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Site response analysis of Vartholomio W-Greece from singular spectrum analysis of microtremor and weak motion data

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ABSTRACT

Twenty six sites were instrumented in the city of Vartholomio following the December 2, 2002 Ms 6.0 earthquake. Thirty weak events from the aftershock sequence as well as microtremors were used to identify amplifications due to geological site effects. Horizontal-to-vertical spectral ratios (HVSR—Nakamura estimates) and weak events ratios were calculated and the singular spectrum analysis (SSA) method was used. The results showed that the effects of SSA on the stability of the frequency peak and amplitude distribution of HVSR for both weak motion and microtremors. The data analysis confirms the role of near surface geology in causing locally significant variations of the predominant frequencies and amplitudes of ground shaking as already inferred from the distribution of damages. The site response spectra exhibited significant peaks within the range of 1.5–2.6 Hz and the amplification factor did not exceed 6.5. Finally the parts of the HVSR ratios from ~0.2 up to 10 Hz were used, in order to create an automatic optimal zonation of the study area using a genetic algorithm. This procedure resulted in the division of the city into 2 main zones.

1. Introduction

Local site conditions are one of the most important factors which characterize the distribution of earthquake damage. Well known examples from San Francisco (1989), Guerrero Michoacan (1985), Northridge (1994), Kobe (1995), Armenia (1999) and Turkey (1999) earthquakes have been extensively cited to illustrate the role of surface geology on seismic waves. Reliable site response models are essential to estimate the amplification potential and the probabilistic and deterministic distributions of the peak and spectral amplitudes of ground shaking at the surface.

Many experimental methods have been used to quantify the site effects and define the site response functions (e.g. Field and Jacob [14]). Although the best determination of site response functions is obtained from strong ground motions [30], spectral analysis of microtremors (low amplitude ground motion continuously recorded when earthquakes are not recorded) and weak motions from earthquakes can be an alternative tool to quantify site effects [2].

The horizontal-to-vertical spectral ratio (HVSR) (the ratio between the Fourier amplitude spectra of the horizontal and vertical components of the microtremors) was first introduced by Nogoshi and Igarashi [27] and was widely spread by Nakamura [24–26]. Since then, many investigators have reported the successful application of the method for estimating the fundamental frequency f_0, which has been applied also inside urban environments e.g. [3,4,11,13,15,20,29,31]. Furthermore, several studies e.g. [8,33] found that the HVSR results are correlated with the distribution of damages, after taking vulnerability into consideration.

Several theoretical 1D investigations that have computed microtremor synthetics using randomly distributed near-surface sources e.g [14,18], have shown that H/V ratios sharply peaked around the fundamental resonance frequency of SH waves whenever the surface layer exhibits a sharp impedance contrast with the underlying stiffer formations.

A simple straightforward modification of the above technique consists in taking the spectral ratio between the horizontal and the vertical components of weak earthquake recordings. This technique is in fact a combination of Langston's [19] receiver function method for determining the velocity structure of the crust from the horizontal to vertical spectral ratio of teleseismic P waves, and Nakamura's method. In the literature several studies can be found where weak motion data where applied to assess site effects in urban areas, even though originally they were not proposed for cities e.g. [10,23,31,32,34,36,38,39] exhibiting a rather good correlation with surface geology, and in many cases are able to predict site resonance frequencies, whereas there is a lower reliability on the amplification factors [2]. Most of the earthquake data examined in the HVSR investigations are relevant

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to weak motion recorded at short term temporary networks deployed for microzonation purposes. To obtain a statistically significant database of weak events we need long recording periods, with the exception if we install the network to record an aftershock sequence, as it is in our case. Theodulidis et al. [34] using a dataset of 22 earthquakes at the Garner Valley array, concluded that the HVSR applied to weak motion data showed good stability and it was not influenced by source location of mechanisms. In another investigation Mucciarelli et al. [23], after analyzing two years worth of data, concluded that HVSR is a remarkably stable site dependant feature.

Recently Carniel et al. [9], showed that the application of the singular spectrum analysis (SSA) methodology on Nakamura's approach can improve the results. The SSA allows the time series to be decomposed into different components, e.g., the signal itself, as well as various noise components, which can be subsequently removed from the time series. Since microtremors and weak motions are measured along two horizontal directions and one vertical direction, we get two Nakamura spectral ratios that in many cases show considerable difference. The cause of this difference may be the presence of artificial noise (e.g. ghost transients) and the application of the SSA methodology can reduce this effect.

Finally in order to identify parts of the study area that have similar ground-motion behavior, an automatic method using genetic algorithms as in [5,6] is employed. This method uses the classification of the HVSRs as objective criteria for an initial microzonation of the area.

2. Geological setting and data

The city of Vartholomio is located in the most seismically active part of Greece, and is undergoing urban development. During its history, strong earthquakes have severely affected the site. On 16 October 1988 an M_s=5.9 earthquake reached a seismic intensity of 7 on the MSK scale, causing serious damages in the city. The seismic intensity was higher than would normally be expected from the magnitude and epicentral distance of the earthquake (Fig. 1). More recently, the M_s=6, December 2, 2002 earthquake, severely damaged many parts of the town, reaching a seismic intensity of 5–6 on the MSK scale. It is likely that the structural damages all over the area of Vartholomio, after taking into account the vulnerability of the structures, are caused by local site effects of the sedimentary layer that may have amplified the earthquake ground motion.

Following the December 2, 2002 Ms 6.0 earthquake and during the period from December 7, 2002 to January 7, 2003, the University of Patras seismological lab installed and operated a 26 stations seismological network in and around the city of Vartholomio (Fig. 1). The stations were instrumented with a LandTech LT-S01, three component velocity sensor with flat response between 0.2 and 100 Hz and a sensitivity of 1000 V/m s. The seismological data have been recorded using an EarthData 24bit digitizer with a sampling rate of 100 samples /second.

The study area is situated on the external part of the Hellenic Arc and therefore subjected to intense neotectonic deformation and high seismicity. More specifically, this area is part of the neotectonic depression (graben) of Pirgos, which is delimited by two faults of NW–SE and NNE–SSW direction and it is characterized by co-sedimentation tectonism [21].

To the west of the city of Vartholomio, there are outcroping alpine formations (Ionian zone). These are considered as the bedrock of Vartholomio. In geochronological order, three geological formations can be located [22]:

The Vounargo formation, having a total thickness that can exceed 500 m, comprises of various sandstones and shales. This formation outcrops to the west of Vartholomio.

Developing unconformably over the previous Vounargo formation, are the Calcitic Sandstones. They contain locally fine or coarser material, from various rocks. This unit has a thickness of up to 20 m.

Alluvial formations, composed of clayey sands and sandy clays, overlying unconformably the previous formation. These occupy the major plain of Vartholomio and their thickness is increasing towards the east.

The topmost layer, inside the city, has a thickness increasing from 6 m in the Western part to 15 m in the Eastern part, and

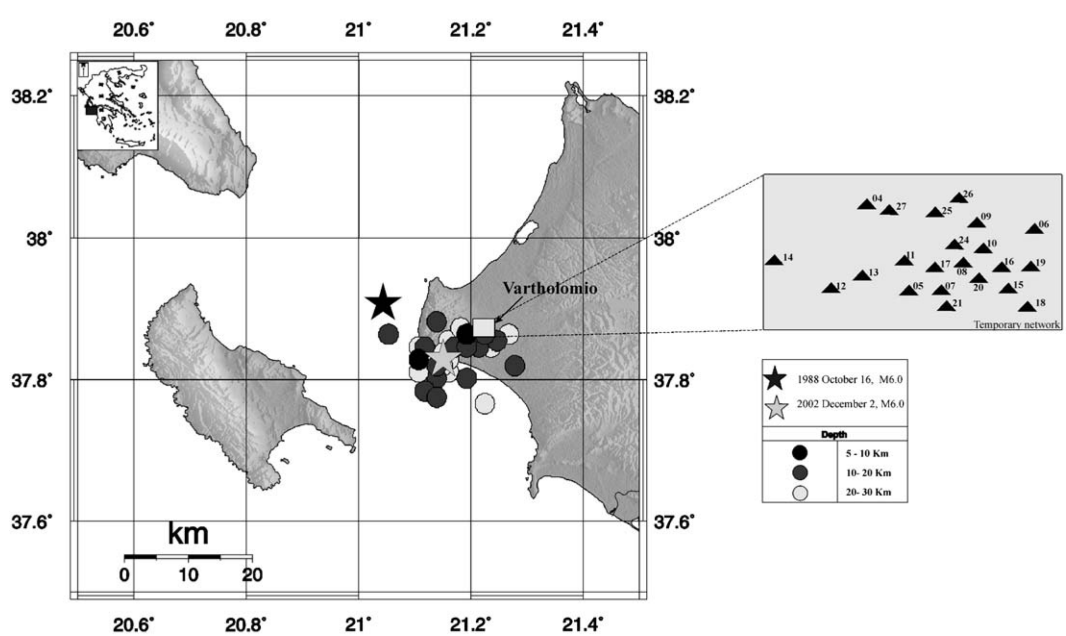

Fig. 1. Epicenters of the M_s=5.9 1988 (black star) and M_s=6.0 2002 (grey star) earthquakes. Triangles depict the installed microearthquake network within the Vartholomio city. Circles are the epicenters of the weak motion data used in the present investigation.