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2012 J. Geophys. Eng. 9 261

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Spatial spectral variations of microtremors and electrical resistivity tomography surveys for fault determination in southwestern Crete, Greece

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Received 17 October 2011
Accepted for publication 6 March 2012
Published 3 April 2012
Online at stacks.iop.org/JGE/9/261

Abstract

The horizontal to vertical spectral ratio (HVSR) technique using microtremors and electrical resistivity tomography (ERT) surveys reveal a potentially seismic active source in southwestern Crete located within the outer forearc of the Hellenic subduction zone in one of the most seismically active deformed regions in Europe. The combined approach is applied on the Pahia Ammos coast southwest of the Paleohora peninsula and reveals an almost E–W-striking fault crosscutting the dense populated area. Spatial HVSR variations in the fundamental frequencies and HVSR shapes using microtremors pattern the effects of surface and subsurface structure on seismic ground motion and are capable of delineating fault zones. One clear HVSR peak in the low frequencies is related to the thickness of the alluvial deposits. Two amplified frequencies are attribute to lateral heterogeneities/irregularities induced by the fault zone and thickness variations of the geological column overlying the lateral irregularities of near-subsurface structure. Dipole–dipole and Wenner–Schlumberger configuration arrays are conducted to model the surface and subsurface structure variations. The identified fault zone striking E–W inland is capable of enhancing ground seismic motion and significantly contributes to the seismic hazard assessment of the studied area. Geophysical results are cross-correlated, verifying the validity of the research outcome.

Keywords: Nakamura technique, HVSR, ERT, fault determination, southwestern Crete

(Some figures may appear in colour only in the online journal)

1. Introduction

The determination of potentially seismic active sources and the dynamic response evaluation of surface and subsurface structure at sites where the geometric and dynamic properties of the ground can strongly amplify seismic motions are key areas in seismic hazard assessment studies. The horizontal to vertical spectra ratio (HVSR) or Nakamura technique using microtremors and electrical resistivity tomography (ERT) surveys are conducted to determine the surface and subsurface structure of Paleohora in southwestern Crete. The purpose of the HVSR technique is applied to pattern the local ground
seismic response variations and to delineate a fault zone. ERT survey is conducted to reveal geological and tectonic structures not directly observable at the Earth’s surface and to model the subsurface resistivity changes in depth used also for correlation of the research outcomes of the HVSR technique. The purpose of the combined approach that is part of a multi-disciplinary approach (Moisidi 2009) is twofold: (a) to reveal and model the subsurface structure on the coast of Paleohora and (b) to provide validation in fault determination that significantly contributes to the seismic hazard of the studied area.

The study area is located in southwestern Crete, in the outer arc of the Hellenic subduction zone. The high seismically active tectonic region has been studied by many authors (McKenzie 1978, Taynax et al. 1991, Jackson 1994, Le Pichon et al 1995, Papazachos and Kiratzi 1996, Papazachos et al. 1998, Papazachos et al. 2000, Laigle et al. 2004). The recent tectonic evidence of uplift and the numerous active faults striking almost E–W and NNE form a complex tectonic environment for the Paleohora area (Moisidi 2009). The coastline of the studied area of the Paleohora and Grammeno peninsula is bounded by a continuous E–W normal fault (figure 1) which is one of a series of E–W faults that occur at intervals up to several kilometres inland (Moisidi 2009). The surface geology of Pahia Ammos in the north is characterized by alluvial deposits (clayey–sandy and unconsolidated clay sand) and south of the basin by the Lissos beds (composed of cobbles of pre-Neogene units lithified with calcitic and marly cement) (Tsalahouri and Fontou 2002).

HVSR using microtremors to estimate ground seismic response has been proposed by many authors. The HVSR fundamental frequency correlates with the ground fundamental resonance frequency and the HVSR amplification with the impedance contrast between surface and subsurface structure. The one HVSR frequency in the low frequency range is related to soft sites or thicker deposits while in the high frequency range it is related to thin deposits overlying the bedrock (Lermo and Chavez-Garcia 1993, 1994), Duval et al. (1994), Field and Jacob (1995), Teves-Costa et al. (1996), Lebrun et al. (2001), Bonnefoy-Claudet et al. (2008), among others). Köhler et al. (2004) related the low frequency band (0.5–0.9 Hz) and high frequency band (7–10 Hz) to sediment thickness variations. The clear amplified frequency in the high frequencies (7–10 Hz) was related to shallow Quaternary deposits of low velocity layers overlying the Tertiary sediments, in Southern Rhine Rift valley, close to Basle in Switzerland. Gosar (2007) related the high fundamental
frequency HVSR (18–22 Hz) to very shallow geological formations (very shallow till or sand gravel layer overlying flysch bedrock or shallow conglomerates) in the Bovec basin (NW Slovenia).

In contrast, a few studies exhibit a more complex pattern of two or more peaks due to (a) topographic effects (Lebrun et al. 2001) and (b) lateral irregularities of the subsurface (Giampiccolo et al. 2001, Gueguen et al. 2007) induced by large-scale voids (Moisidi et al. 2004) or to the effects of the topmost layer and lateral heterogeneities of 2D/3D structures that are attributed to fault zones (Moisidi 2009). Toshinawa et al. (1996) in Santiago (Chile) and Gueguen et al. (2000) in Equador proposed that the higher amplified frequency (fundamental frequency) corresponds to the ground response of the soft superficial layer while the second amplified frequency defines the resonance frequency of the whole soil layer above the bedrock. Lebrun et al. (2001) in the Grenoble basin correlated the second amplified frequency at 3 Hz to the resonance response of the surficial topmost layer in a depth range 20–40 m. Cornou et al. (2003) in the Grenoble basin observed one fundamental frequency at 0.3 Hz and a second amplified frequency at 2.5–4.4 Hz. The second amplified frequency (2.5–4.4 Hz) was correlated to the topmost layer of the basin. Roten et al. (2008), using numerical simulations, found one clear fundamental frequency at the low frequency band (0.6 Hz) correlated with the deep embanked valley with high impedance contrast in the Rhône valley in Switzerland. According to Oros (2009), the low frequency corresponds to a thick Quaternary layer while the high frequency might be correlated to the structure a few metres under the surface. Lombardo and Rigano (2007) used the HVSR technique and microtremors across the Tremestieri fault and an eruptive fracture, and found amplification in the HVSR technique and microtremors across the Tremestieri valley in Switzerland. According to Oros (2009), the low frequency band is correlated to the structure a few metres under the surface. Lombardo and Rigano (2007) used the HVSR technique and microtremors across the Tremestieri fault and an eruptive fracture, and found amplification in the frequency range 1.5–2.0 Hz and 4.0–8.0 Hz. Significant ground amplification is observed at the frequency range 4.0–8.0 Hz at sites located close to the Tremestieri fault (Lombardo and Rigano 2007). ERT based on the reconstruction of resistivity images of the subsurface from current and voltage measurements conducted on the Earth’s surface or in boreholes has been conducted to model the geoelectrical subsurface structure proposed by several researchers (Störz et al. 2000, Lapenna et al. 2003, Wise et al. 2003, Nguyen et al. 2007, Caputo et al. 2007, Soupios et al. 2008, Martinez et al. 2009).

2. Methodology

Nakamura (1989, 1996, 2000), based on the effect of seismic ground response in earthquake distribution, suggested the applicability of the HVSR technique using microtremor recordings in estimating dynamic ground response characteristics. Local site effects that are attributed to the effects of surface and subsurface structure on ground seismic motion can be modelled from the horizontal to vertical spectra ratio of microtremors recorded on the surface (Nakamura 1989, 1996). The horizontal ($H_f$) and vertical ($V_f$) spectra recorded on the surface ground of the sedimentary basin provides the transfer function of the seismic response of the sedimentary basin given by the equation

$$\text{QTS} = \frac{H_f}{V_f} = \frac{A_f \cdot H_b + H_s}{A_f \cdot V_b + V_s} = \frac{H_b}{V_b} \cdot \left[ \frac{A_b + \frac{H_b}{V_b}}{A_v + \frac{V_b}{V_s}} \right]$$

where $H_b$ and $V_b$ are the spectra of the horizontal and vertical motion in the basement beneath the sedimentary layer, $H_f$ and $V_f$ are the spectra of the horizontal and vertical motions of surface waves, and $A_b$ and $A_v$ are the amplification of horizontal and vertical motions of the vertically incident body wave, respectively (Nakamura 2000). The interpretation is based on the following assumptions: (1) Rayleigh wave effects are equal for the vertical and horizontal component at the basement, (2) the horizontal component of microtremor is amplified through multi-reflections of the S-wave and the vertical component of the microtremor is amplified through multi-reflection of the P-wave, (3) the Rayleigh wave effect is existent only in the vertical spectrum at the surface and not in the vertical spectrum at the basement, (4) for a wide frequency range (0.2–20 Hz), the amplification ratio of the horizontal and vertical ratio at a rock site is close to unity ($H_b/V_b = 1$). Rayleigh wave dominance suggests that $\text{QTS} = H_f/V_f$. Considering the above assumptions, the transfer function of the geological column can be modelled using the horizontal and vertical spectra ratio recorded at the surface from a single seismological station (Nakamura 2000).

The HVSR technique is applied to microtremors conducted along Pahia Ammos to evaluate the dynamic ground seismic response of the surface and subsurface structure. Microtremor data are recorded using a Lennartz 3D/5 s seismometer oriented to north connected with the Cityshark II acquisition system. Microtremors were recorded according to Mucciarelli (1998) and J-sesame (Bard and Sesame Team 2005) guidelines. Microtremor measurements of 10, 15 and 20 min sampled at 125 Hz were collected. The J-sesame software based on a Java application for site effect studies was used for HVSR calculations. Microtremor processing for HVSR calculations to determine the surface and subsurface structure in Pahia Ammos includes (a) time window selection of the stationary signal window, (b) the selected time windows of each time series corrected for the baseline and for anomalous trends, tapered with a cosine function to the first and last 5% of the signal, band bass filtered from 0.2 to 20 Hz smoothing, and horizontal components merged, (c) calculation of the average HVSR spectra ratio, $H_{SV}/V$ and $H_{EVS}/V$ ratios of the selected $N$ time series window.

The automated multielectrode IRIS-Syscal Jr Switch 48 instrument is used to measure the subsurface distribution of the apparent resistivity of the studied area. Dipole–dipole and Wenner–Schlumberger acquisition configuration was applied for achieving good lateral and in-depth resolution. An electrode spacing of 5–10 m was used to image the geoelectrical structure to a depth of 70 m. The dense configuration of 5 m electrode spacing is used to acquire high-resolution data and to accurately image the shallow complex subsurface geological structure. After the preliminary processing of the acquired tomographies, a spacing of 15 m was used to detect deeper structures and define the geometry.
Figure 2. (a) Microtremor recordings (sites A–F) along Pahia Ammos (profile L1–L2). HVSR curves at sites A to F pattern the surface and near-subsurface variations along the microtremor profile L1–L2. (b) Average HVSR (blue curves), $H_{SS}/V$ (red curves) and $H_{EW}/V$ (green curves) spectra ratios are calculated. The x-axis on the HVSR curves shows the frequency range of the investigation (0.2–20 Hz) and the y-axis corresponds to the HVSR, $H_{SS}/V$ and $H_{EW}/V$ amplification. The fundamental frequency is presented with a black vertical line while the shadow grey zones represent the standard deviation of the fundamental frequency. The black curves represent the standard deviation of the HVSR, $H_{SS}/V$ and $H_{EW}/V$ spectra ratios. The one amplified frequency (site A and E) correlates with thick or soft alluvial deposits. The two amplified frequencies (sites B, C and F) are attributed to the effect of alluvial deposits and subsurface heterogeneities/irregularities of the structure. The amplified HVSR frequency in the medium or high frequency is attributed to the effect of lateral heterogeneities of the near subsurface and the amplified HVSR frequency in the low frequencies to the effect of the alluvial deposits overlying the subsurface.
Spatial spectral variations of microtremors and electrical resistivity tomography surveys for fault determination in southwestern Crete, Greece

![Image of ERT profile]

**Figure 3.** Shallow (a) and deep (b) ERT profile along Pahia Ammos. An almost E–W faulting zone is revealed. The tectonic zone is depicted by a thick dashed black line. The thin short-dashed black line represents the unconformity. The RMS error, the resistivity scaling measured in ($\Omega\text{m}$) and the electrode spacing are presented in the right upper and lower corners and left lower corner of the ERT model, respectively. Hot colours define the resistive structure and cold colours the conductive structure. The shallow ERT profile (a) of 235 m line provides a detailed mapping of the lateral heterogeneities north of Pahia Ammos at a depth of 30 m. The deep ERT profile (b) of 345 m models the subsurface structure at a depth of 80 m. The two ERT profiles reveal a fractured zone of at least 80 m width south of Paleohora.

3. Results of the combined approach

In figure 1, the orange solid line defines the microtremor profile ($L_1L_2$), the green dashed line the orientation of the shallow and deep ERT profiles (P1), and the red dashed lines the E–W faulting on the coastline of Paleohora.

Microtremor recordings were acquired along Pahia Ammos (profile $L_1L_2$, figure 2(a)) to evaluate the dynamic ground seismic response of the surface and subsurface structure. A shift in the fundamental frequency and variations in the shape of HVSR curves using microtremor recordings (figure 2(b)) were observed along the microtremor profile $L_1L_2$. HVSR ground seismic spatial variability along Pahia Ammos (profile $L_1L_2$, figure 2(b)) indicates alluvial thickness variations and lateral heterogeneities/irregularities of the subsurface structure. One amplified frequency in the low frequencies (site A, site E) and two HVSR amplified frequencies with the one...
Figure 4. The shallow and deep ERT profiles presenting the tectonic model along Pahia Ammos southwest of the Paleohora peninsula characterized by a large scale E–W fault of width 80 m dipping to north at a depth of at least 80 m.

ERT profiles were conducted along Pahia Ammos to model the tectonic structure that governs the coastline southwest of Paleohora and to verify the validity of the HVSR technique in determining sites characterized by lateral heterogeneities in the subsurface structure. Wenner–Schlumberger and dipole–dipole configurations were conducted along an ERT resistivity line of total length of 235 m (figure 3(a)) and 345 m (figure 3(b)) with 5 m and 15 m electrode spacing, respectively. A fractured zone located 120 m from the Fortezza bedrock is patterned in the two ERT profiles. The 2D inverted resistivity profile of the shallow ERT line reveals the presence of a left-oblique normal fault with a width of almost 80 m in the near surface, dipping to the south and striking almost E–W at a depth of 30 m (figure 3(a)). The electrode spacing is 5 m along a 235 m ERT line. The final RMS was 44.5%. The 2D inverted ERT of the deep ERT profile reveals an almost E–W striking fault zone of width 80 m in the near surface, dipping to the south down to a depth of at least 80 m (figure 3(b)). The fracture zone is saturated with salt water. The RMS error was 58.9% after ten iterations. The high RMS error is related to the high resistivity contrast (high inhomogeneity) between the seawater intrusion (less than 1 Ωm) and calcitic bedrock (greater than 2500 Ωm), as mentioned above. The ERT profile of the Pahia Ammos beach reveals a thick cemented sandy layer at a distance of 100 m of the Fortezza bedrock (start point of the ERT line). The shallow ERT (figure 3(a)) provides a detailed model of lateral heterogeneities of the substructure (60–120 m) compared to the tectonic substructure of the deep ERT profile at a distance of 120–180 m, which provides depth details. In the southern part of the ERT in Pahia Ammos, the low resistive zone (blue colours) is consistent with the Quaternary alluvial fan deposits (figure 3(b)). The high electrical resistivity amplified either in the medium or high (sites B, C, D and F) frequencies are observed. The one amplified frequency in the low frequencies (site A and E) correlates with thick or soft alluvial deposits. The two amplified frequencies (sites B, C, D and F) are attributed to the effect of alluvial deposits and lateral heterogeneities/irregularities of the subsurface. The one amplified HVSR frequency in the medium or high frequencies is attributed to the effect of lateral heterogeneities of the subsurface while the second amplified HVSR frequency in the low frequencies to the effect of the alluvial deposits overlying the subsurface. At each local investigated site HVSR average, Hns/V and Hew/V spectra ratios present similar ground fundamental frequencies and amplification (figure 2(b)).

The one clear HVSR fundamental frequency at sites A and E with fundamental frequencies 1.31 Hz (site A) and 0.75 Hz (site E) with amplifications 2.11 and 2.3, respectively, indicates thick or soft deposits. The two amplified frequencies are related to the effect of surface deposits and near-subsurface irregularities (sites B, C, D and F). At site B, the fundamental frequency in the low F0 = 0.99 Hz is attributed to the effect of alluvial deposits and the second amplified in the medium F1 = 4.44 Hz indicates the effect of subsurface lateral irregularities. At sites C, D and F, the fundamental frequencies in the medium and high frequencies (9.66 Hz, 11.65 Hz and 7.35 Hz) are related to the near-subsurface lateral heterogeneities/irregularities and the second amplified frequencies in the low frequency range (0.75–0.99 Hz) with the effect of alluvial deposits overlying the near-surface lateral heterogeneities. The shift of the amplified frequency in the medium and high frequencies (7.35–11.65 Hz) indicates depth variations of the subsurface lateral irregularities and is attributed to the effect of the near-surface lateral heterogeneities.
Spatial spectral variations of microtremors and electrical resistivity tomography surveys for fault determination in southwestern Crete, Greece

Figure 5. Cross-correlation of the research outcomes of the combined HVSR and ERT to model the surface and subsurface structure along Pahia Ammos (profile $L_1$,$L_2$). Sites A–F where microtremors acquired along profile $L_1$,$L_2$ are depicted along the deep and shallow ERT profiles. Site F is not presented in the shallow ERT model since the total length of the shallow ERT line is 235 m. HVSR amplified frequencies correlate with the effects of alluvial deposits, thickness variation and lateral irregularities of the subsurface. The lateral irregularities of the subsurface are due to the E–W striking fault zone defined by the ERT survey. South of Pahia Ammos, the one clear amplified low frequency corresponds to the thick sand deposits. The two amplified frequencies are attributed to the effects of alluvial deposits and lateral heterogeneities/irregularities of the subsurface structure. HVSR fundamental and second amplified frequencies at sites B, C, D and F correlate with the subsurface structure irregularities induced by the fault zone.
value (711–3500 Ωm) correlates with the electrical physical properties of the limestone/calcite bedrock (red colour, figure 3(b)). The blue colour is attributed to seawater intrusion (0.34–4.4 Ωm) and the green colour to fresh groundwater (15.6–55.8 Ωm) discharged into the seawater (figure 3(a)). Shallow and deep ERT profiles define a large-scale E–W fault of width of 80 m dipping to the north at a depth of at least 80 m along Pahia Ammos southwest of the Paleohora peninsula and model the tectonic setting along Pahia Ammos (figure 4).

The combined HVSR and ERT surveys applied to model the surface and near-subsurface structure in Pahia Ammos verify that the amplified HVSR frequencies are related to thickness variations of alluvial deposits and the effects of subsurface heterogeneities/irregularities of the structure. ERTs define a large-scale E–W fault zone of width 80 m dipping to the north (figures 3(a) and (b)) at a depth at least 80 m (figure 3(b)). South of Pahia Ammos, the one clear amplified low frequency correlates to the thick sand layer overlying the bedrock. The one clear HVSR fundamental frequency at \( F_0 = 1.3 \) Hz (site A) with an amplification of 2.11 corresponds to a site of alluvial thickness of up to 50 m (figure 5). At site B, the fundamental frequency in the low frequency range \( F_0 = 0.99 \) Hz indicates thick alluvial deposits of thickness of up to 50 m. The second amplified in the medium \( F_1 = 4.44 \) Hz indicates the effect of subsurface lateral irregularities (thick dashed black line, figures 3(b) and 5) induced by the fractured zone. The one clear HVSR fundamental frequency at \( F_0 = 0.75 \) Hz (site E) with an amplification of 2.3 corresponds to a site of alluvial thickness of 20 m (figure 5). The spatial frequency variations at sites C, D and F of the fundamental frequencies in the medium and high frequencies (9.66, 11.65 and 7.35 Hz) is an indicator of depth variations of the lateral subsurface heterogeneities/irregularities induced by the fractured zone (dashed black line, figure 5), while the second amplified frequencies in the low frequency range \( 0.75–0.99 \) Hz are related to the alluvial deposits overlying the near-surface lateral heterogeneities induced by the fractured zone. The shift of the amplified frequency from medium to high frequencies, perpendicular to the lateral heterogeneities, is attributed to the effect of the near-surface lateral heterogeneities induced by a fault zone and indicates closer proximity to the fault structure. A geological ground-truth survey on the coast of Paleohora verified the E–W striking fault, providing justification of the research outcomes. ERT verifies that the lateral heterogeneities recognized using microtremors are induced by the fault zone structure. The combined HVSR and ERT surveys provide a system of cross-comparisons for the determination of surface and subsurface structure and enhances the justification of the HVSR technique to evaluate local site effects induced by lateral heterogeneities/irregularities of the near subsurface.

The contribution of the research outcome of the combined survey in site characterization studies is the applicability and validity of the HVSR technique using microtremors in fault zone delineation. The importance of this contribution is highlighted by the determination of near-subsurface fault zones that are not directly observable at the Earth’s surface. This work suggests that microtremors recorded by a single seismological station are an effective tool for surface and near-subsurface characterization including fault zone delineation, especially in urban areas where other geophysical techniques cannot be applied. However, attention should be given to data acquisition and processing for a reliable and valid research outcome.

The shallow ERT profile north of Pahia Ammos provides a detailed model of the near lateral heterogeneities. Despite the fact that ERT and microtremor methods allow identification of the location of a fault, the activity of the fault cannot be directly estimated using ERT and microtremors. Currently discrimination between active and inactive faults is possible by field observation of the fault plane surface; however, fault activity can be monitored using displacement gauges placed across faults (outside the scope of this study), although this

4. Conclusions

Spatial variability in the HVSR frequency and shape allows patterning of the surface and near-subsurface structure heterogeneities/irregularities induced by a fault zone. The combined HVSR and ERT survey along an E–W fault zone, ground truthed geologically in Pahia Ammos, suggests that (a) HVSR frequencies are related to thickness variations of alluvial deposits and to lateral discontinuities in the near subsurface induced by a fault zone and (b) verifies the applicability and validity of two amplified HVSR frequencies, with one HVSR amplified frequency either in the medium or high frequencies to evaluate near-subsurface lateral heterogeneities/irregularities induced by 2D/3D structures. The one clear HVSR fundamental frequency in the low frequencies is related to thick or soft alluvial deposits. The two amplified frequencies are related to the effect of alluvial deposits and near-subsurface irregularities induced by the fault zone and indicate lateral irregularities of the near-subsurface structure. The HVSR amplified frequency in the medium or high frequencies is attributed to the effect of the near-surface lateral heterogeneities of the subsurface due to a fault zone while the amplified HVSR low frequencies to the effect of the alluvial deposits overlying the subsurface on seismic ground motion. The HVSR shift in the low frequency is relative to the thickness variation of the rest of the geological column that overlies the subsurface structure. The shift of the amplified frequency from medium to high frequencies, perpendicular to the lateral heterogeneities, is attributed to the effect of the near-surface lateral heterogeneities induced by a fault zone and indicates closer proximity to the fault structure.

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cannot be done so easily in the case of buried faults. In seismic hazard studies, of importance is the delineation of faults, since active and inactive faults behave as wave-guides in an impinging seismic wave front. However, the possibility that a previously inactive fault may become active during an earthquake should be considered in earthquake hazards studies.

A detailed survey of the surface and subsurface structure of an area will significantly contribute to seismic hazard reduction planning. The presentation of geological investigations combined with electrical resistivity tomography surveys can reveal the complex tectonic structure of the area. In addition, the presentation of a detailed microzonation study will provide a crucial step in earthquake scenarios, seismic regulation, land use planning and earthquake hazard reduction programmes in the area.

Acknowledgments
This study is partly supported by the SERISK project. We thank Dr G Romano and Dr A Ciocoli for their collaboration in the ERT surveys. MM is sponsored by the Greek State Scholarships Foundation (200430098). We thank the two anonymous reviewers for their amendments.

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