AMBIENT NOISE VIBRATIONS AS A TOOL FOR SEISMIC RESPONSE ASSESSMENT OF SELECTED MONUMENTAL STRUCTURES OF CRETE

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ABSTRACT

The contribution of local site conditions to the observed unequal spatial damage distribution, particularly for historical and monumental structures has been revealed by destructive worldwide earthquakes as well as by recent advances in soil-structure interaction studies. The importance of strengthening resilience of cultural heritage against natural disasters has been articulated in the Sendai Framework, while the proactive disaster risk management has been annotated by the global agenda 2030. This study is particularly focused on important historical and monumental structures and religious cultural heritage masonry structures (such as minarets, church bell towers) in the cities of Chania, Rethymno and Heraklion of Crete. The Horizontal to Vertical Spectral ratio (HVSR) technique applied to ambient noise recordings is used to assess the frequencies of vibration of historical and monumental structures of Crete and to examine potential soil - structure interaction phenomena. The geological setting of the studied historical and monumental structures is mainly characterized by Quaternary and Neogene deposits - locally very loose deposits - and by the presence of large scale fault zones. Considering the geotectonic setting, the surface geology and the numerous historical and monumental structures of Crete, the determination of prone resonating buildings and the development of integrated tools for situational awareness towards to a proactive earthquake risk management are important issues with the purpose to support civil protection preparation and local operational decision making authorities of Crete in terms of earthquake disaster.

Keywords: historical-monumental buildings; high rise structures; HVSR, ambient noise; Crete

1. INTRODUCTION

The importance of strengthening resilience of cultural heritage against natural disasters has been annotated in the 2013 EU Civil Protection legislation and articulated in the Sendai Framework, while the global agenda 2030 for sustainable development proposes a new way to manage and prepare for disasters based on proactively managing risks and fostering risk-informed sustainable development. Considering the above, assessments of local site effects, monitoring seismic structural response and soil-structure interaction studies predominantly for historical and monumental structures are essential issues in a proactive managing strategy towards to the seismic risk resilience undertaken by the civil protection authorities.

The contribution of local site conditions on the excitation of seismic ground motion has been well documented after destructive earthquake events worldwide (e.g Loma Prieta, 1989; Athens, 1999; L’Aquila, 2009 and the most recent earthquake 2016 in Norcia in Italy), while recent advances in soil-structure interaction highlight the importance of local site condition to the observed unequal spatial damage distribution (e.g Douglas et al.2013). Several studies have indicated structural failures due to the interaction with the surface fault rupture after the occurrence of earthquakes events (e.g. Kawashima 2001; Faccioli et al. 2008). The Port-au-Prince Cathedral in Haiti is an outstanding example of high rise bell tower failure due to complex rupture during the devastating Mw 7.0 Haiti earthquake on the 12th January 2010.

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Several methodological approaches have been proposed to study the effects of local geology on seismic ground motion, while several theoretical and experimental approaches have been presented to study soil-structure interaction. The spectral ratio of horizontals over the vertical components (HVSR) of microtremors and earthquake data recorded by a single seismological station installed in the ground surface for site response evaluation has been initially proposed by Japanese researchers. Nakamura (1989) considered that the H/V ratio of microtremor at peak frequency range can be explained with vertical incident SH wave. The efficiency of the Horizontal to Vertical Spectra Ratio (HVSR) applied to ambient noise or earthquake recordings to assess the local site conditions has been applied in various geomorphological cases and microzonation studies worldwide (e.g Field and Jacob, 1995; Mucciarelli et al. 2003; Bonnefoy Claudet et al. 2008; Moisidi 2009; Strollo et al. 2011). In addition, the HVSR has been applied to reveal the spectral characteristics of fractured/fault zones (e.g Lombardo and Riganò, 2006; Marzorati et al.2011) or as a valuable tool for the detection of hidden faults and/or for fault zone delineation (Moisidi et al. 2012; Moisidi et al. 2014). Nakamura (1997), used microtremors and provided seismic vulnerability indices for ground and structures.

After the pioneering work of Nakamura et al (1999 and 2000) regarding the determination of the dynamic characteristics of the Tower of Pisa and the Roman Colosseum, the HVSR technique using microtremor or earthquake data has been applied in several studies to estimate primarily the building fundamental frequency of vibration and soil structure interaction phenomena in urban environment (e.g Irie, Y and Nakamura.K, 2000; Volant et al. 2002; Gallipoli et al 2004; Navarro et al. 2009; Mucciarelli et al. 2011a and Mucciarelli et al. 2011b). In Crete, HVSR using microtremor data has revealed a large scale buried reservoir in the archaeological site Aptera and the extracted results where cross-correlated with electrical resistivity tomography to verify the outcomes (Moisidi et al. 2004). Sato et al. (2008) conducted microtremor recordings to examine the dynamic characteristics of Suleymaniye mosque and minarets, among others important structures in Istanbul, before and after 1999 Kocaeli earthquake and observed that the shift of the natural frequency is small for the case of minarets. Specifically, the natural frequencies of the minaret Suleymaniye Mosque was shifted from 0.843 Hz and 0.867 Hz (for WHT minaret) before the earthquake to 0.819 Hz and 0.842 after the earthquake for HL (NW-SE) and HT (NE-SW) component, respectively. However, for minaret Suleymaniye Mosque (EWT) the natural frequency before and after earthquake is observed at 0.842 Hz. In the city of Rhodes (Greece) HVSR has been applied in the minaret of Suleiman mosque (Manakou et al. 2011) and observed frequencies in the range 0.39 -0.41 Hz and 1.6 Hz for the first floor and 1.63 Hz for the second floor while the amplification reaches to 100 in horizontal components.

The main purpose of this study is to assess the frequencies of vibration using ambient noise recordings processed through Horizontal to Vertical Spectral ratio (HVSR) technique. The study is particularly focused on the seismic response assessment of important historical and monumental structures and high rise religious cultural heritage masonry structures (such as minarets, church bell towers) in the cities of Chania, Rethymno and Heraklion, Crete. The geological setting of the studied historical and monumental structures is mainly characterized by Quaternary alluvial (Holocene) and Neogene (Pliocene) deposits - locally very loose deposits - and by the presence of large scale fault zones. The study highlights the importance of incorporating the determination of prone resonating buildings into urban planning towards to a proactive earthquake risk management planning of Crete, considering the high seismic activity of the area, the surface geology, the fault zones and the numerous historical and monumental structures. Therefore, soil-structure interaction studies and the development of integrated tools for situational awareness are important issues in Crete with the purpose to support civil protection preparation and local operational decision making authorities of Crete in terms of earthquake disaster.

2. DATASET AND METHODOLOGY

Ambient noise was recorded at basement and at each n-floor of the studied building constructions and on foundation soil, using Lennartz 3D/5sec seismometer, connected with Cityshark II acquisition system. The guidelines given by Mucciarelli (1998) and Bard and J-Sesame were followed. Microtremor measurements of 20 and 30 minutes sampled at 125 and/or 128 Hz were collected. The J-
sesame software based on Java application for site effects studies was used for HVSR calculations as presented by Nakamura (1989, 2000). Microtremor processing for HVSR calculations includes: a) time window selection of the stationary signal window, b) the selected time windows of each time series are corrected for the baseline and for anomalous trends, tapered with a cosine function to the first and last 5% of the signal, band pass filtered and smoothed with triangular windows. Horizontal components NS and EW components were averaged to derive the horizontal (H) spectrum. c) The average HVSR spectra ratio, $H_{NS}/V$ and $H_{EW}/V$ ratios (and their standard deviations) of the selected time series window were calculated.

3. RESULTS

3.1 Saint George Church Bell Tower (Heraklion)

Microtremors were recorded at the base and at top most level of the bell tower of Saint George church. The spectral $H/V$, $Hns/V$ and $Hew/V$ of microtremors recorded in Saint George Bell Tower are shown in figures 1 and 2. The H/V analysis of microtremors at the base of the structure revealed a broad HVSR ($H/V$, $Hns/V$ and $Hew/V$) curve in the frequency range 1.39-3.38 Hz, while the $H/V$ amplitude reaches approximately to 2.0. A second peak is observed at higher frequency 8.62-8.78 Hz of relatively low amplitude (reaching approximately to 2.0). Microtremor measurements were recorded at each side (north, south, east and west) of the bell tower. At the north side of the bell tower $H/V$ microtremors indicate two amplified peaks at 6.16 Hz and 11.08 Hz (amplitudes 6.0-6.5, respectively). At the south side of the bell tower the $H/V$ resonant frequency is observed at 9.5 Hz (with an amplitude 7.5). The $H/V$ fundamental frequency at east side of the bell tower is observed at 6.4 Hz, while the amplified peak at this frequency reaches to 11.43. At the west side of the bell tower two $H/V$ amplified peaks are observed at 6.7 Hz and 10.5 Hz, (amplitudes 4.6 and 4.7, respectively). At the north, south and west part of the bell tower the HVSR amplitude range from 4.6-7.5, while at the east side of the bell tower the HVSR amplification reaches to 11.4. The $Hns/V$ ratio at all sides of the bell tower (Fig.2) revealed two amplified peaks: i) the $Hns/V$ fundamental peak is observed at medium frequencies 6.0 Hz to 6.3 Hz. At the north and east side of the bell tower the amplification is 14.9 and 22.6, respectively. At the south and west side the amplification is 7.0 and 8.6, respectively, ii) a second amplified peak is observed at frequencies 11.0 Hz-12.0 Hz with $H/V$ amplification between 6.5 -7.5. $Hew/V$ ratio at all sides of bell tower indicates an amplified peak in the frequency range 9.0-9.5 Hz. At the south and east side of the bell tower the $Hew/V$ amplification is 15.5 and 12.8, respectively. At the north and west side the amplification is 7.5 and 6.6, respectively. The east side of the bell tower present considerable higher value compare to the amplification observed at other sides of the bell tower. The $Hns/V$ ratio shows high amplification at north and east side of the bell tower. The $Hew/V$ ratio shows high amplification at south and east side of the bell tower.
Figure 1. H/V, Hns/V and Hew/V spectral variations of microtremors recorded at the base foundation (a) and comparison of the H/V (b) at north, south, east and west side of the bell tower of Saint George. (c) and (d) comparison of the Hns/V and Hew/V at north, south, east and west side of the bell tower of Saint George.
3.2 Saint Konstantinos and Eleni church Bell Tower

Microtremors were recorded the ground foundation of the church, at the base foundation and at the topmost accessible level of the bell tower of Saint Konstantinos and Eleni Church (Fig. 3). The H/V ground foundation resonant frequency is observed at 0.67 Hz and is related to the marine terraces and coastal sands. The H/V resonant frequency at the base foundation and at the topmost accessible level of the bell tower is also observed at 0.67 Hz. The H/V, Hns/V and Hew/V ratios present an amplified peak at 0.67 Hz and amplification ranging from 5.15 to 7.7 (Fig.3). At the topmost level of the bell tower, the Hns/V ratio indicates a second peak at frequency 5.2 Hz with amplitude reaching to 5.08. This peak is not presented in the Hew/V ratio. The extracted H/V ratios of microtremors at the ground foundation of the church, at the base foundation of the bell tower and at the topmost accessible level of the bell tower indicate fundamental frequency at 0.67 Hz suggesting that resonance phenomena can be observed in this case study.

Figure 3. Microtremor measurement and seismic ground response at the ground foundation of, at the base foundation and at the topmost accessible level of the bell towers Saint Konstantinos and Eleni church.
3.3 The Clock Tower of Chania

Microtremors were recorded at various sites at the ground foundation, at the base and at the top level of the clock tower structure of Chania. Microtremor recorded at the east and south side of the top level of the clock bell tower. The HVSR ratios (average H/V, Hns/V and Hew/V) of microtremors recorded at the ground foundation present two amplified peaks at frequencies 0.4 Hz and 3.06 Hz (Fig. 4). The HVSR amplification at fundamental frequency at 0.4 Hz is about 2 (2.19 to 2.22). The amplitude of the second peak ranges from 1.66-1.83. At the base foundation of the clock structure, HVSR ratios present three amplified peaks. The fundamental frequency is observed at 0.4 Hz with amplitude about 2.0 (2.04-2.09). The second and third amplified peaks are observed at about 3.0 Hz (3.06-3.14 Hz) and at about 8.5 Hz, respectively. The amplitude of the second and third HVSR peaks is about 2.0 (1.95-2.2). At the east side of the top level of the clock tower, HVSR indicated two amplified peaks at 2.98 Hz (amplitude about 7.5) and at 9.5 Hz (amplitude about 4.0). At the south side of the top level, HVSR indicated two amplified peaks. The fundamental peak is observed at 2.98 Hz (amplitude reaches to 6.5) and the second amplified peak is observed in the frequency range 9.26 Hz -9.58 Hz (amplitude ranges from 3.08 to 4.74).

Figure 4. Microtremors recorded at the clock bell tower of Chania and the derived H/V ratios using microtremors.

3.4 The Metropolitan Church Bell Tower (Chania)

Microtremors measurements were acquired at the base of the structure and at top most level of the Metropolitical Church Bell Tower of Chania. The H/V, Hew/V and Hns/V spectral characteristics of
the microtremor recordings at each recorded site are shown in Figure 5. The HVSR ratios (H/V, Hns/V and Hew/V) at the base foundation (Level 1) present two amplified peaks at 0.4 Hz and at frequencies 2.95 Hz to 3.53 Hz. The amplitude of the fundamental peak at 0.4 Hz and the amplitude is about 2.0 (2.04-2.11). The second H/V amplified peak ranges from 1.89 to 2.16. At the Level 3, the HVSR ratios present two amplified peaks at 2.74 Hz - 2.92 Hz and 6.08 Hz - 6.32 Hz. The amplitudes at those peaks are 6.08-7.2 and 2.75-3.4, respectively.

Figure 5. Microtremors recorded at various levels of the bell tower structure of Metropolis church.

Figure 6. H/V, Hns/V and Hew/V variations at the base foundation and at various levels of the bell tower structure of Metropolitical church.

3.5 Seismic response Minaret Valide (Rethymno)
Microtremors were recorded at the ground foundation and at top most level of the Minaret Valide (Fig. 7). The H/V, Hew/V and Hns/V ratios of microtremor recordings at the top most level are shown in Figure 7 (a,c). The H/V resonant frequency is observed at 1.86 Hz (amplitude 18.5). The Hns/V resonant frequency appears at 1.79 Hz (amplitude 14.5). The Hew/V resonant frequency is observed at 1.86 Hz (amplitude 25.0). The HVSR of the ground foundation (Fig. 7 b,d) present one clear peak at 2.02 Hz (amplitude range from 2.8 to 3.05).

Figure 7. Microtremor recordings at the topmost level of the minaret and on soil foundation and the extracted H/V ratios of MinaretValide.

4. DISCUSSION

For the case study of Saint George Church the H/V analysis of microtremors at the base of the structure revealed a broad HVSR (H/V, Hns/V and Hew/V) curve in the frequency range 1.39-3.38 Hz, while the H/V amplitude reaches approximately to 2.0. This broad peak could be related to the materials debris of previous older buildings or to local heterogeneities of the local geological structure. A second peak is observed at higher frequency 8.62-8.78 Hz of relatively low amplitude (reaching approximately to 2.0). At the east side of the Bell Tower, spectral ratios indicates significantly higher amplitudes compared to the amplitude of the west, north and south side of the Bell Tower (6.2-8.62) at high frequency (e.g 9.34 Hz). Considering that the area is characterized by a NNW-SSE fault structure, further microtremor recording should be conducted in the surrounding area in order to ensure potential fault amplification effects at high frequencies (e.g 9.0 Hz).

The HVSR microtremor survey for the case study of Saint Konstantinos and Eleni Church Bell Tower indicated that soil-structure resonance phenomena could observed. The HVSR of microtremors at the foundation soil indicated fundamental frequency at 0.67 Hz (related to the marine terraces and coastal sands). The HVSR of microtremors at the base foundation and at the topmost accessible level of the bell tower showed also one amplified peak at 0.67 Hz. The spectral ratios show that amplification of seismic motion could be expected to be higher in the EW direction of bell tower compared to NS direction. It is highlighted that future survey is of paramount importance to be conducted in this area.
considering: i) the close proximity (300 m) of the structure to the presence of large scale NE-SW large scale fault zone that crosscuts the area and ii) the presence of fluvial deposits, sands, marine terraces (soft soil). Moreover, considering that in this geological zone other natural disaster could be observed (e.g. flooding), particular focus should be given in terms of earthquake risk management planning, giving priority to earthquake early warning systems and further soil-structure interaction studies for high importance building structures.

For the case study of the Clock Tower of Chania, the H/V microtremor spectra at the measured sites on the ground soil, at the base and at the top east level (at east and south side of the clock bell structure) indicate two amplified peaks at low and medium frequencies. At the base and at the ground foundation the low frequency (0.4 Hz) is related to the geological structure while medium and high frequencies might be related to the structural material remnants at the base foundation that have not been removed during the reconstruction date. In this case study, resonance phenomena effects and high seismic motion amplification could be induced in a case of strong motion shaking.

Microtremors measurements were recorded at the base of the structure and at top most level of the Metropolitical Church Bell Tower of Chania. At the base of the structure two amplified peaks are observed at 0.4 Hz and 3.46 Hz. The amplified peak at low frequency is due to the geological setting of the area, while the second amplified peak at the medium frequencies could be due to surface layer overlying the rest geological column. At the topmost level of the bell tower two amplified peaks observed at 2.74 Hz (amplitude 6.55) and another peak at 6.24 Hz (amplitude 3.11). However, further microtremor and other geophysical should be conducted at this site to verify the presence of a local surficial layer either due to structural material or due to effects of the local geology (e.g local heterogeneities, irregularities). Microtremors recorded at the ground foundation and at the top level of the Minaret Valide (Rethymno), revealed one HVSR amplified peak. The H/V resonant frequency is observed at 1.86 Hz and the amplitude of the peak reaches to 18.36, while the H/V ratio at the ground foundation present one clear peak at 2.02 Hz and the amplified peak reaches to 2.91. The ground resonant frequency and the resonant frequency of the topmost level are observed in the frequency range. For this case study, resonance phenomena could be observed.

In the frame of this study in the three cities of Crete, Heraklion, Rethymnon and Chania it is highlighted that seismic resonance effect could be induced after strong motion shaking. The majority of historical and monumental structures are located in the center of the historical cities of Crete. The surface geology at those sites is characterized predominantly by Holocene alluvial deposits (soft soils) of varying thickness, locally marine deposits, sands, clayey-marly deposits, marly limestones, marly sandstone. The soil fundamental frequency in the cities of Chania, Rethymnon and Heraklion is predominantly observed in the low frequency range 0.4 Hz-2.0 Hz, related to the geological setting, characterized by soft deposits. It is highlighted that soft sediments can amplify seismic ground motion and extend the duration of the propagation (e.g Aki, 1993) and therefore are capable to induce greater damage to the buildings founded on those sites (e.g Verma et al. 2014).

In addition, several of the investigated historical and monumental structures are located near to fault zones striking predominantly to N-S and NE-SW. Faults can amplify seismic ground motion in the frequency range 1-10 Hz (e.g Lewis et al. 2005). HVSR using microtremors showed spectral pattern of two amplified peaks at low and at medium-high frequencies, whereas the peaks at medium to high (e.g 3.0 Hz -15 Hz) were related to fault zones (Moisidi et al. 2014). In addition it was observed that several monuments indicate a second and/or a third amplified peak at medium to high frequencies therefore it could be inferred that structural failures due to the interaction with the surface fault rupture after strong motion shaking could be expected. Several studies have indicated structural failures due to the interaction with the surface fault rupture after the occurrence of earthquakes events (e.g. Chang et al. 2000; Kawashima 2001; Anastasopoulos and Gazetas 2007; Faccioli et al. 2008). Recently, Gazetas et al (2015) based on theoretical and experimental studies focusing on the effects of normal and thrust of dip-slip faulting on massive bridge pier caisson foundations and revealed new failure mechanisms which showed that failure depends profoundly on: a) the faulting type, b) the exact location of the foundation relative to the fault, and c) the magnitude of the fault offset. Therefore, further studies should follow to examine possible effects induced by the near subsurface structure (e.g lateral heterogeneities) at the sites where historical and monumental structures are located.
5. CONCLUSIONS

The HVSR spectral variations of the examined historical and monumental structures indicate or peculiar amplifications or broad H/V ratios at the base of the studied structures (e.g the Clock Tower of Chania). These HVSR variations could be related to the structural material remnants or material debris at the near subsurface geological structure. The importance of assessing the induced strong and/or peculiar amplifications of those cases has been recently acknowledged and specifically it has been stated that: “the guidance given by the code design regulations for the construction of modern structures above those sites might be totally insufficient”, (Douglas et al. 2013). Actually, in Crete, as in other ancient cities (e.g Rome) it is a typical practice of construction to build the more recent historical structures on the material debris of previous older buildings and monuments - dating centuries ago (Douglas et al. 2013). Moreover, it is emphasized that not only the presence of various ground conditions of their characteristics in the foundation of monumental monuments can affect the seismic stability of monuments, but also the quality of the implementation of fundamental, wall and other structures, their operating conditions and many other factors also affect the state of the historical object during an earthquake. In the frame of this study in the three cities of Crete, Heraklion, Rethymnon and Chania it is highlighted that seismic resonance effect could be induced after strong motion shaking. The majority of historical and monumental structures are located in the center of the historical cities of Crete. The surface geology at those sites is characterized predominantly by Holocene alluvial deposits (soft soils) of varying thickness, locally marine deposits, sands, clayey-marly deposits, marly limestones, marly sandstone that can amplify seismic motion and extend the duration of the propagation. Moreover, the presence of fault zones (striking predominantly to N-S, NNW-SSE and NE-SW) can amplify seismic motion in the frequency range of engineering interest 1-10 Hz. Therefore, in the frame of this study the development of integrated response system tools comprised of earthquake response planning, dynamic structural health monitoring, situational awareness and detailed site effects studies is of paramount importance to support civil protection preparation and operational decision making in terms of earthquake disaster, specifically in Crete which is a high seismic active region.

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7. REFERENCES


Institute of Geology and Mineral Exploration (IGME) 1988 Geological map of Rethymno

Institute of Geology and Mineral Exploration (IGME) 1996 Geological map of Heraklion

Institute of Geology and Mineral Exploration (IGME) 1971 Geological map of Chania


Manakou M (2011). PERPETUATE PERPerformance-based aPproach to Earthquake proTecTi on of cUlturAl heriTage in European and mediterranean countries FP7 - Theme ENV.2009.3.2.1.1, ENVIRONMENT Grant agreement n°: 244229, DELIVERABLE D18 Title: results of in-situ microtremors surveys and array measurements at selected sites.


Mucciarelli, M., Bianca, M., Ditommaso, R., Gallipoli, M.R., Masi, A., Milkereit, C., Parolai, S., Picozzi, M., Vona, M (2011b) Far field damage on RC buildings: the case study of Navelli during the L’Aquila (Italy)


