Assessment of site specific earthquake hazards in urban areas. A case study: the town of Afula, Israel, and neighbouring settlements

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ABSTRACT Quantifying the seismic hazard in terms of acceleration response spectrum, we present a methodology in which dense measurements of the horizontal-to-vertical (H/V) spectral ratios from ambient noise are used to assess the site-specific uniform seismic hazard across urban areas. This process of hazard assessment involves: detailed mapping of the fundamental and other natural frequencies and amplitudes of H/V spectral ratios; compiling geological, geophysical and borehole data and integrating it with H/V observations to develop models for the subsurface of many sites across the study area. The subsurface model serves as input for computing the expected Uniform Hazard Site-Specific Acceleration Response Spectra at the investigated sites. The final stage is generalizing the hazard by mapping zones that feature similar seismic hazard functions. This paper demonstrates the methodology and the applied procedures by presenting the studies performed in the town of Afula in Israel. The study area is slightly extended to include close-by settlements around the town.

1. Introduction

The Holy Land has a long documented history of destructive earthquakes (e.g. Amiran *et al*., 1994). This information, descriptive in its nature, is very useful for learning about the earthquake history of the region. However, questionable reliability of many historical "facts", the dramatic change in the demographic conditions, the changing engineering characteristics of the buildings and changes in geographical locations of towns and villages present great difficulties in using the macroseismic information to reliably assess the earthquake hazards.

In a series of previous studies we successfully applied the procedure developed by Shapira and van Eck (1993) to assess the site specific uniform hazard acceleration response. That procedure which we term SEEH (Stochastic Estimation of the Earthquake Hazard) is based on the stochastic method developed and used by Boore (1983), Boore and Atkinson (1987), Boore and Joyner (1991) among others. In brief, the SEEH process starts by performing Monte Carlo simulations of the expected seismic activity in seismogenic zones that may affect the study area. The seismicity and other regional parameters that characterize earthquake hazards in Israel are presented and discussed by Shapira and Hofstetter (1993), Shapira and van Eck (1993), e.g. Hofstetter *et al*. (1996), Jiménez *et al*. (2001), Shapira (2002), Begin (2005) and Begin *et al*. (2005). These studies were used to specify the seismogenic zones affecting the region and their seismicity in the form of frequency-magnitude relationships. Considering the uncertainty in estimating the frequency of occurrence, we generate several possible earthquake catalogues (artificial catalogues) for a long time span (thousands of years). These simulations are followed by synthesizing S wave ground motions at the investigated site from each of the earthquakes in the artificial catalogues using the stochastic method (e.g. Boore 1983, 2000). The site response due to the propagating waves from the base-rock to the site's surface are computed given the properties and structure of the subsurface at the analysed site. This wealth of synthetic free surface motions, representing what may happen in a long time span are used to compute the corresponding acceleration response spectra for a 5% damping ratio. In the final stage of SEEH all generated response spectra are assembled to estimate the spectral accelerations which correspond to a prescribed probability of exceedance and yield the uniform hazard, site specific acceleration response spectrum. The uncertainties associated with the values assigned to different parameters in the computations are considered by performing Monte Carlo simulations throughout the SEEH process. These involve the uncertainty in Q-values, magnitudes, seismic moments, stress drop and attenuation derived from previous studies performed in the region. For more details about the SEEH approach see Shapira and van Eck (1993). Implementation of the SEEH process for assessing the earthquake hazard throughout a limited size region, e.g. a town, practically requires the same input data except for data that characterize the subsurface. These parameters which determine the expected site response to seismic waves may vary significantly over very small distances.

Various empirical techniques for site response estimations were summarized and discussed by Field and Jacob (1995). It is likely that the best evaluation of site effect will be based on comparing strong motion observations at sedimentary sites with those of bedrock reference sites. Such observations also include effects of the nonlinear behaviour of the materials. Empirical response functions obtained from measurements of different earthquakes may still vary significantly due to nonlinear effects as well as other effects such as directivity, differences in the propagation path and properties of the earthquake source functions (see also Boore, 2004). This empirical approach, however, is impractical in regions where seismicity is moderate as in Israel. Furthermore, attempts to derive site response estimations from simultaneous recordings on sediments and on hard rock in an urban area may not be possible.

Nakamura (1989) hypothesized that the site response could be estimated from the spectral ratio of the horizontal versus vertical (H/V) components of ambient noise observed at the same site. Many authors, among them Lermo and Chávez-García (1994), Seekins *et al*. (1996), Toshinawa *et al*. (1997), Chávez-García and Cuenca (1998), Enomoto *et al*. (2000), Zaslavsky *et al.* (2000, 2003), Shapira *et al*. (2001), Mucciarelli and Gallipoli (2004), show that the H/V spectral ratio technique can be a useful tool for the assessment of ground motion characteristics on soft sediments. However, other authors [for example, Bonilla *et al*. (1997), Horike *et al*. (2001), Satoh *et al*. (2001)] conclude that a predominant peak of H/V ratio is well correlated with fundamental frequency, but amplitude of this peak is not similar to those obtained from sediment-to-bedrock spectral ratio of earthquake records. Our measurements of ambient noise in urban environments in Israel (more than 3000 sites) show that in sites with relatively high level of ambient noise and impedance contrast of shear wave velocity between rock and soil (velocity ratio more than 3.0) there is a good agreement between H/V amplitudes of the fundamental mode (sometimes also second mode) and the theoretical transfer function calculated by e.g. the SHAKE program (Schnabel *et al.,* 1972).

Site specific hazard assessment in urban areas requires additional studies focussing on modelling and characterisation of the subsurface at different locations within the study area. These in turn are used to determine the expected site effects due to the structural and geotechnical site conditions.

In this paper, we demonstrate the process of seismic hazard microzoning by describing the study performed in and around the town of Afula, Israel. Afula is a relatively small town of about 30,000 inhabitants. Afula is one of Israel's developing urban areas. It was chosen for the microzonation study due to its proximity to the major seismogenic zone of the Dead Sea Rift and its branching faults (e.g. the Carmel fault). Several major historical earthquakes occurred during the present millennium with epicentres as close as 25-70 km from the investigated area. Because it is a relatively new town, there are no clear historical records of earthquake effects in the vicinity of Afula, yet, the town is built on soft sediments overlying basaltic bedrock. This geological setup suggests high site amplification effects.

2. Geological setting

The town of Afula and surrounding settlements are situated in the Lower Galilee, where NW-SE trending tectonic depression of the Yizreel valley meets the Jordan rift. The region is underlain by a volcano-sedimentary sequence up to 800 m thick of Miocene to Pleistocene age. Fig. 1 shows the geological map (after Dicker, 1969). Based on this geological information, the study area may be divided into three structural zones.

(a) The Givat Hamore block. This zone is an uplifted block, structurally controlled by normal marginal faults directed NW- SE. The western part of the block slopes down towards the Yizreel Valley. It consists of the Limestone complex of Eocene age. The top of the hill is composed of igneous intrusive basic bodies of Miocene age. The Lower Basalt flowed from Givat Hamore, where it is discordantly resting on the Limestone complex.

(b) The Balfouriyya - Afula Illit Lower Basalt ridge. A low, 3.5 km long basalt ridge extends in a western direction as a continuation of the Givat Hamore block, from Afula Illit in the east to Balfouriyya in the west. The Lower Basalt of Miocene age in this zone crops out in the central part of the ridge. To the north, it is overlain by the recent sediments 10 m thick.

(c) The Afula Depression. It includes the Lower Afula and the settlements of Merhaviya and Sulam. This zone is a flat plain of Neogene age. Neogene sediments consisting of clay, marl, calcareous sandstone or chalky limestone, Cover Basalt, conglomerate and recent sediments overlie the Lower Basalt. The total sediment thickness increases from Givat Hamore to the southwest by almost 500 m.

3. Ambient noise measurements and analysis

This study covers an area of 40 km^2 and includes the town of Afula and surrounding villages. Ambient noise measurements were carried out in this area from September to December 2005.

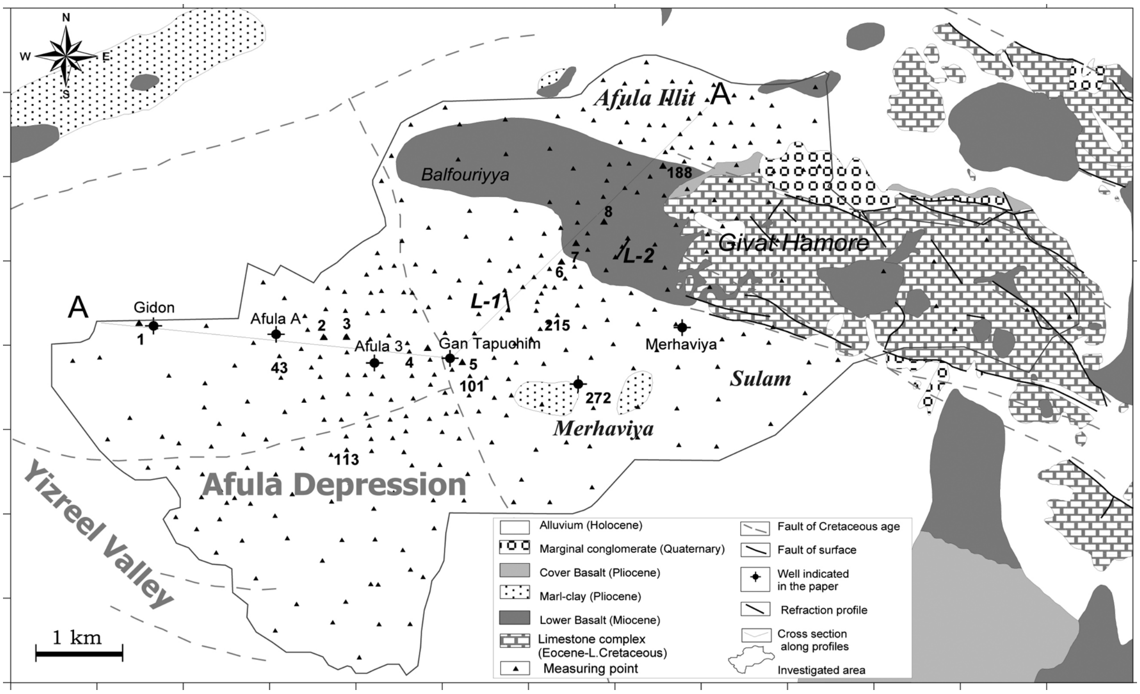

Fig. 1 - Geological map of the Afula area (scale 1:50,000). Locations of sites used as examples in the paper are numbered.

The distribution of measurement points over the study area is shown in Fig. 1. We designed a large spacing between measurement points (500 m grid). High variations in the observations led us to increase the density to a grid spacing of 250 m and in some sites even 150 m. Ground motion (particle velocity time history) was recorded using the multi-channel digital seismic data acquisition system designed for site response field investigations (see Shapira and Avirav, 1995). The data acquisition system includes: a multi-channel amplifier with band pass filters 0.2-25 Hz, GPS (for timing) and a laptop computer with a 16 bit/word analog-to-digital (A/D) conversion card with a sampling rate of 100 samples/s. The seismometers are velocity transducers (L4C by Mark Products) with a natural frequency of 1.0 Hz and damping at 70% of critical. At each site, the ambient noise was recorded continuously for 60-70 minutes, creating data files of 3 minutes each.

To study the spectral character of the ambient noise, we computed spectra and spectral ratios. The record length (time window) used for spectral calculations depend on the fundamental frequency; 30 s records at sites with frequencies above 1 Hz and 60 s records for sites with frequencies less than 1 Hz. The selected time windows were Fourier transformed, using cosine-tapering (1 s at each end) before transformation and then smoothed with a triangular moving Hanning window. The H/V spectral ratios were obtained by dividing the individual spectrum of each of the horizontal components [$S_{NS}(f)$ and $S_{EW}(f)$] by the spectrum of the vertical component [$S_V(f)$]. To obtain consistent results from the spectra of ambient noise, we used 60-70 time windows and then averaged the spectral ratios. When the $S_{NS/V}$ and $S_{EW/V}$ are similar, the H/V

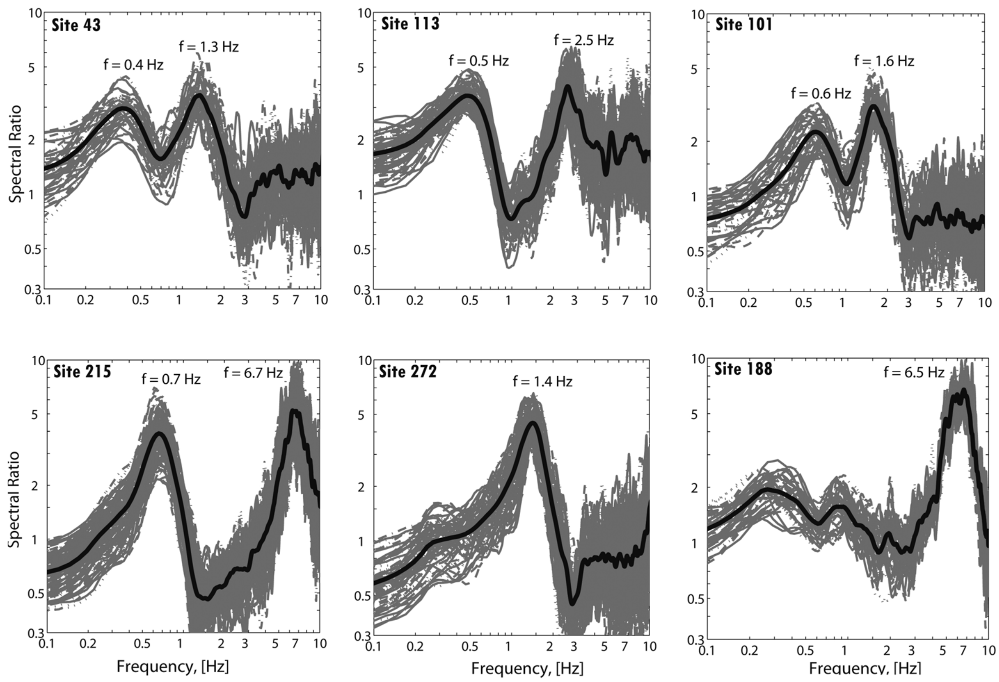

Fig. 2 - Examples of average spectral ratios at sites with different geology.

spectral ratios is the average of the two spectral functions. The program SEISPECT (Perelman and Zaslavsky, 2001) was specially developed for routine analysis in the frequency domain.

4. Results

4.1. Examples of H/V spectral ratios

Examples of the individual and average H/V spectral ratios calculated for stations deployed at sites with different subsurface structures are displayed in Fig. 2. These examples demonstrate the high variability in the site response across the study area. The main feature of spectral ratios at sites 43, 113, 101 and 215 (for site location see Fig. 1) is the two clear peaks appearing at different frequencies. Our recent studies (see e.g. Zaslavsky *et al.*, 2006) show that such an observation is associated with two impedance contrasts: one at deeper and the other at shallow strata. The corresponding frequencies are interpreted as fundamental (f_0) and other natural (f_1) ones. Similar conditions are observed in most of the analyzed sites.

4.2. Distribution of H/V resonance frequencies and their associated amplitude levels

The increased intensity of the damage during earthquakes is, to a great extent, correlated with resonance effects, therefore mapping of resonance frequencies and their associated H/V amplitudes is very useful for at least a qualitative assessment of the seismic hazard.

Fig. 3 presents maps of the contoured fundamental resonance frequency (f_0) and the associated

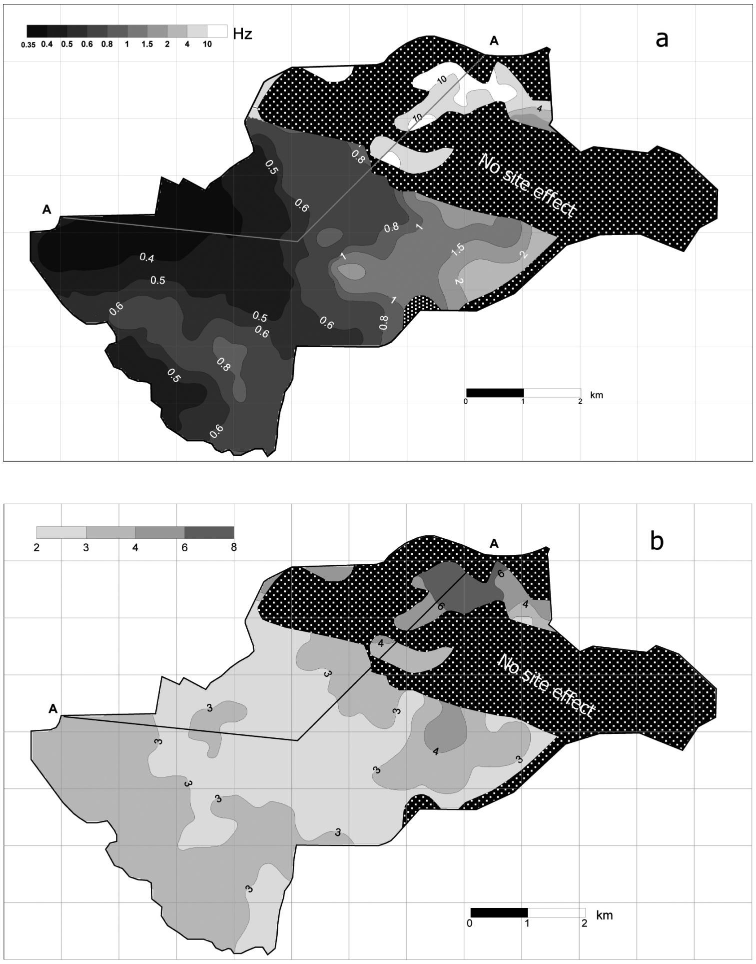

Fig. 3 - Maps of the distribution of: a) the fundamental (f_0) frequency and b) its associated H/V level.

H/V amplitude ratio. The spectral peaks vary from 0.3 Hz to 12 Hz with H/V amplitude in the range of 2-8. These frequencies are associated with the Lower Basalt of Miocene age and its morphology is reflected in the measurement results. For example; the trend of increasing frequency from 0.3 Hz to 3 Hz, reflects the thinning toward the east and northeast of the sediments overlying the Lower Basalt layer.

Based on the observed distribution of the fundamental frequency within the Afula depression that is covered by alluvial sediments, we may - as a first approximation - divide the territory into four zones which are highly correlated with the local geology. We observe a good concurrence between the boundaries of the selected areas and deep faults of Cretaceous age indicated in the geological map (Fig. 1). This observation may suggest that those faults were also active in Neogene time when the Afula depression was forming.

The 4 zones are:

- The zone characterized by f_0 = 0.3-0.6 Hz in the northwest part of the study area where the Lower Basalts are deepest. According to the "Gideon" well data the Lower Basalt is at a

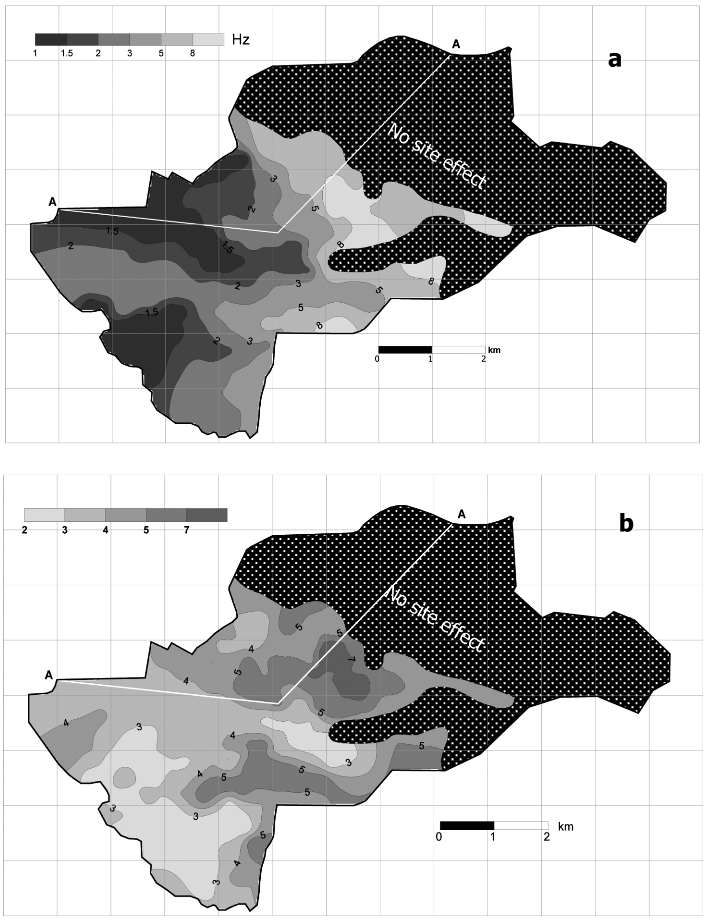

Fig. 4 - Maps of the distribution of : a) the natural (f_1) frequency and b) its associated H/V level.

depth of 476 m.

- The zone characterized by f_0 = 0.6-0.8 Hz in the northeastern part of the study area. The zone is discontinued by the Lower Basalt ridge, that implies presence of faults, probably, an extension of the southern margin faults of Givat Hamore to the west. In the southern border of this zone we suggest another fault, which is indicated by increase of f_0 from 0.8 Hz up to 1 Hz over a short distance.
- The upstanding block in the southeast part of the study area, where the Lower Basalt is found at a depth of 40 m (“Kfar Merhavia” well) and is characterized by f_0 of 1-3 Hz. Sharp decrease from 1 Hz down to 0.8 Hz in the western border of this block may be connected with faults, which likely limits the extension of the Cover Basalt to the east.
- The zone characterized by f_0 = 0.5- 0.8 Hz in the south of the Afula depression.

The impedance contrast responsible for the fundamental peak of the H/V function is formed by the Pliocene-Quaternary sediments overlying the Lower Basalt. The amplitude varies mostly from 2 up to 4. Only in the southeastern part of the Afula depression, where the Pleistocene

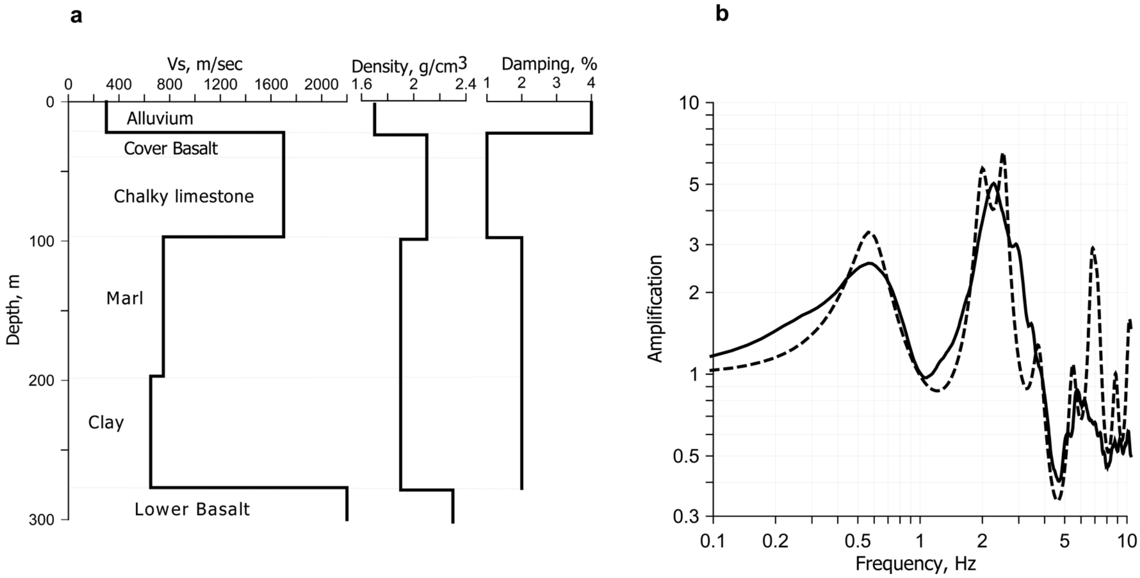

Fig. 5 - a) Geotechnical parameters of the subsurface at "Gan Tapuchim" well site; b) comparison between the observed H/V spectral ratio (solid line) and the analytical response function (dashed line) of that site.

conglomerates overly directly the Lower Basalt, H/V amplitudes reaches 5. Flat H/V spectral ratios with no resonance frequency are observed at sites located in the Balfouriyya-Afula Illit ridge (outcrop of the Lower Basalt) and Giv'at Hamore block (exposure of the Eocene deposits). Within this zone we detected some anomalies characterized by f_0 = 4-12 Hz and H/V amplitudes of 3-9. They are associated with the weathered basalt, alluvium and conglomerates covering the Lower Basalt. Not as would have been expected from the mapped surface geology, basalt outcrops do show site effects and sites with alluvium do not indicate possible amplifications. Apparently, geological maps are not good enough to reliably indicate where significant site effects should be expected.

Contour maps of f_1 and its associated H/V amplitude are presented in Fig. 4. The second peak in the H/V spectral function is related to a shallower reflector that is the Cover Basalt and limestone of Pliocene age. In the southeastern part of the Afula Depression the shallower reflector is probably the Quaternary conglomerate. High H/V amplitudes are observed in the eastern part of the Afula Depression, where alluvium of a thickness of few meters overlies the uplifted Cover Basalt.

4.3. Validation of H/V spectral ratio

Nakamura (1989) implies that the H/V spectral ratio of ambient noise is a fair representation of the site response function. This claim is a rather controversial topic. However, we would like to add to that discussion by comparing the observed H/V spectra with analytical site response functions computed for sites with known subsurface geology and located in the study area. This is done by examining H/V measurements made near boreholes and where a geophysical refraction survey was conducted. The location of the refraction lines and the wells are shown on

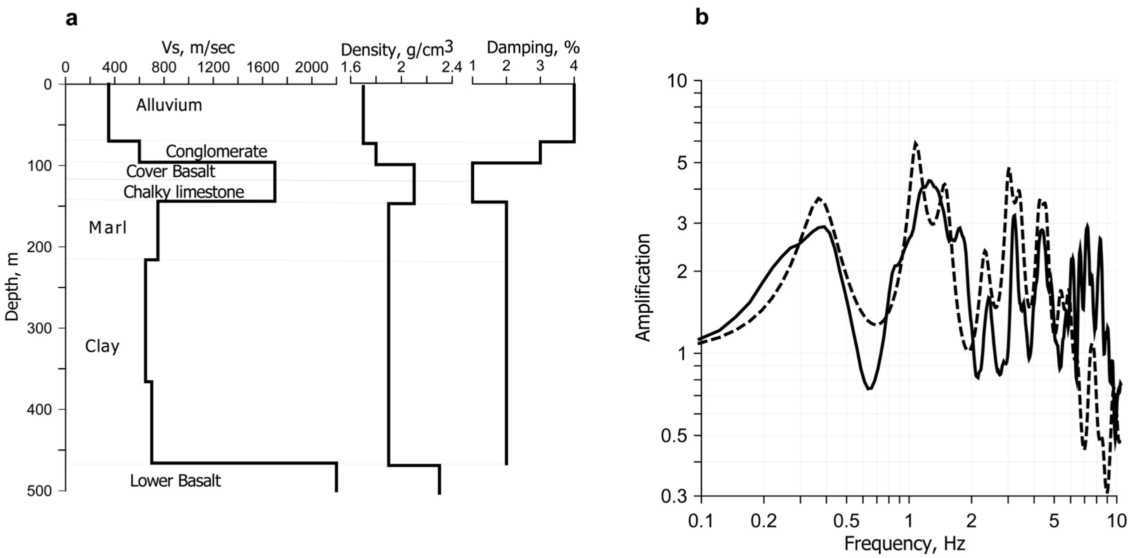

Fig. 6 - a) Geotechnical parameters of the subsurface at "Gideon" well site; b) comparison between the observed H/V spectral ratio (solid line) and the analytical response function (dashed line) of that site.

the map in Fig. 1.

The geotechnical data and soil profile for the "Gan Tapuchim" well, characterizing generally the lithological structure of the Afula Depression and reaching the Lower Basalt, is shown in Fig. 5. Shear wave velocities of V_s=250 m/s for alluvium and V_s=1800 m/s for the Cover Basalt are provided by the refraction survey along profile L-1 conducted close to the "Gan Tapuchim" well. V_s=2200 m/s for the bedrock was obtained in the refraction survey along profile L-2 carried out at the Lower Basalt ridge. V_s=750 m/s for marl and V_s=650 m/s for clay were taken from geophysical surveys at different places in Israel and validated in previous studies (see e.g. Zaslavsky *et al.*, 2004a).

The sediment and bedrock density and damping values required for the computation of the site response functions are copied from literature sources. The calculated analytical transfer function for "Gan Tapuchim" soil column is shown in Fig. 5. The two modes of the analytical transfer function related to the Lower and Cover Basalts well match both peaks of the H/V spectral ratio.

The other example is the site near the "Gideon" well. The geotechnical set up of the "Gideon" well is shown in Fig. 6. The "Gideon" well penetrates the Lower Basalt at a depth of 470 m. V_s for the conglomerates layer is inferred from seismic refraction Line-2. Considering the fact that the thickness of the clay layer is 250 m, we increase its velocity from 650 to 700 m/s in accordance with V_s-Depth dependence derived by Zaslavsky *et al.* (2004b). The good match between the observed H/V spectral ratio and the calculated site response function is shown in Fig. 6. We will note that agreement between experimental H/V spectrum and analytical response functions for the higher harmonics is occasional. Usually, we do not expect the Nakamura technique to reveal high harmonic features.

It should be emphasized that other studies conducted by us at different sites in Israel also

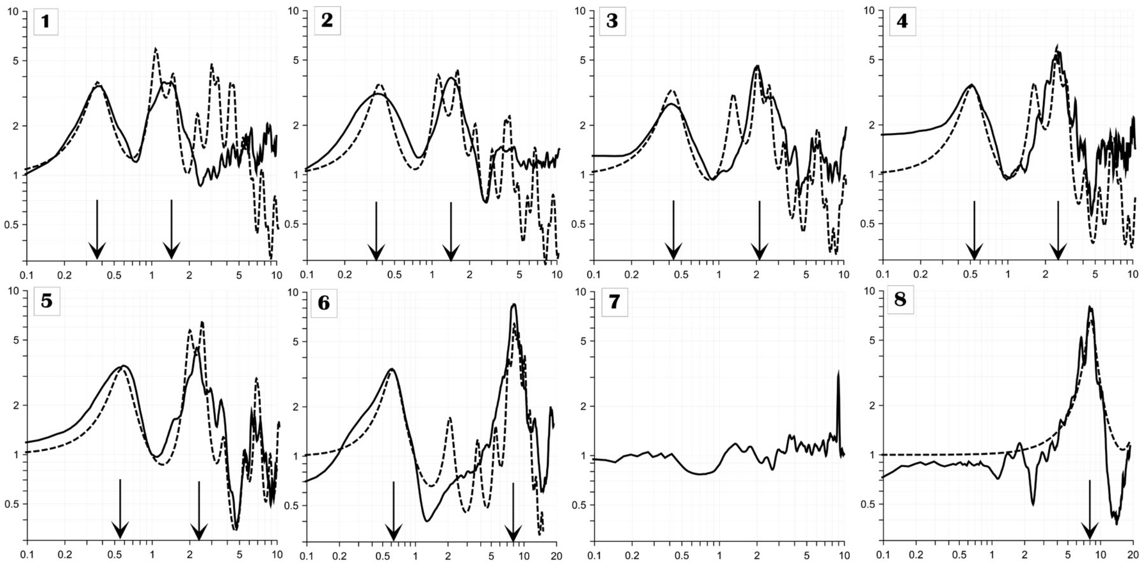

Fig. 7 - Comparison of H/V spectral ratio (solid line) and theoretical transfer function (dashed line) at selected sites along profile A-A-A'. Number in graph corresponds to number of site in profile.

clearly and convincingly indicate that the H/V spectral ratios are a good representation of the expected site response (fundamental and other natural frequencies and their corresponding amplifications) to small strains as computed by commonly used programs such as SHAKE.

4.4. Estimation of subsurface structure along profile

Encouraged by the good fit between the H/V spectral ratios and the analytical response functions computed for the local site conditions, we use observed resonance frequencies and their corresponding H/V amplitudes across the investigated area to construct subsurface models which in turn will be used for site response computation. The constructed subsurface models will thus be based on available geological and geophysical data and constrained by the empirical H/V information. The dense grid of measurement sites puts further constraints on depths and the V_s values used in the models and helps to maintain consistency across the investigated area.

As in the case of Afula, V_s velocities are well constrained by well logs and seismic refraction surveys, here, H/V spectral ratio information contributes mainly in estimating layer thicknesses where well data or other data are not available. When considering both frequencies, the layer thickness may be estimated quite accurately, using the second resonance peak as additional constrain in selecting a plausible value.

The practical relevance of ambient noise investigations may be illustrated by means of cross-sections, whose positions are indicated in Fig. 1. H/V spectral ratios obtained at eight of 32 measuring points along profile A-A-A' are shown in Fig. 7. A simplified sketch of the geological cross section A-A-A' reconstructed using ambient noise measurements, is shown in Fig. 8. The prominent feature for H/V ratios from point 1 to point 6 is the shape of the curve showing two peaks correlated with the Lower and Cover Basalts within the Afula Depression. From the

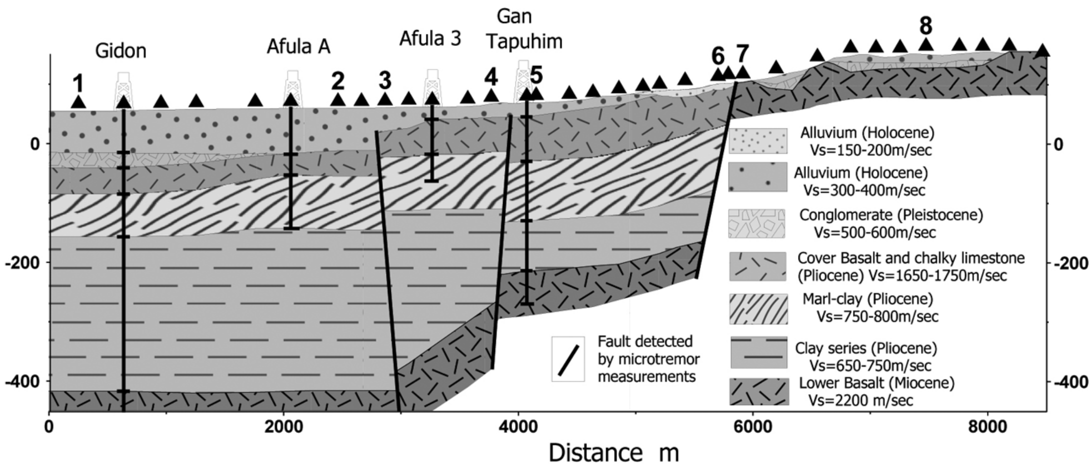

Fig. 8 - Simplified sketch of geological cross section along profile A-A-A' reconstructed on the basis of interpreting the H/V spectral rations of ambient noise measurements, surface geology, limited borehole data and regional refraction surveys. Measuring sites are marked by triangles.

beginning of the profile at point 1 to point 2 there are no noticeable changes in frequency and amplitude, reflecting the quiet relief of the basement. The calculated layer thicknesses are confirmed by the "Gideon" and "Afula A" well information. Between points 2 and 3 there is an increase in both f_0 (from 0.35 Hz to 0.45 Hz) and f_1 (from 1.5 Hz to 2 Hz). The observations suggest an unmapped fault with a vertical displacement of about 50 m. The central part of the profile (from point 3 to point 4) goes over a tilted block of the Lower Basalt layer located between two horizontally layered basalt blocks underlying points 1and 2 at one side and points 5 and 6 on the other side (the uplifted block). The maps in Figs. 1 and 4 suggest that there is a fault between points 4 and 5 and that point 6 is located at the edge of the uplifted block. This interpretation is also supported by information from the well logs. Within this uplifted block f_1 increases and reaches 8 Hz with amplitude H/V= 8, indicating a thinning of the upper alluvium layer and a decreasing of its S wave velocity. Along the profile and up to point 6 we observe spectral ratio functions of the same shape and with H/V amplitudes to be of the same order (see examples in Fig. 7). This indicates vertical shifts of the basement with no significant change in velocity contrasts. The amplitudes are mainly influenced by the variations in V_s of the alluvium layer. It is important to understand that similar changes in frequency and amplitude are also detected at the surrounding points.

Point 7 shows no site effects and is located on an outcrop of the Lower Basalt. The vertical displacement of the Lower Basalt layer underlying points 6 and 7 is estimated to be about 300 m. Point 8 is one of the points located over the Lower Basalt ridge. Its H/V spectral ratio exhibits single high amplitude peak at a frequency of 8 Hz which corresponds to the thin alluvium layer overlying the basalt. The very thin conglomerate layer underlying the alluvium has no effect on the H/V spectrum.

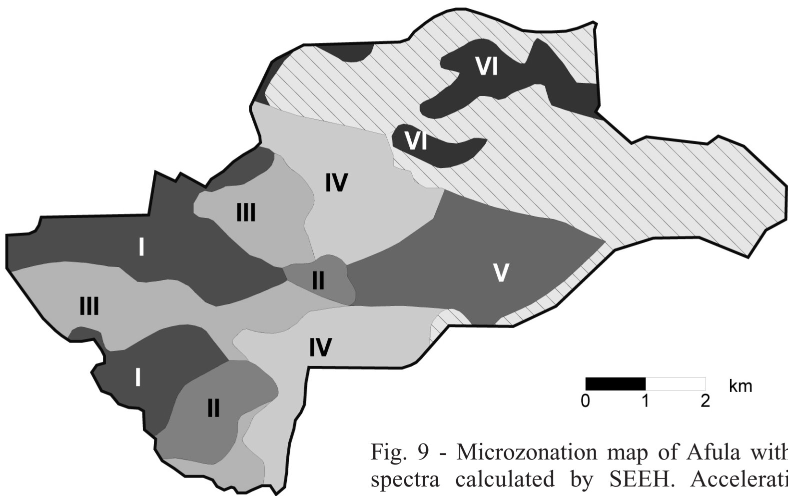

Fig. 9 - Microzonation map of Afula with respect to acceleration response spectra calculated by SEEH. Acceleration spectrum for hatched zone corresponds to the Israel Building Code.

4.5. Seismic hazard microzonation

The design acceleration spectrum is essentially a representation of the maximum acceleration amplitudes for a prescribed probability of occurrence developed on a set of one degree of freedom oscillators with a given damping ratio. Since seismic activity in areas such as Israel is low, local acceleration data from strong earthquakes is insufficient to estimate directly the design acceleration spectrum. Neither do we have good reasons to assume that empirical attenuation functions of spectral accelerations that have been developed from observations in other parts of the world are applicable in Israel, let alone in areas where we expect geological site effects. Consequently, we prefer to resort to the use of synthetic data where local and regional characteristics of the geology and the seismicity are incorporated into the modelling.

The SEEH procedure developed by Shapira and van Eck (1993) and briefly described above, generates synthetic site specific acceleration response functions while considering; possible scatter of the attenuation parameters of S waves propagating the region, estimations of seismic moments from local magnitudes, possible stress drop values that are likely to be associated with earthquakes in the region etc. All mentioned uncertainties are incorporated in the process by using Monte Carlo statistics. The latter is also used to incorporate the uncertainty in estimating the seismic activity in the regional seismogenic zones located within 200 km of the investigated site. The response function of the soil column of the site is calculated by using the program SHAKE. The seismic hazard function, i.e., the uniform hazard site-specific acceleration response spectrum is computed for 10% probability of exceedance in an exposure time of 50 years and a damping ratio of 5%.

By comparison to the Uniform Hazard Acceleration Spectra calculated for 60 selected sites and in consideration of the constructed subsurface models across the investigated area excluding that part where no site effect is revealed, we subjectively divided the area into 6 zones (see Fig. 9). Each zone is characterized by a generalized seismic hazard function representative of the sites

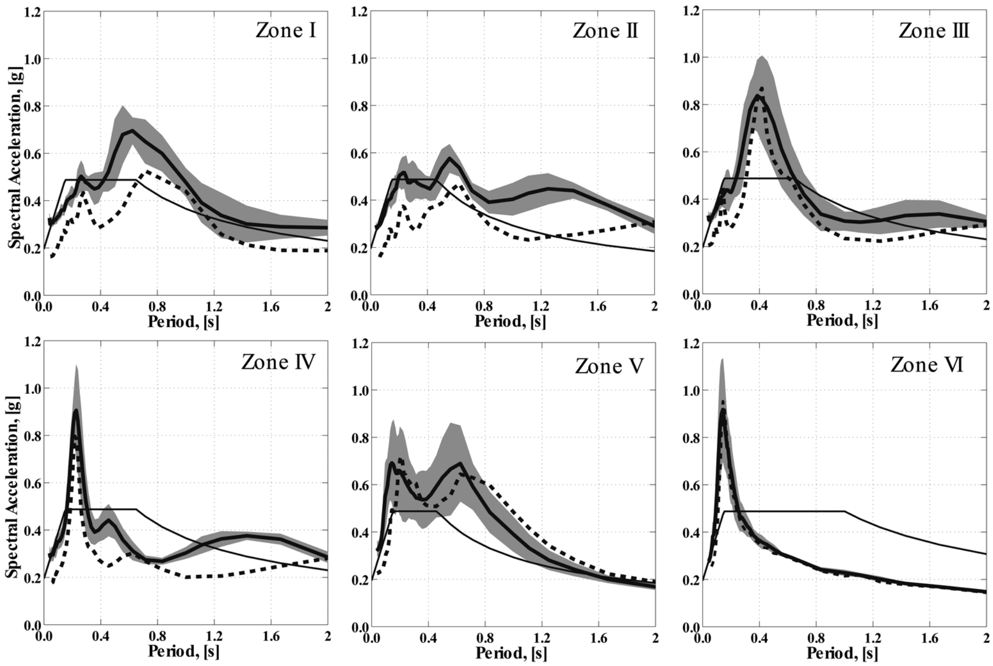

Fig. 10 - Characteristic uniform hazard site specific acceleration response spectra for 6 seismic hazard zones across Afula. The solid thick line represents linear behaviour of the soils +/- one standard deviation (shaded area); dashed line represents the hazard allowing for non-linear behaviour of the soils; solid thin line represents the acceleration design function according to the Israel Building Code. All functions adhere to the same probability of exceedance (10% in 50 years), same damping ratio (5%) and same soil type.

within that zone. The characteristic acceleration response spectrum for each zone plus and minus one standard deviation is shown in Fig. 10.

For comparison, also plotted are the design spectra required in the same area by the current Israel Standard 413 (IS-413) and for ground conditions that meet the BSSC (1997) soil classification scheme. The shape of the hazard functions differ significantly from those prescribed by the IS-413 code in all zones but Zone 2 where both curves practically coincide. For the rest of the zones the Israel code underestimates the acceleration in the period range from 0.2 to 0.5 s. It should be noted that fundamental periods of many of the buildings in Afula also have the same diapason.

5. Discussion and conclusion

In order to characterize seismic response in the study area (40 km^2), the ambient noise survey was carried out at 300 sites. An important issue that is raised before and during the investigations is the question of how dense should the grid of measured points be? In retrospective, we may state that, as in many previous, similar studies, we gained reliability of the obtained results only because we had a dense grid of measured sites. The reliability issue is frequently challenged when using ambient seismic noise and especially in urban conditions. The problem is further emphasised by the very limited availability of densely distributed geotechnical information such as S-wave velocities and densities of the materials particularly at greater depth beyond that needed to design the foundations of the buildings. We could compensate for the need for a dense grid of measured points of ambient noise by drilling new boreholes, conducting many geophysical surveys and monitoring strong enough earthquakes at points across the area. These alternatives are by far more expensive, time consuming and may not always provide the necessary information.

The spacing of measured sites is also controlled by the observations in the sense that spectra with high fundamental frequencies may suggest a dense grid of measurements. Similarly, when detecting rapid changes in the fundamental frequency over short distances, we should increase the density of points to be measured, as this may indicate the existence of an unmapped fault.

The field observation of recent earthquakes using surface and downhole vertical array of accelerometers (Satoh *et al*., 1995; Pavlenko and Irikura, 2002, and other) indicated that nonlinear behaviour of the soils have great seismic engineering implications. Numerous methods and programs were developed to calculate the ground response in strong motion in various conditions of the stress-strain relation. In this study we used an algorithm elaborated by Joyner and Chen (1975) and a program of Joyner (1977). The physical properties of soil layers such as thickness, density and shear wave velocity were taken from the linear models. Estimates of the dynamical shear strength for different soils were inferred from the work of Hartzell *et al.* (2004). As shown in Fig. 10, there are significant differences when assuming linear and nonlinear soil behaviour in Zones 1, 2 and 4. The uncertainty in the parameters we used for assessing the hazard while allowing nonlinear effects is high. Consequently, our hazard assessments under nonlinear behaviour of soils are only of an illustrative character.

Our results point to the fact that H/V spectral ratio from ambient noise adds very useful information and when integrated with other different data sources, often limited in quantity and quality, allows us to obtain a systematic picture of the characteristics of site effects in the investigated region. The application of this methodology is very important in Israel and probably other regions where big earthquakes present a long return period, but might exhibit a high seismic risk.

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