THE EARTHQUAKE HAZARD IN ISRAEL

Project 3

EMPIRICAL DETERMINATION OF SITE EFFECTS FOR THE ASSESSMENT OF EARTHQUAKE HAZARD AND RISK TO KEFAR SAVA

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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>LIST OF FIGURES</th>
<th>Page No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>getListOfFigures</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LIST OF TABLES</th>
<th>Page No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>getListOfTables</td>
<td>5</td>
</tr>
</tbody>
</table>

1. ABSTRACT 6
2. INTRODUCTION 7
3. GEOLOGY OF THE INVESTIGATED AREA 9
4. HORIZONTAL-TO-VERTICAL (H/V) SPECTRAL RATIO METHODS 14
5. OBSERVATIONS AND ANALYSIS 16
6. RESULTS 20
   6.1 Stability of Site Effect Measurements 20
   6.2 Frequency Characteristics of Microtremors and Spectral Ratio Classification 22
   6.3 Site Effects along East-West Cross-section 26
   6.4 Site Effects along North-South Cross-section 29
   6.5 H/V Spectral Ratios from Seismic Events 32
   6.6 Comparison of H/V Spectral Ratio Obtained from Seismic Events and Microtremors 39
   6.6 Fundamental Resonance Frequency and Amplification Maps 41
7. VERIFICATION OF THE S-WAVE VELOCITY STRUCTURE USING H/V SPECTRAL RATIOS FROM AMBIENT VIBRATIONS 45
8. ESTIMATION OF GEOLOGICAL STRUCTURE IN THE KEFAR SAVA AREA USING AMBIENT VIBRATION MEASUREMENTS 48
9. GROUND MOTION PREDICTION 58
10. CONCLUSIONS 60

ACKNOWLEDGMENT 62
REFERENCES 63

APPENDIX A

Table A1. Basic input parameters used for calculation of the generalized transfer functions 71
LIST OF FIGURES

Figure 1. Structural map of the Top Judea Group

Figure 2. Subcrop map of the base Kurkar Group (Fleischer, 2000)

Figure 3. Isopach map of the Kurkar Group

Figure 4. Locations of observation points in the Kefar Sava area.

Figure 5. Examples of microtremor measurements during field site effects investigation.

Figure 6. Influence of selected time windows of microtremors on site effect estimation:
(a) pilot spectral ratios and (b) refined spectral ratios.

Figure 7. Examples of H/V spectral ratios of microtremors for two horizontal components observed at Point KS16: (a) continuous measurements (day and night) during 2000; (b) temporary measurements during 2003

Figure 8. (a) Average spectra of two horizontal (dashed line) and vertical (continuous line) components of motion obtained at Points KS110 and KS199 and (b) horizontal-to-vertical spectral ratio. The shaded area represents the frequency range of motion amplification.

Figure 9. (a) Average spectra of two horizontal (dashed line) and vertical (continuous line) components of motion obtained at Points KS070 and KS078 and (b) horizontal-to-vertical spectral ratio. The shaded area represents frequency range of motion amplification.

Figure 10. (a) Average spectra of two horizontal (dashed line) and vertical (continuous line) components of motion obtained at Points KS045 and KS139 and (b) horizontal-to-vertical spectral ratio. The shaded area represents frequency range of motion amplification.

Figure 11. (a) Average spectra of two horizontal (dashed line) and vertical (continuous line) components of motion obtained at Points KS181 and KS207 and (b) horizontal-to-vertical spectral ratio. The shaded area represents frequency range of motion amplification.

Figure 12. Some examples of average spectra and spectral ratios with two close predominant frequencies.

Figure 13. Geological cross section in the Kefar Sava district below line A-A in Figure 4.

Figure 14. Geological cross section in the Kefar Sava district below line B-B in Figure 4.

Figure 15. Seismograms of different seismic events recorded at Site KS12:
(a) Earthquake in the Eastern Mediterranean (2000-06-13 14:03, M\text{L}=5.4, epicentral distance R=750 km); (b) Earthquake in Greece (2000-06-15 21:30, M\text{L}=5.2, epicentral distances R=1400km; (c) Explosion in the Samaria region (2000-06-15 09:24 M\text{L}=2.0, epicentral distance R=20 km.
Figure 16. Amplitude spectra (a) and horizontal-to-vertical spectral ratios (b) observed at site KS12 from three seismic events.

Figure 17. Seismograms of different seismic events recorded at Site KS70: (a) Earthquake in Shomron (2000-09-02 04:02, ML=2.1, epicentral distance R=50 km); (b) Explosion in the Samaria region (2000-08-31 09:23 ML=2.0, epicentral distance R=20 km).

Figure 18. Amplitude spectra (a) and horizontal-to-vertical spectral ratios observed at site KS70 (b) from two seismic events.

Figure 19. (a) Seismograms from an explosion in the Samaria region (2000-10-15 11:49 ML=2.4, epicentral distance R=20 km recorded at Site H234; (b) the corresponding amplitude spectra and (c) spectral ratios.

Figure 20. Comparison of different estimates of site amplification based on H/V spectral ratio techniques applied to earthquakes, explosions and ambient noise recordings. Green line is the microtremor average spectral ratios. Black line represents the average spectral ratios computed over earthquakes. Red line represents the average spectral ratios computed over explosions.

Figure 21. Map of predominant frequencies of soils based on microtremor measurements.

Figure 22. Map of maximum amplification of soils based on microtremor measurements.

Figure 23. Comparison of analytical and experimental transfer functions for Qalqillia, K-5GH, N.Yamin-1, KS20, and Zofit-39 wells. Solid lines are empirical spectral ratios; dashed lines are calculated transfer functions.

Figure 24. Fundamental frequency of site response function obtained from ambient vibration measurements vs. depth of the Top Judea group taken from digital structural map. Blue points denote measurements at boreholes. Red line is fit to the data points.

Figure 25. Distribution deviations of depth of the Top Judea Gr. from structural map from that calculated using expression (6) with respect to resonance frequency.

Figure 26. a– experimental spectral ratio at point KS150 (black solid line) compared with analytical transfer functions corresponding to lithological column “b” in assumption that depth reflector is 80 m (red line) and 160 m (blue line). Analytical transfer function corresponding to column “c” is shown by red line.

Figure 27. a - Trial and optimal transfer functions for Neve Yamin-2 well. First trial model, shown by red line, is calculated in assumption that reflector depth is 130 m and upper Kurkar layer of 88 m thick (Gvirtzman, 1969) is represented by sand and loam; second one is calculated by assumption that upper layer is calcareous sandstone (blue line); optimal function is derived by trial-and-error fitting (black dashed line). (b) - Lithological section corresponding to optimal model.
Figure 28. a – lithological column of Sharon-103 well according to geological data; b – comparison of trial (blue and red lines) and optimal (black dashed line) transfer functions with experimental spectral ratio (solid black line); c – suggested lithological column.

Figure 29. a – lithological column of Sharon-102 well according to borehole description; b – experimental spectral ratio (black solid line) compared with trial (blue line) and optimal (black dashed line) transfer functions; c – modeled lithological section.

Figure 30. a – experimental spectral ratio at Point KS21 (black solid line) compared with trial and optimal transfer functions. By red line is shown transfer function corresponding to lithological column “b” of Sharon-101 well with reflector of 270m; by blue line is indicate transfer function corresponding to column “c”, where depth of reflector is 207m; and by black dashed line is shown optimal transfer function; d - lithological section corresponding to optimal function.

Figure 31. Fundamental frequency vs. depth of reflector calculated by fitting of the multi-layer analytical transfer functions to the empirical ones.

Figure 32. Frequency-depth dependence fitted separately for the low and high frequency ranges.

Figure 33. Experimental spectral ratios obtained at points KS144 (blue line), KS158 (red line), and KS288 (green line).

Figure 34. a - analytical transfer functions for points KS141 (blue line); KS153 (red dashed line is a trial transfer function; red solid line is the optimal one); KS288 (green line); b – corresponding lithological sections.

Figure 35. Map of zones division in the Kefar Sava town.

Figure 36. Uniform Hazard Site-specific acceleration response spectra for all zones of the Kefar Sava area. Dashed line shows spectrum according to the IS-413 (PGA of 0.1g)

LIST OF TABLES

Table 1 Stratigraphic Nomenclature of Sedimentary Rocks
Table 2 Events Used in Determining Site Response
Table 3 S-Wave Velocity Model Inferred from Previous Investigations in the Lod-Ramla, Hashefela and Hasharon Areas
1. ABSTRACT

In regions with low seismicity but high seismic risk, as in Israel, it is of high importance to derive the ground shaking characteristics, predominant frequency and amplification factor from the microtremor observation results in order estimate the dynamic behavior of structures for seismic-resistant design and seismic microzoning for damage assessment by future predicted earthquakes. In order to obtain the variations of these characteristics in the Kefar Sava area, systematic microtremor measurements, involving over 300 individual measurements, were carried out. Many measurements were made at or close to borehole sites. Maps of predominant frequencies and amplifications were obtained and correlated with the subsurface geology. In the studied area the ground motion amplification is factor 3.5-7.0 over a frequency range of 0.35 to 3.5 Hz.

Additionally, weak ground motion amplifications were determined using horizontal-to-vertical spectral ratios for S-waves generated by earthquakes and explosions at three sedimentary sites. The coincidence between weak motion and microtremor amplification factors facilitated extrapolation of microtremor measurements to estimate site response.

The predominant frequencies observed and their amplifications were correlated with analytical functions that correspond to a 1-D subsurface model. The joint application of empirical and analytical techniques for soil response analysis provided a useful feedback tool to improve the reliability of the soil response results. But at the same time we observed at many sites in the central part of the study area that the experimental transfer functions cannot be represented using 1-D modeling owing to very wide frequency interval or even presence of two close peaks in the maximum of spectral ratio curves.

The analysis of the relationship between the measured resonance frequency and depth of the Top Judea group in the Kefar Sava area revealed great scatter in the both parameters of interest. Therefore, this relationship cannot be used for accurate estimates of the soil thickness.

Based on our observations we divided the study area into ten zones, each characterized by a fundamental resonance frequency of the soil column. The optimal 1-D models for these zones were implemented to predict the acceleration response spectra using ground motion simulations. Uniform Hazard Site-Specific Acceleration Spectra obtained in this study are significantly different from the spectrum of the seismic code currently used in Israel.
2. **INTRODUCTION**

It has been observed that local site effects caused by the impedance contrast between soil layers and underlying bedrock strongly affects seismic ground motion. The damage from recent earthquakes was significantly related to the surface geology. This is particularly important for Israel since most of the existing urban areas built and those to be built in the future are located on soft surface deposits. An accurate estimation of the seismic ground motion across cities is of prime importance for urban development and mitigation of seismic risk. The site response variations are significant over very short distances (Shapira et al., 2001), therefore land use planning, design critical facilities and earthquake loss scenarios should be based on the site response function obtained over a relatively dense grid of measurement points. Many techniques have been developed to evaluate site amplification. Several reviews include a detailed description of the different methodologies (Field and Jacob, 1995; Bonilla et al., 1997; Satoh et al., 2001). Reference site technique or standard spectral ratio (Borcherdt, 1970) uses simultaneous measurements of ground motion at the sediment site and at a nearby hard-rock site during earthquakes for a direct comparison in order to estimate relative amplification. Numerous publications on earthquake measurements have been issued (Rogers et al., 1984; Singh et al., 1988; Jarpe et al., 1988; Darragh and Shakal 1991; Borcherdt and Glassmoyer 1992; Gutierrez and Singh, 1992; Satoh, et al., 1995; Aguirre and Irikura, 1997; Su, et al., 1998; Beresnev, et al., 1998; Hartzell, 1998; Reinoso and Ordaz, 1999; Zaslavsky and Shapira, 2000). This is the best approach to site effect evaluation, but such observations are limited to high seismicity areas and by their high cost.

The spectral analysis of microtremors (ambient vibrations) is a very convenient tool to characterize earthquake site response since it is relatively fast and economical. Large regions can be surveyed in a relatively short period of time. The idea of evaluating site characteristics from microtremor records originated from the pioneer work of Kanai and Tanaka (1961). They pointed out that the predominant frequency of horizontal spectra of microtremors is related to local geological conditions. Since then it has been reported that this technique has proved to be effective in estimating fundamental frequencies (Tanaka et al., 1968; Katz, 1976; Katz and Bellon, 1978; Ohta et al., 1978; Kagami et al., 1982, 1986; Zaslavsky, 1984, 1987). However, in most cases, due to the influence of artificial sources from dense population, heavy traffic and industrial activities, resonance frequency cannot be directly identified in the microtremor spectra (Zaslavsky et al., 2001b).
Kagami et al., (1982) proposed that the ratio of the horizontal components of the velocity spectra at the sediment site to those at the rock site could be used as a measure of microseism ground motion amplification. This technique is widely used for site response estimations (Rovelli et al., 1991; Field et al., 1990, 1992; Hough et al., 1990; Malagnini et al., 1996; Dravinski et al., 1995; Gaul et al., 1995; Zaslavsky et al., 1995; Shapira et al., 2001). Our experiments (Zaslavsky et al., 2002a) show that bedrock ground motion can be considered a good reference site with distances as small as 0.5-0.8 km from the soil site.

Nakamura (1989) hypothesized that site response could be estimated by simply evaluating the spectral ratio of horizontal versus vertical components of noise observed at the same site (non-reference-site technique). Most studies show that the H/V ratio obtained from microtremors coincides with response functions of near surface structures to incident shear waves (Ohmachi et al., 1991; Lermo and Chavez-Garcia, 1994; Zaslavsky et al., 1995; Gitterman et al., 1996; Konno and Ohmachi, 1998; Mucciarelli and Monachesi, 1998; Chavez-Garcia and Cuenca, 1998; Toshinava et al., 1997; Shapira et al., 2001). There is also another conclusion regarding microtremor horizontal-to-vertical spectral ratios. Recently, Field and Jacob, 1995, Bonilla et al., 1997, Horike et al., 2001 and Satoh et al., 2001 contended that estimates of the frequency of the predominant peak are similar to those obtained from standard sediment-to-bedrock spectral ratio of earthquake records, however the absolute level of site amplification does not correlate with the amplification obtained from this method. Based on measurements of explosions, earthquakes and ambient noise by reference and non-reference techniques, Malagnini et al. (1996) showed that the Nakamura technique failed to identify either the resonance frequency or its amplification. Nevertheless, Seekins et al. (1996) showed that H/V spectral ratio obtained from microtremors agree better with sediment-to-bedrock spectral ratio from S-waves than the microtremor ratio with respect to the reference site. Also Meneroud et al. (2000) show that the H/V ratio from microtremor measurements is very successful and gives the same result as more expensive and time-consuming methods.

Lermo and Chávez-García (1993) applied Nakamura’s non-reference technique that uses the horizontal-to-vertical spectral ratios of shear-waves. They concluded that this approach was able to estimate reliably the frequency and amplitude of the fundamental resonance mode of site response function. Many studies report that the frequency dependence of site response can thus be obtained from measurements made at only one station at the analysed site (Lermo and Chavez-Garcia 1994; Theodulidis et al., 1996; Seekins, et al., 1996; Zaslavsky et al., 2003a and many others).
The aim of this work is estimation of local site effects caused by the geological conditions and the evaluation of their influence on seismic ground motion. We divided this project into four steps. In the first step, the H/V spectral ratio techniques were used to estimate empirically the site response function. An area of 27 square kilometers was analyzed using ambient vibration records from 320 sites over a seven-month period. For three sites we compared the seismic site response characteristics inferred from ambient vibration with those of seismic events (earthquakes and explosions). In the second step, all available data for the Kefar Sava area were collected, interpreted and mapped. In the third step the shear-wave structure for different sediments was deduced by trial-and-error fitting of the calculating functions to the empirical transfer functions. Finally, one-dimensional optimal models and the Stochastic Estimations method of Earthquake Hazard (Shapira and van Eck, 1993) were used to calculate a map of 5% damped spectral accelerations (SA) levels 0.2 and 1-sec periods with a 10% probability of exceedence in 50 years.

3. GEOLOGY OF THE INVESTIGATED AREA

The subject of the geological investigation in the Kefar Sava area is the carbonates of the Bina Fm. of the Judea Group, constituting the bedrock and the sediment cover rocks overlying these carbonates.

During the initial phase of the project, geological data of the region were collected from Fleischer (2000), Fleischer et al. (1993) and Fleischer and Gafsu (2000). Later on additional data on 170 wells were used in the detailed analysis of the obtained microtremor measurements. Complementary geological information, obtained mainly from the Geophysical Institute of Israel and the Hydrogeology Division of the Geological Survey of Israel, included primarily core descriptions, some log data, and numerous interpretations of lithological data. Unfortunately, the majority of the existing water wells penetrating the top Judea Gr. are completely un-logged and stratigraphically unidentified (Fleischer et al. 1993), and this makes it difficult to reach an unequivocal interpretation of lithological sections, reliable definitions of the boundaries between the different layers and, finally, leads to mistakes in identification of the reflector depth. These difficulties also limit subsequent use of several wells for numerical calculations.

The basic lithological units of the rocks overlying the carbonates of the Bina Formation in the investigated area are presented in Table 1.
Table 1. Stratigraphic Nomenclature of Sedimentary Rocks

<table>
<thead>
<tr>
<th>N</th>
<th>Lithology</th>
<th>Thickness, m</th>
<th>Formation Group</th>
<th>Stage</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Soil, loess, clay and gravel</td>
<td>0 - 10</td>
<td>Alluvium</td>
<td>Holocene</td>
<td>Quaternary</td>
</tr>
<tr>
<td>2</td>
<td>Sand and loam (&quot;Hamra&quot;)</td>
<td>20-130</td>
<td>Rehovot</td>
<td>Kurkar</td>
<td>Pleistocene</td>
</tr>
<tr>
<td>3</td>
<td>Calcareous sandstone (&quot;Kurkar&quot;)</td>
<td>0-30</td>
<td>Pleshet</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Clay</td>
<td>0-350</td>
<td>Yafo</td>
<td>Saqiye</td>
<td>Neogene</td>
</tr>
<tr>
<td>6</td>
<td>Chalk, chalky limestone</td>
<td>0 - 60</td>
<td>Zor'a</td>
<td>Avedat</td>
<td>Paleogen</td>
</tr>
<tr>
<td>7</td>
<td>Shale and marl</td>
<td>0-120</td>
<td>Taqiye</td>
<td>MT.</td>
<td>Paleogen</td>
</tr>
<tr>
<td>8</td>
<td>Argillaceous chalk</td>
<td></td>
<td>Ghareb</td>
<td>Scopus</td>
<td>Maastrichtian</td>
</tr>
<tr>
<td>9</td>
<td>Bituminous marl and chalk, calcareous shale</td>
<td></td>
<td>'En Zetim</td>
<td>Campanian</td>
<td>Up. Cretaceous</td>
</tr>
<tr>
<td></td>
<td>Limestone and chalky limestone</td>
<td>Half-space</td>
<td>Bina</td>
<td>Judea</td>
<td>Turonian</td>
</tr>
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**Bina Formation - Bedrock**

The structural map of the Top Judea Group for the Kefar Sava area is presented in Fig. 1 (Fleischer and Gafsu, 2000). (The depth to the top Judea is recalculated from the surface). The Bina Fm. consists of white to gray limestone, containing rudist and coral fragments, in some places alternated with chalky limestone or marly limestone. The Judea Group forms the basins of the Yarkon-Taninim rivers. The Top Judea Gr. structure is situated in a basin disposed between the western slopes of the Ramallah anticline and the structural axis of Petah-Tiqva and traversed in the central and northern parts by transversal normal faults and longitudinal reverse fault (Fleischer, 2000). The depth of the top Bina Fm. increases from 20m in the eastern part of the area to 550m in the western part. In the central part of the area the Bina Fm. is unconformably overlain by the ‘En Zetim Fm. of the Mt. Scopus Gr. as indicated by the Sharon-101, 102, 103 wells. In the western part, the Bina Fm. is covered by the Yafo Fm., though this contact has not been penetrated by any well. In the northern, northwestern and southwestern parts, the Kurkar Gr. deposits unconformably overlie the Bina Fm. and this is confirmed by the Zofit-3, N.Eliahu-1, Qalqilia, and Sd.Chemed-7 wells.
Figure 1. Structural map of the Top Judea Group

**Mount Scopus Group**

The Mount Scopus Gr., bedding on erosive relief of the Top Judea Group, is represented by marl-chalky facies (Flexer, 1968). This group, found in the central part of the area only, forms dome-shaped structures of varying thickness and is overlain by the Avedat and Kurkar groups as shown in Fig. 2. The Mt. Scopus Gr. has a maximum thickness of 116m in the central area (Sharon-103 well) and wedges out in the western and eastern parts of the area.

The Mount Scopus Group is represented in the lower part by bituminous marl and chalk, sometimes calcareous shales of the ‘En Zetim Fm. and by argillaceous chalks of the Chareb Fm. and limonitic shales and marls of the Taqiye Fm. in the upper part.
The Avedat Group. 

The Avedat Group, consisting of Eocene chalk and chalky limestone, overlays the Mount Scopus Gr. rocks and occupies a very limited area in the central-eastern part (see Fig. 2.) The thickness of these deposits varies from 0 to 60m. The Avedat Gr. is unconformably overlain by the Kurkar Gr. deposits.

Saqiye Group

The Saqiye Group is associated with four major sedimentary cycles, each starting during a marine transgression and terminating with a sharp westward regression, accompanied by deeply cutting erosional unconformities caused by tectonic and sea level movements (Gvirtzman, 1969, 1970). The fourth sedimentary cycle of Pliocene age is represented by the transgressional Yafo Fm. The Yafo Fm. consists of homogenous clay. The Saqiye Gr. is found mainly in the western part of the study area and wedges out in the central part. Owing to the lack of borehole information on the clay thickness in the western part of the study area, we estimated the maximum thickness from the structural map at approximately 350m. The Yafo Fm. is overlain by the diachronous Kurkar Group.
**Quaternary Rocks**

The alluvium sediments of Holocene age outcrop only in the southeastern area in the upper basin of the Ha-Yarkon river and are represented by soil, loess, clay and gravel and have a maximum thickness of 15 meters.

The Kurkar Group of Pleistocene age unconformably overlies the Judea, Mt. Scopus, Avedat and Saqiye Groups. It is represented by a typical Far Eastern province-type section (Gvirtzman et al., 1984). The lower part of the Kurkar Group consists of marine and eolian calcareous sandstone (“kurkar”) with a thickness of 0-30m and conglomerates of the Pleschet Fm. with a thickness of 0-10 meters. The thickness increases from east to west. The upper part is characterized mainly by eolian sands and sandy loam of the Rehovot Fm. To the east the upper Kurkar becomes more clayey (“hamra”). The total thickness of the Kurkar Gr. changes from 20m in the east up to 150m in the west. The isopach map of the Kurkar Gr. constructed by L.Fleischer is shown in Figure 3.

![Isopach map of the Kurkar Group.](image-url)
4. **HORIZONTAL-TO-VERTICAL (H/V) SPECTRAL RATIO METHODS**

The Nakamura technique, or H/V spectral ratios of microtremors, which we used for site-response estimation in the Kefar Sava area, requires only one recording station and consists of dividing the spectrum of the horizontal component by that of the vertical component. It is based on the following hypotheses (see Nakamura 1989, 2000):

- the soft soil layer (or several such layers) lie on the rigid half-space; microtremors are originated by local surface sources;
- the H/V peak of the microtremor is explained by multiple refracted vertical incident SH waves; vertical motion is not affected by soft soils.
- the layer is excited by this ambient noise (microtremors).

The transfer function is shown by the expression:

\[
TF(\omega) = \frac{H_S(\omega)}{H_B(\omega)} \quad (1)
\]

where \(H_S\) and \(H_B\) are the spectrum amplitudes of the horizontal components of microtremors measured at the surface (S) and at the base (B) of the soft layer. This transfer function has a maximum at the main resonance frequency of the soil layer.

The signal recorded at a site is influenced by the source excitation characteristics, the vibration route and local peculiarities of the site. According to Nakamura, the source spectrum, \(S(\omega)\) given by the following expression

\[
S(\omega) = \frac{V_S(\omega)}{V_B(\omega)} \quad (2)
\]

where \(V_S\) and \(V_B\) are the spectral amplitudes of the vertical components of the microtremors at the surface and at the base of the soil layer which must be removed from the soil transfer function. After dividing (1) by (2), corrected for the source, the soil transfer function under the assumption that \(H_B/V_B = 1\), may be written as

\[
TF(\omega) = \frac{H_S(\omega)}{V_S(\omega)} \quad (3)
\]
i.e. the site response can be estimated by measuring microtremors with only one station.

According to Nakamura, Lermo and Chavez-Garcia (1993) show that it is possible to estimate empirical transfer function of sites from the spectral ratios between horizontal and vertical components of motion using the S-wave part of earthquake records. This method (receiver function) was introduced by Langston (1977, 1979) to determine the crystal velocity structure from recordings of teleseismic, steeply incident, P waves. The assumption made by Langston is that the vertical component of motion is not influenced by the local structure, whereas the horizontal components contain the P-to-S conversions due to the local geological layering. Thus, by deconvolving the vertical component from the horizontal, one could estimate the site response. In the spectral domain this corresponds to a simple division of the horizontal spectrum by the vertical one:

\[
R_s(\omega) = \frac{|S_{vh}(\omega)|}{|S_{vs}(\omega)|} \tag{4}
\]

where \(S_{vh}\) and \(S_{vs}\) denote horizontal and vertical amplitude spectra, respectively, computed at a sediment site from S-wave.

This technique has been used in many studies of the Earth’s crustal structure, as, for example, by Ammon (1991) and Mangino et al. (1993). By analogy to this technique, the H/V spectral ratios for S-wave (but not for P-waves) have been computed also to study site-amplification effects.

5. Observation and Analysis

During the period February 2002 to October 2003, about 320 microtremor measurements were carried out in the Kefar Sava (W-189000; E–196000; S–1673000; N-1679000). The work area is approximately 27 km\(^2\). The distribution of measurement points is shown in Figure 4. The measurements points were selected to give good coverage of the various sediments and sediment thicknesses. Many measurements were made either at or close to the borehole sites.

Ground motions (velocity time history) were recorded using the multi-channel digital seismic data acquisition system designed for site response field investigations (see Shapira and Avirav, 1995). The system includes: a multi-channel amplifier with band pass filters 0.2-25 Hz, GPS (for timing) and a laptop computer with analog-to-digital (A/D) conversion card.
The seismometers (L4C) used are sensitive velocity transducers with a natural frequency of 1.0 Hz and damping at 70% of critical. The ambient vibrations motions were digitized at the ratio of 100 samples per second by a 16-bit A/D converter. Prior to and during the measurements we checked and determined the transfer function of the round motion data, i.e., particle velocity. One vertical and two horizontal seismometers (oriented north-south and east-west) are installed at each site. These seismometers can also work at a reasonable range below the fundamental frequency, as demonstrated in Zaslavsky et al., (2003b). In that report the analysis of the horizontal-to-vertical spectral ratio shows that, for the instrumentation used, it is possible to obtain successful measurements up to 0.4 Hz. The seismometers were installed on leveled metal ground plates and connected to the data acquisition system by cables. All the equipment – sensors, power supply, amplifier, personal computer and connectors – were installed on a vehicle, which also served as a recording center. At each site, the ambient vibration was recorded continuously for 90 minutes, creating data files of 3 minutes each of ambient vibration data. In Figure 2 we present examples of the locations of the seismic stations during the site investigation.

Figure 4. Location of observation points in the Kefar Sava area.
Figure 5. Examples of microtremor measurements during field site effects investigation
The signal treatment is described in the following. We selected two different
time windows, which consisted of 30 sec records for sites with resonance frequencies above
1 Hz and with resonance frequencies of 60 sec records for sites with resonance frequencies
less than 1 Hz. The selected time windows were Fourier transformed (Perelman and
Zaslavsky, 2003), using cosine-tapering (1 sec at each end) before transformation and then
smoothed with a triangular moving Hanning window. The H/V spectral ratio was 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 systematic and reliable results from
the spectra of microtremors, we used several time windows (60-70) that yielded a number of
spectral ratios that, in turn, were averaged. We also experimented with computing the average
of the spectral ratios and found the differences to be negligible.

The horizontal-to-vertical spectral ratio \([A_{H/V}(f)]\) is 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)\]). The average of the two horizontal-to-vertical ratios is defined as
the site amplification function:

\[
A(f) = \frac{1}{2n} \left[ \sum_{i=1}^{n} \frac{S_{NS}(f)_i}{S_v(f)_i} + \sum_{i=1}^{n} \frac{S_{EW}(f)_i}{S_v(f)_i} \right]
\]  

(5)

We have consistently observed that averaging the spectral ratio arithmetically or
generically does not significantly change the results. It is worth noting the importance of
this averaging procedure, the main problem related to the selection of time windows.

In the terminology of the practical aspect of spectral analysis of time series the main
objectives in estimating spectra are high stability and high fidelity. The procedure for spectral
estimates of random data (see, for example, Jenkins and Watts, 1969; Bendat and Piersel,
1986) consists of different stages and requires special research knowledge, experience and
intuition. However, where we use the Nakamura method for estimation, the predominant
frequency of site response function, observation all rules of proceeding of random date cannot
warrant true evaluation. In fact, even in cases of “standard spectral ratio” when we have the
earthquake recordings obtained at the base of the soil layers or a nearby bedrock site (input)
and at a sediment site (output), the true determination of site response is very problematic
because surface-rock sites can have a site response of their own, which could lead to
underestimation of the amplification by a factor of 2 to 4 at frequencies above 1.0 to 5 Hz (Steidl, 1993; Steidl et al., 1996, Zaslavsky et al., 2002b). In the Nakamura method the “input” is the vertical motion of the ambient vibration and the “output” is the horizontal motion. In most cases this input may be contaminated with “noise”, but in the terminology input-output cannot infer ambient noise from the “true” input of their wave fields. On the other hand, excitation of resonance vibration by ambient noise in a multi-layered medium, in our opinion, is a stochastic process. Therefore, it is most important to select the appropriate ensemble of windows of the ambient vibration in the spectral estimation procedure.

The estimates of the spectral ratio for Points KS171 and H158 obtained from pilot analysis and refined analysis are plotted in Figure 6. We should point out again here that estimation of the frequency response function may be obtained from the spectral ratio of input and output of the linear system, but not every spectral ratio is really a response function. Strictly speaking, horizontal-to-vertical spectral ratios or spectral ratios to reference site do not necessarily give a transfer function of the rock-soil system, but an estimation of transfer functions that may be obtained from different methods is very important for site characterization or engineering purposes.

Figure 6 Influence of selected time windows of microtremors on site effect estimation: (a) pilot spectral ratios and (b) refined spectral ratios
6. **Results**

6.1 **Stability of Site Effects Measurements**

The stability of microtremors must be confirmed before an accurate interpretation of microtremor data can be made. We therefore investigated the stability of microtremors by using data from the continuous measurements. First time observations of microtremors in Kefar Sava were carried out during the period September to November 2000 (Zaslavsky et al., 2001a) using two types of measurements: continuous measurements at seven sites and temporary measurements at 16 sites. For the continuous measurements, we installed a seismometer in pumping station buildings. The microtremor measurements were continuously weak, creating data files of 3 minutes each.

Examples of the H/V spectral ratio of the microtremors obtained at Point KS16 displayed in Figure 7. Expect for the spectral ratios (Figure 7a) obtained during continuous (day and night) measurements may be summarized as follows:

Variations of individual spectral ratio curves are small and all the curves are similar in shape. The dominant feature of the spectral ratios is a high near frequency of 1.2 Hz with an amplification 6.0-6.5. The general shape of the average spectral ratios, as well as good agreement between both horizontal components, suggest that for this site the 1D approach provided a good approximation of the free-field motion.

Figure 7b shows the spectral ratio observed at Point KS16 during temporary measurements over three years later (September 2003). The spectral ratios have the same characteristics as those for Point KS16 three years ago; namely, a single peak at frequency near 1.2 Hz with amplification up to 6.5.

6.2 **Frequency Characteristics of Microtremors and Spectral Ratio Classification**

The spectral analysis of microtremors is an alternative way to characterize the site response in places where the geological site conditions have an important role in the damage pattern observed after an earthquake or which may be observed from future earthquakes. In this investigation we would like to draw attention to two different techniques used for site response evaluation: direct computation of amplitude spectra and calculation of spectral ratios between horizontal and vertical components of motion at the same site (Nakamura ratio).
Figure 7. Examples of H/V spectral ratios of microtremors for two horizontal (NS and EW) observed at Point KS16: (a) Spectral ratios during the continuous measurements (day and night) in 2000; (b) Spectral ratios during the temporary measurements in 2003.
Figure 8 shows the average spectra of two horizontal (NS and EW) and vertical components of motion obtained at Points KS110 and KS199, respectively. The horizontal spectra at Point KS110 have a sharp peak near frequency 3.5 Hz and at Point KS199 we can see that an increase in the spectral level of the horizontal component is clear at frequency 0.8 Hz. In addition, the spectra of vertical components are flat in the frequency range where there are peaks at the horizontal components of the spectra. Therefore, spectral ratios show prominent peaks at about 3.5 Hz (Point 110) and 0.8 Hz (Point 199) with an amplification factor for both points of about 5.0.

Comparing the average horizontal and vertical spectra obtained at Points KS70 and KS78 (Figure 9), we can see that the general characteristics of these spectra are gradual amplification of low-frequency energy starting at frequency 0.2 to 0.6 Hz and high-frequency energy starting at frequency 2 to 4 Hz. If we look at spectra of vertical motions at both points, we can see that there are narrow-bandwidth “holes” (troughs) near frequency 1.0 Hz.

Figure 8. (a) Average spectra of two horizontal (dashed line) and vertical (continuous line) components of motion obtained at Points KS110 and KS199 and (b) horizontal-to-vertical spectral ratio. The shaded area represents the frequency range of motion amplification.
Figure 9. (a) Average spectra of two horizontal (dashed line) and vertical (continuous line) components of motion obtained at Points KS070 and KS078 and (b) horizontal-to-vertical spectral ratio. The shaded area represents frequency range of motion amplification.

Hence, the general character of the spectral ratios is clear amplification at frequency 1.2 Hz. Consequently, the high levels of amplification obtained from H/V spectral ratios are controlled not only by peaks in the spectra of the horizontal components but also by troughs in the spectra of vertical components. This fact may be interpreted as evidence of de-amplification (or destructive interference) of vertical motion (Zaslavsky et al., 2000).

Another example of the average spectra and spectral ratios obtained at Points KS045 and KS139 are displayed in Figure 10. Looking at this figure, we notice that the spectra shapes for all components show a sharp peak near 2.5 Hz. This peak is related to background noise in the town and it is, therefore, very difficult to identify its sources.
Figure 10 (a) Average spectra of two horizontal (dashed line) and vertical (continuous line) components of motion obtained at Points KS045 and KS139 and (b) horizontal-to-vertical spectral ratio. The shaded area represents frequency range of motion amplification.

The vertical spectra for Points KS045 and KS139 are flat in frequency ranges 0.2-1.3 Hz and 0.2-0.7 Hz, respectively. Comparing the spectra horizontal and vertical components (Figure 10a) we can see that the frequency ranges where the two spectra deviate are 0.7-1.3 Hz (Point KS045) and 0.4-0.8 Hz (Point KS139). At these frequencies, the spectral amplitudes for horizontal components are considerably higher than the spectral amplitude for vertical components. This feature, clearly visible looking at the spectral ratios (Figure 10b), relates to amplification of ground motion.
Figure 11a shows the average spectra at Points KS181 and KS207. The figure again shows one sharp peak centered near 2.5 Hz at horizontal and vertical components for these sites. However, the general character of the horizontal spectra is increased spectral amplitude at frequencies 0.5 Hz and 1.5 Hz. The spectral ratios (Figure 11b) reveal well-defined peaks at about 0.5 Hz, reaching an amplification factor of about 3 and a second peak near 1.5 Hz, having an amplification factor up to 2. We interpret frequency 0.5 Hz as fundamental resonance and frequency 1.5 Hz, as the first higher harmonic.

Figure 11. (a) Average spectra of two horizontal (dashed line) and vertical (continuous line) components of motion obtained at Points KS181 and KS207 and (b) horizontal-to-vertical spectral ratio. The shaded area represents frequency range of motion amplification.
Finally, we display some examples of average spectra and spectral ratios where the predominant frequency cannot be clearly determined. H/V spectral ratios of the sites have a high overall amplification within the whole frequency range (Figure 12). Three features of this figure are apparent: (1) at all points, amplitude spectra of both horizontal and vertical components of the microtremor show a sharp peak at a frequency near 2.5 Hz caused by manmade activity, such as traffic and industry; (2) the band frequency where horizontal and vertical spectra deviate is broader than in the cases discussed earlier; (3) in spectral ratios we can see two close predominant frequencies. The results obtained from an experimental study of site effects are not confirmed by 1D modeling. On the other hand, for the purposes of earthquake resistant design, engineers must consider the site response at specific periods. For example, at Point KS245 the first frequency is 0.8 Hz and this is the structural frequency of a 12-storey building, while the second frequency of 1.5 Hz is the structural frequency of a 6-7 storey building. It is, therefore, important to understand the limits of 1D modeling in order to simplify the problem while avoiding potentially dangerous errors when evaluating seismic response.

6.3 SITE EFFECTS ALONG EAST-WEST CROSS SECTION

In order to obtain an idea of the fundamental frequency of resonance and amplification and its variations within the area of interest, we compare site effects obtained along profiles A-A in Figure 4. Figure 13 shows a simplified sketch of the geological section across Kefar Sava along line A-A and the average H/V spectral ratios for points along this line. An estimation of the bottom of the sediment basin was made according to the structural map of the Top Judea Group (Fleischer, 2000). As seen from this figure in general, sites have a wide range of amplification values (from 3.5 to 7.0) over a wide range of frequencies between 4.0 to 0.4 Hz. It should be mentioned here that all these points are located on sand. Common surface lithology is not a guarantee of similar site response because amplification effects of soft surface layers is a multi parameter phenomenon, determined not so much by surface geology but by shear wave velocity as well as the thickness and density of the subsurface layers. An important parameter is the impedance ratio between sediments and underlying rock.

At KS110 (Figure 13) site, the soil profile is very simple, i.e. a 40m thick layer of sand and loam directly overlying a basement rock constituted of limestone. In addition, we have a good contrast in S-wave velocity values between the surface soil layer and the basement. Therefore, the characteristic H/V spectra appear at a very clear peak of 3.5 Hz with
amplification factor up to 4. The soil profiles are mainly characterized by the presence of 40m of sand and 40m of marl for KS115 and 55m of sand and 55m of marl for KS227. For these cases, the site amplification curves exhibit clear peaks around 2.0 Hz (KS115) and 1.4 Hz (KS227) with amplification factor 5.0. These results are in agreement with two-layer, 1-D theoretical models. It is important to note that if we use a 1-D model with one layer and an average shear wave velocity obtained from a two-layer model, this will produce a large difference in terms of resonance frequency and amplification factor obtained from field measurements. For three to five layer models we will obtain very significant deviations with respect to the simple one layer 1-D model.

The soil profile at sites KS19, KS14, KS21, KS27 and KS75 (Figure 13) is characterized by sand from 50m to 70m thick and marl from 60m to 150m thick. The results of H/V spectral ratios obtained at these sites are displayed in Figure 13. Two features of these figures are apparent: (a) the frequency interval at 75% of the largest spectral ratio amplitude is considerably wider than in the examples that we examined earlier; (b) in these cases it is possible to detect two peaks in the spectral ratio curves. These differences are very clear and cannot be interpreted as statistical variability in the site response determination. In these cases we can see that a 1-D algorithm does not yield accurate results. It should be remembered that the 1-D approach is based on the assumption that response in soil deposits is caused by the upward propagation of shear waves from the underlying rock. Bruno et al. (1999) showed that divergence between 1-d and 2-D models becomes significant when S-wave velocity contrast between layers within cover sediments overlaying hard bedrock, is less than 0.5. Thus, in the central area of Kefar Sava the site response may be better represented by 2-D or 3-D modeling.

In Figure 13 we also plot the site amplification factor obtained for three sites KS098, KS296 and KS131 located in the western part of profile A-A. The cross section (Figure 13) again shows 100m sand, 30m sandstone and a thick deposit of clay with 200-500m thick. The site response at these sites is generally below 4.0 and predominant frequencies correlate well with the thickness of the deposits. It is very interesting that for these sites we again observe good agreement between experimental data and simple 1-D model.
Figure 12. Some examples of average spectra and spectral ratios with two close predominant frequencies.
6.4 SITE EFFECTS ALONG NORTH-SOUTH CROSS SECTION

In Fig. 14 is depicted a geological cross-section B-B (Fig.4) over Kefar Sava oriented south north (coordinate NS=193000) with average spectral ratios obtained at points located along this section. The measurement points have a wide range of amplification of factors 3-7, but relative narrow frequency range (0.8-1.4 Hz). Like as at the previous profile, all measurement points are located on sand. General trend in decreasing amplification level from the north to the south, we observe, might be explained by dipping of the reflector and simultaneous decreasing of the sand and sandy loam thickness. Three structural blocks divided by faults with amplitude about 50-60 meters can be distinguished on the cross section. Anticline folds seen on central and northern blocks are characterized by frequencies 1.3-1.4 Hz (at the top) and 0.8-1.0 Hz (at the limbs). Soil column at points KS305 and KS46 located on north block is represented by 65m of sand, 15m of sandstone for point KS46 and 75 meters of sand, 25m of sandstone, 25 m of marl for KS305. Clear peaks with amplification factor about 7 at frequency of 1.25 HZ and amplification factor 6 at frequency 1.15 Hz for point KS49 and KS305 correspondingly are seen at spectral ratio curves. These results are in agreement with two-layer, 1-D analytical models.

For points KS290, KS308 and KS21 located on the central anticline we observe lowering of the amplification level to factor 4.5-5. The fundamental frequencies for these points don’t change. It is, probably, connected with increasing total thickness of the sediments without significant changing of upper layer thickness. We should note that here we observe the same phenomenon of wider spectral ratio described above for points KS19, KS14, KS21, KS27 located on the cross section A-A. We suppose it might be explained by influence of chalk as additional reflector, which can produce peak at frequency very close to fundamental frequency in conditions where the thickness of upper sand and sandy loam layer is large enough (in our case 60-70 meters). For mentioned points KS290, KS308 and point KS21 that is common point for sections A-A and B-B 1-D modeling does not yield accurate results. It is interesting that for next along the section point KS23 a shape of the amplification curve is different, i.e. we don’t see broad frequency interval and only one clear peak is detected. We have to remark that point KS23 is located on a leg of anticline and upper layer thickness here is about 50 m. Following further along the section B-B we observe between points KS23 and KS24 sharp in both fundamental frequency 0.8 vs. 1.1 at point KS23 and amplification level of factor 3 vs. 4.5 at distance of 200m. It indicates a strong vertical shift in the basement.
Figure 13. Geological cross section in the Kefar Sava town below line A-A in Figure 4.
Figure 14. Geological cross section in the Kefar Sava district below line B-B in Figure 4
accompanying the fault. The assumed fault is displaced 450 meters to the south relative to fault mapped in the structural map of the Top Judea group.

For points KS233, KS155, KS241 and KS158 located on southern anticline and characterized by sand of 40-50m thick and chalk of 100-160m thick we again observe a good agreement between experimental data and simple 1-D model. Amplification level for these points is about factor 3.5-4. Sharp decrease in the fundamental frequency at point KS245 correlated with strong relief of the basement could indicate presence of fault.

### 6.5 H/V SPECTRAL RATIOS FROM SEISMIC EVENTS

In order to record weak motion seismic events at sites in Kefar Sava, three sites were instrumented for varying lengths of time during the period June to October 2000. During this period two regional and one local earthquake and four explosions were recorded. The instruments were installed and removed at different times, so at each site we recorded different seismic events. The seismic events used are listed in Table 2.

Table 2. Events Used in Determining Site Response

<table>
<thead>
<tr>
<th>No.</th>
<th>Site</th>
<th>Date</th>
<th>Origin time</th>
<th>ML</th>
<th>Geographic coordinates</th>
<th>Distance</th>
<th>Region</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>yymmdd</td>
<td>hh:mm:sec</td>
<td></td>
<td>Lat.(N)</td>
<td>Long.(E)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>KS12</td>
<td>2000 13</td>
<td>143 19.8</td>
<td>5.4</td>
<td>34.86</td>
<td>27.44</td>
<td>750</td>
<td>EQ.</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>2000 15</td>
<td>924 16.8</td>
<td>2.0</td>
<td>32.01</td>
<td>34.98</td>
<td>20</td>
<td>EX.</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>2000 15</td>
<td>2130 44.9</td>
<td>5.2</td>
<td>34.44</td>
<td>20.18</td>
<td>1400</td>
<td>EQ.</td>
</tr>
<tr>
<td>4</td>
<td>KS70</td>
<td>2000 31</td>
<td>923 54.7</td>
<td>2.0</td>
<td>32.01</td>
<td>34.98</td>
<td>20</td>
<td>EX.</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>2000 9  2</td>
<td>42 46.8</td>
<td>2.1</td>
<td>32.22</td>
<td>35.41</td>
<td>50</td>
<td>EQ.</td>
</tr>
<tr>
<td>6</td>
<td>H234</td>
<td>2000 10</td>
<td>1149 1.5</td>
<td>2.4</td>
<td>32.01</td>
<td>34.98</td>
<td>20</td>
<td>EX.</td>
</tr>
</tbody>
</table>
Figure 15 shows the two horizontal and vertical components of a scaled seismogram from different seismic events with different magnitudes and epicentral distances recorded at Site KS12. The seismograms of every event are plotted on the same scale and demonstrate the considerable differences in amplitude and duration that characterize horizontal and vertical components. In terms of peak velocity, amplitudes recorded at horizontal components are about three times greater than at vertical components. The quasi-monochromatic nature of the motion of horizontal components strongly suggests sediment resonance. Figure 16 shows spectra and horizontal-to-vertical spectral ratio for all seismic events recorded at Site KS12. To identify the spectrum, the plot title contains number of the events listed in Table 2. A “bump” in the spectra of the horizontal components is clear in the frequency range 1.0-1.5 Hz. Figure 16b shows the average (NS and EW components) H/V spectral ratios. We can see that near surface deposits produce amplification up to 8.0 near 1.0 Hz, but the general features of these curves possibility identify two close peaks in the curves of spectral ratio.

Figure 17 shows the three components of seismograms recorded at Site KS70 during an earthquake and an explosion. There is a very noticeable difference in the duration and amplitude of the shear waves. The shear waves on the horizontal components exhibit many more cycles of motion and larger amplitudes than the vertical components. The amplification in the time domain in this part of the record is comparable to that seen in the frequency domain. Figure 18 displays amplitude spectra and horizontal-to-vertical spectral ratios observed at site KS70 from two seismic events. As regards the earthquake (event 4), increases in the spectral levels of the horizontal components are clear at the frequency near 1.5 Hz, whilst for the explosion (event 5) we can see a trough on the vertical component near frequency 0.8 Hz and peaks near 1.5 Hz on the horizontal components. Nevertheless, as in earthquakes in a similar way to explosions, H/V spectral ratios show an amplification factor of about 4.0-5.0 in the frequency range of about 1.0 to 1.5 Hz.

In Figure 19 we present seismograms, corresponding amplitude spectra and spectral ratios from an explosion recorded at Site H234. Here again we can see that peak velocity amplitudes observed on horizontal components are about 3-4 times larger than the amplitudes at the vertical component. If we look at the spectra (Figure 19b) we can see that there is a deviation between horizontal and vertical spectra components of motion in the frequency range from 0.5 to 1.5 Hz. Figure 19c shows the site amplification factor obtained from horizontal-to-vertical spectral ratios. As shown from these figures, Site H234 has an amplification factor of about 5.0 over a frequency range of 0.8-1.5 Hz.
Figure 15. Seismograms of different seismic events recorded at Site KS12: (a) earthquake in the East Mediterranean (2000-06-13 14:03, $M_L=5.4$, $R=750$ km); (b) earthquake in the Greece (2000-06-15 21:30, $M_L=5.2$, $R=1400$ km); (c) explosion in the Samaria region (2000-06-15 09:24 $M_L=2.0$, $R=20$ km)
Figure 16. Amplitude spectra (a) and horizontal-to-vertical spectral ratios (b) observed of site KS12 from three seismic events.
Figure 17. Seismograms of different seismic events recorded at Site KS70:
(a) earthquake in the Shomron (2000-09-02 04:02, $M_L=2.1$, $R=50$ km);
(b) explosion in the Samaria region (2000-08-31 09:23 $M_L=2.0$, $R=20$ km).
Figure 18. Amplitude spectra (a) and horizontal-to-vertical spectral ratios (b) observed of site KS70 from two seismic events.
Figure 19. (a) Seismograms from an explosion in the Samaria region (2000-10-15 11:49 $M_L=2.4$, $R=20$ km recorded at Site H234; (b) the corresponding amplitude spectra and (c) spectral ratios.
6.6 COMPARISON OF H/V SPECTRAL RATIO OBTAINED FROM SEISMIC EVENTS AND MICROTREMORS

In recent years, the use of microtremors has increased within the seismological community as an alternative method of empirical evaluation of site effects. After the technique was made popular by Nakamura (1989, 2000) an intensive line of research on the effectiveness of this method to determine site effects developed. Nevertheless, the estimation of the amplification of ground motion at resonance frequency using different techniques is still very controversial, with some authors finding good results while others find significant differences between the various methods of site response evaluation. During the last decade, many sites in Israel have been investigated in an attempt to estimate the possible amplification of the seismic ground motion (Zaslavsky et al., 2001b; Zaslavsky et al., 2002abcd; and Zaslavsky et al., 2003ab). All these studies are based on the analysis of ambient vibration and weak motion measurements incorporated with geological and geophysical information on the subsurface. We used various empirical methods to determine the site response functions including reference and non-reference techniques and referring to different sources of excitation – earthquakes, explosions and ambient vibration. Appropriate ensembles of carefully selected windows of ambient vibration provide estimations of site response similar to those obtained from H/V spectral ratio of seismic events. However, there were cases in which the Nakamura technique failed to yield conclusive results. This often happens when the ratio of the shear-wave velocity of the soil to the shear wave velocity of the underlying half space (bedrock) is higher than 0.5-0.6 (amplification up to a factor of ~2) or when we are dealing with a complicated 3D structure of the underlying geology. Other examples are associated with poor excitation of the soil column due to weakness or remoteness of the microtremor sources. Thus, in many cases, this poor behaviour of the Nakamura method could be foreseen and other methods should have been used. In other cases, where the situation is better suited to the feasibility of the method, the results showed great similarity to the results obtained by other techniques and, thus, provide useful feedback to improve the reliability of the experimental results.

The average site response functions observed at Sites KS12, KS70 and H234 for different data sets (ambient vibration, earthquake and explosion) are shown in Figure 20. The earthquake and explosion spectral ratios for Site KS12 (Figure 20a) look surprisingly similar in the frequency range from 0.2 to 10 Hz, despite differences in azimuths, incidence angles and mechanisms of shear- and surface-wave generation at source. In this case the fundamental frequencies determining earthquakes, explosions and microseism are the same.
Figure 20. Comparison of different estimates of site amplification based on H/V spectral ratio techniques applied to earthquakes, explosions and ambient noise recordings. Green line is the microtremor average spectral ratios. Black line represents the average spectral ratios computed over earthquakes. Red line represents the average spectral ratios computed over explosions.
All ratios show a well defined peak about 1.1 Hz. The amplification levels determined from seismic events are higher than the ones determined using microtremors. This may be because the variations in amplitude of spectral ratios obtained from seismic events are significant (more than factor 2) but we have only a very small sample (only two earthquakes and one explosion).

In the case of Site KS70 (Figure 21b) the amplification factors obtained from different data sets are the same (up to 5.5), but the fundamental frequency determined from explosions has shifted slightly to lower frequencies. The curves of spectral ratio obtained from earthquakes and explosions have a second peak near 4.0 Hz, having an amplification factor up to 3. This frequency may be interpreted as the first higher harmonic.

In Figure 21c we compare the H/V ratio of microtremors with earthquake H/V ratio at Site H234. Examining the shear-wave spectral ratio obtained from the explosion, we find a clear peak at frequency 1.0 Hz with amplification about 5.0. A comparison between the microtremors H/V spectral ratio and the seismic shear-wave H/V spectral ratios shows they are in good agreement.

6.7. FUNDAMENTAL RESONANCE FREQUENCY AND AMPLIFICATION MAPS

For the purposes of earthquake-resistant design, seismological engineers must consider the site response at a specific frequency. Therefore, in our study, we plotted out the contour map to understand frequency response in the Kefar Sava area. Figures 22 and 23 represent distributions of the predominant frequency and amplification factor contours for these frequencies. An important issue that is raised in the stage of planning and during the measurement campaign is the question of the density of the measurement grid. Primarily, we planned to carry out ambient vibration measurements with a uniform grid of approximately 500m². In the process of accumulating the data and understanding the general picture of site effect distribution, we made operative decisions as regards changing the grid to gain reliability of the results obtained. Sharp alterations of frequency and/or amplification over a short distance, the presence of faults, disagreement with geological data and equivocal measurement results are the reasons for additional points and a denser grid.

Ambient vibration measurements in the Kefar Sava area reveal predominant frequencies in the range of 0.3 Hz in the west up to 4 Hz at the northeastern edge of the area. From comparison of the results with the geological structure, we can see that a gradient increase in the predominant frequency toward the east is in agreement with the depth of the
reflector represented by chalky limestone and dolomite of the Judea Group, which changes from 500m in the west to 20m in the east of the study area. A synclinal structure in the central part of the area is visible in the frequency contours. We also observe to the north and south of the syncline two structures with slightly higher frequency band response that may be interpreted as local uplifts of reflector. We should mention that the north uplift is reflected on the structural map, while the southern uplift is not contoured within the limits of the study area. The clear shift in the frequency in the northern part of the area indicating sharp alteration of sediment thickness over a very short distance may be explained by the presence of faults and it is in accordance with the geological data. The second latitudinal fault, mapped in the structural map, isn’t reflected in our measurement, but it is probably revealed at about 500m to the south.

The distribution of the maximum amplification factor in the Kefar Sava area, (see Figure 22), shows that a lower amplification of factor 3-4 was observed in the western part, where impedance contrast is formed by loam and sand of the Kurkar Gr. and clay of Yaffo Fm. overlaying the carbonates of the Judea Gr. Toward the east, the clay of the Yaffo Fm. is thinning and replaced by marl and chalk of the Mt. Scopus and Avedat groups. Decreasing of the total sediment thickness, when thickness of sand and loam is significant (about 60 meters) and doesn’t change, is reflected in the gradual increase of amplification up to factor 6. With regard to the decreasing amplification from the north to the south, such behavior may be explained by changes in the thickness of the marl-chalk facies in the lithological section. The high amplifications (up to factor 7) occur in the northern part of the Kefar Sava area, where the thickness of chalks is a few meters but diminishes to factors 4-5 where the chalk reaches a thickness of 130 meters. Quaternary sediments of the Kurkar group directly overlay carbonates of the Judea group and cause the higher amplification values up to factor 8 that we observe in the east and northeast of the investigated area.
Figure 21. Map of predominant frequencies of soils, based on microtremor measurements
Figure 22. Map of maximum amplification of soils based on the microtremor measurements
7. **Verification of the S-wave Velocity Structure using H/V Spectral Ratios from Ambient Vibrations**

A prerequisite of a reliable analytical model for site response estimation is knowledge of the local geology, including spatial distribution of softer materials above the hard bedrock with corresponding S-wave velocity of each layer. There are many ways to obtain these required parameters. Among these: direct in-situ measurements, laboratory measurements, different approximate relationships with other parameters, drillings, array measurements (frequency – wave number analysis), etc. It is worth noting that many geophysical tools often cannot be used in urban areas because of their high cost, difficulties with installation or limited possibility of obtaining detailed and accurate models more than 40-50m deep. Some techniques for determining Vs in subsurface materials use surface-wave dispersion to infer the shear-wave velocity profile at a site (Aki, 1957). An important component of these works is using a priori information in the inversion of the dispersion curves. Such information could be obtained from geophysical and geotechnical investigations which are problematic in urban areas. The analytical method for site response estimation using an iterative procedure of adaptation the soil parameters to obtain a good agreement between calculated transfer function and empirical one, was used in the previous studies in the Lod-Ramla and Hashefela areas to derive S-wave velocity structure (Zaslavsky et al., 2001, 2003). A description of the representative layers available in the soil column of the investigated area and their S-wave velocities are presented in Table 3.

On the basis of this velocity structure were constructed the geological models for the computational study of the site response estimation taking into account available borehole data, structural map of the Top Judea Group in the Kefar Sava area. Borehole database in the Kefar Sava area incorporated 150 water wells, 24 from those penetrated the Top Judea group. Shallow water wells also were investigated. At sixteen wells we has found further confirmation of velocity model, i.e. we obtain good agreement between analytical transfer functions, calculated using the SHAKE algorithm (Schnabel, 1972) and experimental spectral ratios for measurement points located close or directly at wells. Figure 23 shows a comparison of the transfer functions calculated on the basis of available geotechnical properties with experimental spectral ratios together with lithological sections for Qalqillia, K-5GH, N.Yamin-1, KS20, and Zofit-39 wells. Measurement points close to enumerated wells are KS110, KS196, KS26, KS27 and KS1 correspondingly.
Table 3. S-Wave Velocity Model Inferred from Previous Investigations in the Lod-Ramla, Hashefela and Hasharon Areas

<table>
<thead>
<tr>
<th>Material</th>
<th>Depth 0-50 m</th>
<th>Depth 50-100 m</th>
<th>Depth 100-150 m</th>
<th>Depth 150-200 m</th>
<th>Depth 200-250 m</th>
<th>Depth 250-350 m</th>
<th>Depth 350-400 m and deeper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand, loamy sand and loam</td>
<td>350</td>
<td>350</td>
<td>350</td>
<td></td>
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<td>700</td>
<td>700</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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</tr>
<tr>
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<td>800</td>
<td>900</td>
<td>900</td>
<td>950</td>
<td>1100</td>
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<td>1900</td>
<td>1900</td>
<td>1900</td>
<td>1900</td>
<td>1900</td>
<td>1900</td>
</tr>
</tbody>
</table>

**KS110**

**KS196**

**K-5GH well**
Figure 23. Comparison of analytical and experimental transfer functions for Qalqilia, K-5GH, N.Yamin-1, KS20, and Zofit-39 wells. Solid lines are empirical spectral ratios; dashed lines are calculated transfer functions.

Fairly agreement in the predominant frequency as well as the maximum amplification factor at that frequency indicates an applicability of our velocity model to calculation of the analytical transfer functions for the investigated area.
8. **ESTIMATION OF GEOLOGICAL STRUCTURE IN THE KEFAR SAVA AREA USING AMBIENT VIBRATION MEASUREMENTS**

Recently, different investigations (Ibs-von Seht and Wohlenberg, 1999; Zaslavsky and Shapira, 2000b; Deldago at al., 2000; Parolai, 2002) showed that relationship between main resonance frequency of the soft sediment cover and its thickness can be used to map reflector depth. Using our ambient vibration measurements at 300 sites in the Kefar Sava area and digital structural map of the Top Judea Gr. (Fleischer and Gafsu, 2000) it was possible to derive the relationship between resonant frequency and sediment cover thickness. On Figure 24 is plotted the depth of the Top Judea Gr. versus fundamental resonance frequency.

![Figure 24. Fundamental frequency of site response function obtained from ambient vibration measurements vs. depth of the Top Judea group taken from digital structural map. Blue points denote measurements at boreholes. Red line is fit to the data points.](image-url)
The expression established the relationship for fundamental frequency \( f \) and depth to Top Judea Gr. \( h \) is

\[
h = 156 f^{-1.08}
\]  

(6)

and the coefficient of correlation is 0.7.

In Fig. 25 is shown distribution deviations of reflector depth estimations using expression (6) with respect to measured fundamental frequency. Error of depth estimations is different for different frequency ranges and reaches maximum values (up to factor 4) for frequency range from 0.9 to 1.8 Hz. There is the certain tendency towards overestimating (up to factor 2) the fitted reflector depth values for the frequencies exceed 2 Hz. For low frequencies (0.3-0.5 Hz) deviations are small relatively.

![Figure 25. Distribution deviations of depth of the Top Judea Gr. from structural map from that calculated using expression (6) with respect to resonance frequency.](image)

We should note here that the uncertainties of some initial borehole data themselves not allowing determining reflector unequivocal proved to be one of the reasons for the high scatter of the data points. Dense grid of measurements and consistency of the results enables us to avoid a misinterpretation and derive reliable model and obtain reliable estimate the reflector depth. Below we give some examples.

At measurement point KS150 situated at Neve Yamin-2 well we obtained resonant frequency 1.4 Hz and amplification of factor 5. Spectral ratio is shown in Fig. 26a by solid black line. In order to develop an analytical response function having frequency and
amplification of main peak in agreement with experimental ones we constructed lithological column of Neve Yamin-2 well according to information from Mifalei Mayim (1956). As seen from Fig. 26b, sand and loam layer of 8m thick overlays chalk layer of 70m thick. From the depth of 78 to 133 meters is found the white limestone layer. Below the lithological column is represented by sand down to depth of 159 m. It is also known that limestone underlies sand layer but its true thickness is unknown.

At the first step we calculated the analytical transfer function in assumption that reflector associates with limestone lying at a depth of 78 m (see Fig. 26b). Transfer function yielded amplification of factor 3 at frequency 2.6 Hz (green line in Fig. 26a). These values significantly differ from the experimental ones, obtained at KS150 point. An attempt to use limestone bedding at a depth of 160m as reflector, was not satisfied as well, since analytical transfer function yielded frequency 0.8 Hz and amplification of factor 3 (blue line in Fig. 26a). However, there is another interpretation of Neve Yamin-2 well where Top Judea is identified at a depth of 130 m. This depth is used in the structural map of the Top Judea gr. (Fleischer and Gafsu, 2000). Lithological section constructed on the basis of this interpretation is shown in Fig. 26b. Analytical transfer function yielded amplification of factor 2.5 at frequency of 1.45 Hz (red line in Fig. 26a).

![Figure 26. a– experimental spectral ratio at point KS150 (black solid line) compared with analytical transfer functions corresponding to lithological column “b” of Neve Yamin-2 well in assumption that depth reflector is 80 m (red line) and 160 m (blue line). Analytical transfer function corresponding to column “c” is shown by red line.](image)

We see that obtained fundamental frequency is close to experimental one, while amplification is two times less (factor 2.5 vs. 5 in experiment). Such difference is significant and the model
is not appropriate for site response estimation. We supposed that the thickness of upper layer, as a parameter having great influence upon amplification factor, must be changed. We have to note here that according to Gvirtzman (1969) the upper layer represented by sand, loam and calcareous sandstone of the Kurkar gr. has thickness of 88 m in this borehole. This information justifies our conclusion concerning thickness of upper layer. Since distribution of sand and sandstone within Kurkar group layer is unknown, we modeled two extreme cases: first one – Kurkar group is represented by sand only (red line in Fig. 27a) and second one – by calcareous sandstone (blue line in Fig. 27a). Actually, modeling of the second case is not required because it is known from neighboring wells what thickness of calcareous sandstone does not exceed 10 meters. Using of trial-and-error method we reached agreement between calculated and experimental transfer functions assuming lithological structure presented in Fig. 27b. Corresponding transfer function is shown by black dashed line in Fig. 27a.

![Graph](image)

**Figure 27.** (a) - Trial and optimal transfer functions for Neve Yamin-2 well. First trial model, shown by red line, is calculated in assumption that reflector depth is 130 m and upper Kurkar layer of 88 m thick (Gvirtzman, 1969) is represented by sandy loam; second one is calculated in assumption that upper layer is calcareous sandstone (blue line); optimal function is derived by trial-and-error fitting (black dashed line). (b) - Lithological section corresponding to optimal model.

In Fig. 28a is displayed lithological section for Sharon-103 well constructed according to data Mekorot Co. and Geological and Hydrological Surveys database. Limestone layer bedding at a depth of 220 m was identified as the Top Judea Gr. Transfer function calculated on the basis of this interpretation yielded amplification of factor 3.5 at frequency of 0.95 Hz (blue line in Fig.28b), while measured at point KS20 fundamental frequency is 1.2 Hz and
amplification factor 4.5 (black solid line). We can see that calculated function doesn’t represent in the main characteristics the empirical one for KS20 point.

It is appropriate to mention here that Sharon-103 well is unique in the Kefar Sava area owing to log data available in the depth range 115-250 meters. We observed increase in resistivity curve from 10-15 Ohm up to 20-30 Ohm at a depth of 160 m and up to 80 Ohm at a depth of 220 m. Analyzing resistivity log data available in the Ha-Shefela and Ha-Sharon regions we found that the step observed at a depth of 160 m is typical for stratigraphical boundary between Mt. Scopus and Top Judea groups. Assuming the reflector depth equal to 160m we obtain desirable match in the main frequencies of 1.2 Hz and amplification factor 4.5 (black dashed line in Fig. 28b).

Figure 28. a – lithological column of Shar on-103 well according to geological data; b – comparison of trial (blue line) and optimal (black dashed line) transfer functions with experimental spectral ratio (solid black line); c – suggested lithological column

We should also note that Neve Yamin-1 well (point KS26), located at the distance of 800m from Sharon-103 well yields the main frequency (1.3 Hz) and amplification (factor 4.5) close to those obtained at KS20 point. Its reflector is identified at a depth of 155m that indirectly indicates correctness of our model. At KS-20 well (point KS27) where reflector depth is 220
m we obtained frequency of 0.95 Hz and amplification of 4.5 is another argument in favor of the assumed model.

A depth of 138 m in Sharon-102 well was interpreted by borehole data and used in the structural map as a depth of Judea Gr. bedding (see Fig. 29a). However, comparing calculated function (frequency and amplification are 1.1 Hz and factor 5.5, blue line in Fig. 29b) with experimental ratio obtained at Point KS13 (frequency of 0.9 Hz and amplification of factor 4.5, black solid line) we concluded, that reflector depth must be lowered down to the depth of 216 m. Lithological column corresponded to this model is shown in Fig. 29c. Again, like in previous example we refer to KS-20 well, situated nearby, for which the depth of the Judea Gr. bedding occurs at a depth of 220 m and main site effect parameters are very close to those obtained at Sharon-102 well.

![Figure 29](image)

Figure 29. a – lithological column of Sharon-102 well according to borehole description; b – experimental spectral ratio (black solid line) compared with trial (blue line) and optimal (black dashed line) transfer functions; c – modeled lithological section

At point KS21 located at Sharon-101 well we obtained the fundamental frequency 1.15 Hz and amplification of factor 5. Experimental spectral ratio is shown in Fig. 30a by black solid line. Two different lithological columns constructed according to two descriptions of Sharon-101 well are presented in Fig. 30b,c. Two trials and one optimal model are also shown in this figure. First trial model is calculated in assumption that reflector is limestone.
identified at a depth of 273m (see Fig. 30a). This reflector depth agrees with the depth of the Top Judea Gr., used in the structural map. Comparison calculated transfer function (Fig. 30c, red line) with experimental ratio obtained at point KS21 (black solid line in Fig. 30c) shows significant differences in both fundamental frequency and amplification factor. According to another interpretation of lithological section of Sharon-101 well (Fig. 29b) limestone layer bedding at a depth of 207 m may be identified as reflector. Fundamental frequency and amplification factor of transfer function corresponding to this model are 1.0 Hz and factor 3.5 (blue line in Fig. 30c) that are closer to experimental ones, but optimal fit we obtained placing reflector at depth of 160 m (black dashed line in Fig. 30d).

![Figure 30](image.png)

**Figure 30.** a – experimental spectral ratio at Point KS21 (black solid line) compared with trial and optimal transfer functions. By red line is shown transfer function corresponding to lithological column “b” of Sharon-101 well with reflector of 270m; by blue line is indicated transfer function corresponding to column “c”, where depth of reflector is 207m; and by black dashed line is shown optimal transfer function; d - lithological section corresponding to optimal function.

Taking into consideration the fact that carbonates of the Top Judea Gr. not always may be interpreted as reflector, we calculated analytical transfer function and constructed lithological
model at every measurement point. The cross-plot in Figure 31 presents correlation between measured fundamental resonance frequencies vs. reflector depths, calculated by fitting of the multi-layer analytical transfer functions to the empirical ones.

![Figure 31. Fundamental frequency vs. depth of reflector calculated by fitting of the multi-layer analytical transfer functions to the empirical ones](image)

The relationship between frequency and soil thickness is described by expression

$$ h = 158 f^{-1.27} \quad (7) $$

The coefficient of correlation is 0.9.

This regression is free from outliers caused by divergence in the depth of the Top Judea Gr. and the depth of reflector inferred from H/V frequencies. Correspondingly, error of depth estimation is significantly less than in correlation between frequency and depth to Top Judea Gr. taken from geological data. But even from visual analysis of this regression clearly seen
that it cannot be approximated by one and the same fit, because average Vs is not valid for either sites with lithological section characterized by Kurkar Gr. overlaying clay and those (low frequency range), where sandy loam of the Kurkar Gr. directly overlays limestone of the Judea Gr. (high frequency range). Reducing multi-layer model to one-layer one, averaging their characteristics is another source of errors in the sediment thickness estimates. Therefore mentioned groups were fitted separately and demonstrate small deviations from fits, as shown on Fig. 32.

![Figure 32. Frequency-depth dependence fitted separately for the low and high frequency ranges.](image)

However, in the frequency range from 0.9 up to 1.8 Hz we still observe very high scatter. To analyze this phenomenon we selected three measurement points KS141, KS153, KS288. They are characterized by the same resonance frequency of 1.25 Hz, but different
amplifications: factor 3.5, 5.2 and 6.5 correspondingly. Their experimental spectral ratios are shown in Fig. 33.

Figure 33. Experimental spectral ratios obtained at points KS144 (blue line), KS158 (red line), and KS288 (green line).

Analytical transfer function and corresponding lithological column for point KS141 are shown on Figs. 34a (blue line) and 34b.

Figure 34. a - analytical transfer functions for points KS141 (blue line); KS153 (red dashed line is a trial transfer function; red solid line is the optimal one); KS288 (green line); b – corresponding lithological sections.

In order to calculate transfer function for point KS153 with the same lithological structure and fundamental frequency as at point KS141 but amplification factor 5 we increased the thickness of upper sandy loam layer. Keeping the reflector depth equal the one at point KS141 we calculated transfer function and revealed that fundamental frequency was shifted from...
1.25 Hz to 0.9 Hz (see Fig. 34a, red dashed line). To restore the original value we raised the reflector up to depth 130m (Fig.34 b, second column). Analogous procedure was repeated for point KS288 and reflector depth derived by trial-and-error fitting is 100m (Fig. 34b, third column). This example demonstrates that in the complicated geological conditions of multi-layer system, where thickness of the upper sandy loam layer takes significant part of total thickness of sediments above reflector, we must consider amplification factor for calculating of the reflector depth.

Thus, the analysis of the relationship between the resonance frequency and depth of the Top Judea group in the Kefar Sava area revealed great scatter in the both parameters of interest and, therefore, it is not valid for accurate estimates of the soil thickness.

9. GROUND MOTION PREDICTION

In order to estimate potential earthquake damage and risk it is necessary to assess the seismic hazard and to evaluate vulnerability of structures to seismic ground shaking. The classical approach for developing of the earthquake scenarios is based on direct prediction of the seismic intensity from an empirical function between the magnitude of the event, the hypocentral distance and the predicted seismic intensities. A scenario prepared using this classical approach must be based on up-to-date reliable information. Despite the long documented history of destructive earthquakes in Israel, the use of seismic intensities is rather limited because the types of building and the distribution of the population and its density are very different from those that existed in the area throughout the previous centuries. For lack of any empirical information about seismic intensities relevant to the current engineering and demographic conditions, Stochastic Estimation of the Earthquake Hazard (SEEH) method, in which the seismic intensities could be predicted from the physical parameters that characterize the interaction of ground shaking and buildings was developed by Shapira and van Eck (1993). SEEH computations are based on regional parameters such as distribution of seismogenic zones, frequency-magnitude relationships, stress drop, Q-values, seismic moment, etc. which have been evaluated and routinely updated by the Seismology Dep. of GII from local and regional earthquakes. The uncertainties associated with those parameters are incorporated in the SEEH by simulating several possible lists of earthquakes over a very long time and synthesizing many accelerograms on the free surface of the investigated sites. The regional information is used to synthesize accelerograms for the surface of the underlying
bedrock and then they are convolved with the response function of the site under investigation, to yield the expected accelerations on the free surface of that site.

Preliminary seismic zonation in the Kefar Sava area was based on the distribution of fundamental frequency and corresponding amplification level of ground motions (for these maps see Figures 22, 23). For majority of measurement sites, by means of SHAKE program, were calculated the analytical site response functions using H/V spectral ratios, geological, geotechnical and borehole information. Further, for more than 60 measurement sites distributed within the studied area and grouped into zones the Uniform Hazard Site-specific Acceleration Spectra for a probability of exceedence of 10% during an exposure time of 50 years and a damping ratio of 5% were computed. Some zones characterized by different geotechnical parameters but don’t differ significantly by spectral acceleration functions were joined, and generalized transfer functions and acceleration spectra for each unit calculated. A map of preliminary seismic zonation of the Kefar Sava town is shown on Fig. 35.

Figure 35. Map of zones division in the Kefar Sava town

The parameters used for calculation of the generalized transfer functions are presented in Table A1 of Appendix. Generalized transfer functions and Uniform Hazard Site-specific Acceleration spectra for every zone are displayed as well. Here, in Fig. 36 we plotted the acceleration response spectra for all zones compared with response spectrum for Kefar Sava area that is required by the current IS-413 for ground type S2 with the required design
horizontal Peak ground Acceleration (PGA) value of 0.1g. The shape of the spectral for all zones are significantly different from the spectrum prescribed by IS-413, in this IS-413 underestimates the accelerations in the period range from 0.2 sec to 3 sec.

![Figure 36. Uniform Hazard Site-specific acceleration response spectra for all zones of the Kefar Sava area. Dashed line shows spectrum according to the IS-413 (PGA of 0.1g)](image)

10. CONCLUSIONS

The purposes of this study were to estimate amplification of seismic ground motion in the Kefar Sava area, to develop microzonation maps using cost-effective methods, to evaluate site-dependent seismic hazard in terms of ground motion parameters used for engineering applications with the aim of providing a realistic picture of the consequences of a destructive earthquake. Our conclusions may be summarized as follows:

1. Microtremor recordings can be used to obtain reliable information related to seismic behavior of sediment layers with thickness from 30m to 350m. The horizontal-to-vertical spectral ratio gives a good estimate of the resonance frequency and amplification factor. An appropriate ensemble of carefully selected windows of microtremors, as can be seen from the comparison with spectral ratios obtained from earthquakes and explosions, provide estimates of the site response similar to those obtained from the H/V spectral ratio of seismic events.
2. Performing measurements during different years and using different daily time windows provide reasonably stable results. The peak of the first resonant vibration mode \( f_1 \) is localized not only by a sharp trough in the vertical spectra or by a “bump” in the horizontal spectra, but we also observe that spectra of horizontal vibrations enriched by energy in the broad band of frequencies around \( f_1 \) lead to a H/V peak with a really wide top in the range of 1.0-1.4 Hz.

3. Again, before and during the investigations, the question of the density measurement points is raised. We learned that a grid of 500m is not always sufficient to obtain consistent and reliable results in complicated geological conditions. Taking into consideration that microtremor measurements in combination with the Nakamura technique are much cheaper than such alternatives as drilling new boreholes and conducting geophysical surveys, we state that this is a case in which quantity transforms into quality.

4. Distributions of the fundamental frequency and maximum amplification factor constructed on the basis of 340 ambient vibration measurements exhibit amplifications of factor 3-8 over the frequency range of 0.3-4 Hz. The fundamental frequencies were found to correlate only generally with the dipping of the Judea Gr. from the east to the west. Dense grid of measurements enabled mapping of local geological structures that were not identified on structural map for lack of borehole information and define more accurately the faults location. The amplification, depending on the impedance contrast between soil deposits and firm bedrock, has a minimum in the western part of the area, where a typical section is represented by sand, loam and clay overlaying chalky limestone of the Judea Gr. and reaches factor 7-8, where sand directly overlays the bedrock.

5. Analyzing relationship between fundamental frequency and depth of carbonates of the Top Judea group built up on the basis of 340 measurements we concluded that this dependence does not deliver an accurate estimate of the local sediment thickness and cannot be used for hard-rock basement mapping for the following reasons: local changing in the lithological structure or thickness of layers, especially upper low-velocity layer, leading to variations of velocity-depth function in the study region, reducing multi-layer to one-layer system, and uncertainties in the borehole data themselves – all these factors are the source of errors in the estimates.

6. Obtaining a reliable site response prediction from numerical simulations depends on having an adequate physical model of the site. Comparison between analytical transfer functions calculated by 1D SH wave propagation analysis using the SHAKE program and the experimental transfer functions obtained from microtremors showed that the shear wave
velocity model inferred in the previous investigations in the Lod-Ramla, Hashefela and Hasharon areas could be used in the Kefar Sava area. On the other hand, significant differences between empirical and calculated using 1-D modeling transfer functions for some sites in the central part of the study area suggest that in geological conditions when Vs contrast between layers within cover sediments less than 0.5 and thickness of upper soft layer takes considerable part of total thickness of cover sediments above reflector the site response may be better represented by 2-D modeling.

7. In areas of low to moderate seismicity, ambient noise measurements and detection of small seismic events are the most practical approaches for assessing the site response functions to be implemented in earthquake hazard and delineation of future locations of severe damage. In the larger scheme of seismic risk, this kind of information facilitates the identification of cost-efficient research to assess seismic hazard at sites such as Kefar Sava for which geotechnical studies and data are still incomplete, but seismic risk has increased because of economic and social development.

8. Seismic zones map is proposed, based on distribution fundamental frequency and amplification factor. For each of eleven zones generalized soil-column model is constructed. SEEH procedure was applied to compute Uniform Hazard Site-specific Acceleration Spectra that meets the criterion of accepted hazard in the Israel Standard 413, i.e. a 10% probability of exceedance during an exposure time of 50 years and a damping ratio of 5%. The shape of the spectra obtained is different from the one prescribed by IS-413, in that IS-413 significantly underestimates the requirements (accelerations) across the period range 0.1 sec to 3.0 sec. Thus we strongly recommend that estimations of earthquake loss scenarios should be based on our results.

ACKNOWLEDGMENT

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Appendix A.

Table A1. Basic input parameters used for calculation of the generalized transfer functions

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<th>Zone</th>
<th>Thickness, m</th>
<th>Density, g/cm³</th>
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