases of 15x15cm dimensions were constructed (figure 5). Digital recordings were made with a sampling rate of 125 samples per second for each data channel. During the microtremor measurements the church remained closed to visitors in order to avoid human noise effects. Typically, record lengths were 1200 s. However, the duration of measurements depended on the site noise levels and conditions. Measurements were repeated in case of unstable results.

**Figure 3:** Temporal distribution of seismic velocity on structure (left) and ground (right) during an experiment we conducted in 2003. Seismic velocity appears systematically higher during the metro operation hours (05:00-24:00).

**Figure 4:** The acquisition equipment used in the experiment.
Microtremor measurements were performed simultaneously in the vertical direction at 3 or 4 levels, ground (yard and interior), windows, roof and domes, in order to obtain common noise conditions, which would be efficiently removed when applying ratios between levels. A total of 87 measurements were performed by our research group for ground and structure (Figure 6). The collected data were downloaded from the instruments and archived onto hard disk storage media in SEGY format. Then they were converted to SAC files using the PASSCAL libraries. Finally, using the SAC2000 algorithm [9], all necessary header information was set up for further processing.

Figure 5: Examples of sensor installations (left) on the roof (right) in the interior of the temple.

Figure 6: Locations of the measurement points: a) on the ground b) on the windows c) on the southern face d) on the northern face e) on the western face f) on the eastern face.
Figure 7: Examples of HVSR curves obtained for 4 points Top: on the floor of the chapel. Bottom: on the main dome. Thin colour lines are HVSR curves for each selected window. Thick black line is the average HVSR curve. Dashed black lines indicate standard deviation of the average HVSR curve. Grey vertical bars show the predominant H/V peak. The width of the vertical bars is proportional to the range of the peak frequency.
**Data analysis**

Data were processed by applying HVSR method [6], using the GEOPSY software [12]. The peak frequencies \( f_n \) were calculated for each measurement point. The H/V spectral ratios were calculated from selected time windows of recorded ambient noise using an anti-triggering algorithm. The selected time windows were Fourier transformed, using cosine-tapering before transformation and then smoothed following the [4] approach. The selected and analyzed time windows were 50 s long. However the window length that yielded satisfactory resolution of the peak value being studied, but was still stable in the frequency was derived after experimenting over a range of values. After several tests, we concluded that a 50 s window provides stable results. The selected time window was free of man induced noise, harmonic noise from nearby machinery, spiky data and other transient signals. All the selected time windows of each time series were baseline corrected. The Fourier spectra were calculated for all segments using the Fast Fourier Transform (FFT). The Fourier amplitude ratio of the two horizontal Fourier spectra and one vertical Fourier spectrum were obtained using equation (1).

\[
R(f) = \frac{\sqrt{F_{NS}(T) \times F_{EW}(T)}}{F_Z}
\]

Where \( R(f) \) is the horizontal to vertical (H/V) spectrum ratio (HVSR), \( F_{NS}, F_{EW} \) and \( F_Z \) are the Fourier amplitude spectra in the N-S, E-W and vertical directions, respectively. After obtaining the H/V spectra for the selected segments of the signal, the average of the spectra were obtained as the HVSR curve for each measurement point (figure 7). The peaks of the H/V spectrum plot indicate the dominant frequencies of the site and the respecting amplification factors. Additionally, calculation of standard deviation for each average HVSR curve was also performed.

In case of nearby man produced transient noise or other harmonic vibrations (non stationary signal) the anti-triggering parameter STA/LTA was reduced until both sufficient number of windows was present in the calculations and the transient signal was efficiently removed. Following this procedure, it was succeeded in defining clear HVSR peaks independent from transient noise and reduced the standard deviation of the HVSR curve. The spatial density of measurements allowed the direct comparison of HVSR peaks between neighboring points, as an additional criterion of the HVSR clarity and reliability.

**RESULTS & DISCUSSION**

As previously mentioned, in urban areas, particularly in the central market area of Athens during the day, local noise sources are likely to affect spectral shapes. This effect, however, does not affect the calculated HVSR. Thus, the systematic and consistent spectral ratios derived in this study, are believed to reflect the physical properties of the local site at the measuring point.

It is worth mentioning that in contradiction to our results obtained from the 2003 measurements, the Metro operation does not significantly appear to affect the noise level within or on the chapel, as measurements taken during the night revealed similar amplitudes with those taken during the day (Metro operational hours). This is probably due to the installation of insulation dampers on the track way by the Metro Operation Company.

Predominant frequencies range between 2.8-14.2 Hz. In general 4 frequency bands dominate the HVSR curves, depending on the location of the measurement points. The first band ranges between 2.8-3.9 Hz (band 1 hereafter), the second between 5.5-6.5 Hz (band 2), the third between 8.5-11.1 Hz (band 3) and the fourth between 12.9-14.2 Hz (band four). The majority of HVSR
curves exhibit peaks in band 2 and 4 (Figure 8a). However the average amplification ratio appears higher in the bands 2 and 3 (figure 8b). Having in mind that such dimensions and type of structure are typically characterized by predominant frequencies lower than 7 Hz (0.14 s) and thus, conservatively considering that existing amplified frequencies over 11 Hz should not impact the structure on the one hand and the low amplification ratios on the other, only results regarding the bands 1, 2 and 3 are discussed.

![Figure 8: Overall distribution of amplification frequencies (a) and amplification ratio (b).](image)

**Figure 8:** Overall distribution of amplification frequencies (a) and amplification ratio (b).

![Figure 9: Lateral distribution of HVSR peak frequencies (a) and ratios (b) for the ground measurements. Blue ellipses are drawn to denote that in general lower frequencies present higher amplification ratios. Those areas are the southern and the northeastern parts of Kapnikarea.](image)

**Figure 9:** Lateral distribution of HVSR peak frequencies (a) and ratios (b) for the ground measurements. Blue ellipses are drawn to denote that in general lower frequencies present higher amplification ratios. Those areas are the southern and the northeastern parts of Kapnikarea.

**Microtremor HVSR on the ground**

Differences occur between points located on the ground of the church’s exterior and those located on the floor inside the church (figure 9). The first display a peak in frequency band 1 whilst the latter in band 2. A few measurements show amplification at both bands 1 and 2. The average amplification factor is 1.5 and 2.0 respectively. The observed differentiation between external and internal points is attributed to the ground-structure interaction. The external points reflect the ground response, which appears rather flat as the low amplification factor indicates and can likely be attributed to the rigidity of the underlying geological formations.

The internal points reflect the structure’s response which concentrates between 5.5-6.5 Hz (0.18-0.15 s). Lower central frequencies are observed towards the southern side of the church and could be somewhat related with the larger vertical dimensions of the structure towards this direction. Higher central frequencies are observed towards the northwestern side that could be partially related to the smaller vertical dimensions of the structure at this part. It is, however,
possible that the observed pattern is related to the different construction periods for the southern part (phase I) and the northern and western parts (phase II). Amplification appears higher towards the southern and northeastern parts of the monument.

**Mictrotremor HVSR on the roof**

The prevailing frequencies for 27 measurements performed on the roof are distributed in bands 2 (5.5-6.5 Hz) and 3 (8.5-11.1 Hz) and the amplification ratios range between 5-30 and 3-12 respectively. The spatial distribution of central frequencies in band 2 shows a similar pattern to the ground measurements. Lower values are observed towards the southern and northeastern parts of the building. Higher frequencies are amplified towards the central and western side. Higher frequencies are observed at the northwestern part of the roof could be attributed to the smaller vertical dimensions of this side. They could also be related with the presence of the pitched roofs and the bell tower. On the other hand the amplification factors’ spatial distribution, being partially compatible with the ground’s amplification pattern, follows firmly the pattern of the height of the measurement points, being directly proportional to it. The highest amplification ratios are observed on the main dome of the chapel, showing that there is the centre of the main building vibration. The relatively higher ratios towards the southeastern direction are presumably revealing the directivity of the monuments’ main vibrations (figure 10).

**Figure 10: Lateral distribution of HVSR peak frequencies (a) and ratios (b) for the roof measurements for frequencies 5.5-6.6 Hz.** The blue ellipses are those drawn for the measurements on the ground, showing that peak frequencies follow a quite similar pattern, which is not observed for the amplification ratios. The orange ellipse shows the area of maximum vibration which is directly proportional to the vertical dimensions of the building and reversely proportional to peak frequencies. The black arrow displays the presumed direction of the main vibration of the church.

Regarding the distribution of frequencies within the third band (8.5-11.1 Hz) for the 27 roof points, the pattern of low frequencies is the same as in band 2 (figure 11). However quite high frequencies are observed for measurements obtained on the top of the northern and western walls. A possible explanation could be the different construction periods and variety of materials used between those parts and the rest of the monument. The presence though of two high cypresses, leaning through an iron construction against the northern wall of the structure, gives rise to the suspicion for a possible triggered amplification at those specific frequencies, which in otherwise should not be observed, as shown by the distribution of frequencies in bands 1 and 2. The high frequencies and amplification ratios observed on the western side of the building could be attributed to the quite complex type of construction (pitched roofs and numerous windows of significant dimensions and bell tower), which certainly affects the response and the rigidity of the structure.
CONCLUSIONS

Kapnikarea chapel is one of the most important and popular Byzantine monuments in Athens, attracting thousands of visitors every year. As with most historical monuments, deteriorating with time, damages from severe regional and local earthquakes (i.e. the 1981 Alkyonides, the 1999 Athens earthquake), significantly reduced its structural integrity as one can clearly see when visiting the chapel, increasing thus its vulnerability to future seismic events. An accumulative factor for its reduced rigidity could likely be the construction works for the Athens Metropolitan Subway, which crosses the building along an E-W direction at 17 m depth. Witnesses of the guardians to the church, declare large disturbances in the interior due to the heavy drilling machinery used during the tunnel excavation. Furthermore, failures on the southern side and the northeastern part of the floor of Kapnikarea were observed during the tunnel construction. To assist with the planning for Kapnikarea restoration intervention, our working group conducted a microtremor survey with the technical support of the 1st Ephorate of Byzantine Antiquities [Hellenic Ministry of Culture and Tourism]. 87 measurements were taken on both ground and structure, in order to extract in detail the dynamic characteristics of the monument and to detect damaged or problematic characteristics of the building, imposing increased vulnerability in case of strong ground motion. The HVSR technique was applied and for each measurement point the peak frequencies and the corresponding amplification ratios were determined.

The methodology adopted and described above proved to be easy, systematic and the results attained proved to be reliable and homogeneous. The H/V peaks appear systematically independent of transient signal peaks, thus can be reasonably associated with the amplification levels at the dominant frequencies of the site response functions. The site’s dominant frequencies range between 2.8-14.2 Hz. In general 4 frequency bands dominate in the HVSR curves, depending on the location of the measurement points. The first band ranges between 2.8-3.9 Hz, the second between 5.5-6.5 Hz, the third between 8.5-11.1 Hz and the fourth between 12.9-14.2 Hz. The average amplification ratio appears higher in the second and third band.

In contradiction to microtremor measurements obtained a few years ago by our working team, the Metro operation does not seem to influence significantly the noise conditions within the chapel, as the new measurements (2009) performed during the night revealed similar amplitudes with those taken during the day (Metro operational hours). This is probably due to the installation of insulation dumpers on the track way by the Metro Operation Company. However, to firmly
establish this conclusion, a detailed and complex signal analysis is required, which will be considered in due course.

Concerning the spatial distribution of peak frequencies for the ground measurements taken outside the building they range between 2.8-3.9 Hz, showing a low average amplification ratio of the order of 1.5. The obtained response parameters are attributed to the underlying superficial layers, which are characterized as stiff formations. The response functions determined within the building for both the floor and the roof show a similar pattern, with frequencies in the range 5.5-6.6 Hz. The pattern observed on the floor is more complex due to the ground-structure interaction. However, it is observed that the building is characterized by lower frequencies at the southern and northeastern sides. Such an observation is partially compatible with the vertical dimension of the monument, with the peak frequencies being reversely proportional to it. The amplification ratios follow the pattern of frequencies, in general being reversely proportional to them. That means that larger vibrations are observed towards the southern and northeastern parts. The lateral distribution of the amplification ratio shows that the centre of the main building vibrations is located at the main dome and the direction of it is towards the southeastern direction. The pattern observed for the predominant frequencies of the building (5.5-6.6 Hz) could be related apart of the vertical dimensions of the construction, with the type of materials used at the various parts of it during the two different construction phases of the monument. However, it has been observed that microtremor measurements within damaged structures present lower central frequencies and higher amplification ratios compared to healthy structures. This has been established by researchers [e.g. 10, 11] who performed pre-seismic microtremor measurements on buildings and compared them with post-seismic measurements. This phenomenon is attributed to the decrease in the rigidity of the structure. On the other hand [7] studied the response of the leaning tower of Pisa before and after soil extraction works, in order to reduce its inclination, using microtremor. The results of their measurement showed that the frequency and the amplification factor of the vibration in the tower became slightly higher and lower after the soil extraction, respectively, showing that the microtremor measurement is useful to the validation of retrofitting measures. Taking into account the above, in conjunction with observed failures on the northeastern (masonry failures) and southern (damages on the floor) part of the monument during the works for the metro tunnel construction, it can be presumed that lower frequencies and higher amplification ratios prevailing in these sectors of the building are likely due to its damage from deterioration, past earthquakes and perhaps the tunnel construction works.

The distribution of the secondary peak frequencies of the building are observed only at the measurements performed on the roof and range 8.5-11.1 Hz. The pattern of low secondary peak frequencies is the same as for the predominant central frequencies 5.5-6.6 Hz. Differentiation occurs for measurements obtained on the top of the northern and western walls. This differentiation could be related with the type of materials used during the two phases of construction and the age of the various parts. The high frequencies and ratios observed on the western side of the building could be attributed to the complex type of construction, which certainly increases the vulnerability locally. One additional reason for triggered amplification at the northern side is the presence of two high trees, surrounded by a heavy iron construction of 8 m×1.5 m dimensions which connects the trees to the wall. This formation could dramatically increase the load on the building during a strong earthquake due to its large dimensions and weight, therefore it is strongly recommended to be removed.
ACKNOWLEDGEMENTS

We would like to express our sincere gratitude to Mrs. Aikaterini Pantelidou-Alexiadou (Director of the 1st Ephorate of Byzantine Antiquities, Hellenic Ministry of Culture and Tourism) and the skilful workers of this headship, Mr. Evangelos Korkolis for their significant support during our survey. Also we would like to thank Mr. Nikolaos Stratigeas (Consultant Engineer of Kapnikarea) for his helpful comments.

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