Resume of the first year of the study

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Publication No. ES-54-14
GII report No: 080/802/14
Contract No: 213-17-004

December, 2014
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לאחרת תגוות אחר

דוח שנתי עד הקופה מינואר 2014 עד דצמבר 2014

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תקציר

מרעידות האדמה שהתרחשו lately, ניתן ללמוד כי נזק באתר מושפע ישירות מהגיאולוגיה המקומית. בחישוב מוקדם של תגובות האתר הצפויות,-Token אתגר עיקרי להערכה אמינה של סיכונים סייסמיים. עבורה לחישוב תגובת אתר נדרש לקבוע מודל מהירויות רב שכבתי של גלי גזירה מהקרקע עד לסלע בסיס.

דרך מקובלת לקביעת הפרמטרים הנדרשים היא יישום שיטת יחס ספקטרי אופקי-לאנכי מרעש רקע (HVSR) בשילוב עם שיטות גאופיזיות כגון רפר Mockito גלי גזירה או שיטת ניונית רב-ערוצי של גלי שטח (MASW).

לשיטות הרפר Mockito יש חסרונות: ביצוע יקר במקרים מסוימים היא לא יעילה ומודנית בידור검ה בזול יחיד מקובר. כמן כן גם בשיטת MASW עם שימוש בגיאופונים של 5.4 הרץ עומק של חדירת גלי שטח מוגבל.

במחקר זה השתמשנו בשיטת MASW עם גיאופונים של 5.4 הרץ ועיבוד נתונים משוכלל וレスト עלינו לקבוע מודל מהירויות גלי גזירה עד עומק של יותר מ 11 מ' ועומק של שכבה עמוקה יותר הוערך להיות מ-511 מ'.

במחקר זה התרכזנו באימות של מדידות בשיטת MASW בתנאים גאולוגיים שבהם מתחת לשכבת קרקע רכה ישנן שתי שכבות סלע המשמשות כמחזירים, כאשר התחתונה היא רפלקטור בסיסי. המדידות התבצעו בשתי נקודות מבצעות: נבות (צפון ישראל) ורמת הכובש (השרון).

נמצא כי שיטה מעודכנת של מדידות ועיבוד נתונים משפרת באופן משמעותי את Möglichkeit הבחנה והפרדה של שיטות מסיימיות. שיטת HVSR המשלבת את שיטה מסיימית ו למציאת מודל תורם לחישוב סיכונים סייסמיים וש姮 תרגולים רעידת אדמה בנגב.

מילים מפתח: שיטת HVSR, שיטת MASW, עיבוד, מחזירים, מתכתיות, מודל תורם, מחוזות, התלחיצות, עמידה, לבנגב.
ABSTRACT

Estimating possible site effect is an integral part of evaluation of the seismic hazard and reduction of earthquake damages. In regions with low or moderate seismicity as in Israel, the site response should be determined by analytical tools. These computations require the knowledge of the subsurface geological structure in terms of shear-wave velocity (Vs) profile down to seismic bedrock. Conventionally, this problem is resolved by joint implementation of Horizontal-to-Vertical Spectral Ratios (HVSR or Nakamura’s) technique, which is based on ambient noise measurements and seismic methods such as S-wave refraction or Multichannel Analysis of Surface Waves (MASW) method. The first one is significantly limited in resolution because of weak source of S-waves. The MASW method using 4.5Hz geophones is restricted in penetration depth of surface waves because of frequency (wavelength) limitations. In this study, we have applied 2.5Hz geophones and special data processing to provide constructing Vs section down to bedrock located at 100m deep. Suggested methodology has been tested last year at a number of sites on the Dead Sea shore, where subsurface model is represented by two compact salt layers serving seismic reflectors occur inside the loose sediments. The depth of the upper salt layer is in the range 20-70 m, while the depth of the deeper salt layer was estimated greater the 200 meters. In the presented study we focused on validation of the MASW measurements in geological conditions where soft sediments overlay a hard layer, which is, in turn, underlain by another firmer one. The lower one is the fundamental reflector. Two sites were checked: the Navot site (North of Israel) and Ramat Hakovesh site (the town of Tira, Central Israel). At both sites S-wave refraction surveys were previously carried out. Modified methodology of MASW significantly improves the resolution of the method and being combined with HVSR facilitates constructing Vs sections up to depth of fundamental seismic reflector.

Key words: Seismic Hazard, shear-wave velocity structure, active and passive MASW, HVSR method, ambient noise.
1. INTRODUCTION

Subsurface ground conditions, which might cause significant amplifications due to high impedance contrast between soft soils and a firm basement, requires the need to estimate the expected ground motions and determine the main characteristics of the seismic response of the underground (i.e., resonance frequencies and amplifications) for the seismic hazard assessment and risk mitigation. Techniques developed to identify the main characteristics of site responses for soft deposits (i.e., resonance frequencies and amplification factor) may be grouped into three main categories (Bonnefoy-Claudet, 2006):

1. A numerical simulation approach coupled with classical geophysical and geotechnical tools (such as seismic refraction, seismic reflection, boreholes, penetrometers, etc.) in order to provide reliable estimates of the required input parameters including thickness, density, damping and S-wave velocity of different soil and rock layers at a site.

2. Direct measuring of the site response on the basis of earthquake recordings on specific stations located at carefully chosen sites.

3. Methods based on ambient noise recordings.

The first group of methods based on utilization of seismic exploration to determine subsurface structural models may be very expensive. Moreover, predicting site effect parameters based on models inferred from geological and geophysical information only, may differ significantly from experimental estimates (Zaslavsky, et al. 2005, 2008, and 2009).

The second technique (Jarpe, et al., 1988; Satoh, et al., 1995;) provides an unbiased experimental estimation of the site transfer amplification factor, its use in regions with relatively low seismic activity like in Israel is usually impractical.

Finally, the third group is a practical and low cost tool is becoming more and more popular over the last decades (Kagami, et al., 1982; Yamanaka, et al., 1994). It offers a convenient technique, especially through urbanized areas.

In the last decade, the Geophysical Institute of Israel (GII) used H/V spectral ratios from ambient noise (HVSR) supplemented with on-site geophysical, borehole and geological information to derive the required models of the subsurface. Part of the information (Vs profile) is usually obtained from S-wave seismic refraction surveys (Palmer, 1986). However, use of the latter is often hampered by problems in generating S-waves because of weak source and the difficulties in performing a geophysical survey in urban areas. Another method allowing constructing the subsurface Vs profile is the widely used Multichannel Analysis of Surface Waves (MASW). The MASW technique is based on the study of the dispersion of surface waves (Park, et al., 1999).

Since a surface wave is frequency dependent; i.e., dispersive, the Vs structure can be obtained by inversion of surface-waves dispersion curves (Xia, et al., 1999). Depending how the surface waves are generated active and passive MASW techniques can be applied (Park, et al., 2007). The passive MASW is based on measurements of ambient noise (tidal motion, sea waves, wind, traffic, industry activities). In most cases, passive MASW method is combined with active MASW using a sledgehammer and other active seismic sources (sledgehammer, dropping weight) to excite surface waves (Park, et al., 2005).

The MASW method was largely developed taking into account requests of the National Earthquake Hazard Reduction Program’s (NEHRP) recommending site classification averaging shear-wave velocity (Vs) over 30m (BSSC, 1994). Therefore, the acquiring data for the MASW
conventionally used 4.5Hz geophones, where the penetration depth of surface waves is restricted (usually, to the uppermost 30m) because of frequency (wavelength) limitations (Park and Brohammer, 2003).

Boor et al. (1997) noted that the use of average shear-wave velocity to a depth of 30m as a variable to characterize site conditions is a choice dictated by the relative unavailability of velocity data for greater depths. It is therefore necessary to develop a deeper estimation of Vs profile. That is why one of the objectives of this study is modifying the MASW method to increase penetration depth. The main goal of this study is to combine H/V spectral ratio from ambient noise (HVSRS method) with the modified MASW technique to obtain reliable shear-wave velocity structure of the subsurface. A combination of these methods allows deriving quantitative information on S-wave velocity sections for the study site and enables investigating deep properties of the medium. The main objectives are as follows:

- Modifying of the MASW method to increase the penetration depth and resolution;
- Applying the improved MASW method in its active (passive, combined) modes to constructing of shear-wave velocity (Vs) profile;
- Evaluating 1-D subsurface model down to a seismic reflector via fitting an analytical transfer function to an observed HVSRS considering Vs-depth profile from MASW;
- Testing combination of HVSRS and MASW methods in different geological conditions.

2. P- AND S-WAVE VELOCITIES IN SOILS AND ROCKS OF ISRAEL

2.1. METHODS OF Vs MEASUREMENTS – BRIEF REVIEW.

Shear-wave velocity measurements are an important part in designing buildings in site specific conditions such as soil liquefaction, ground-spectral earthquake response etc. Being mostly independent on soil saturation, shear-wave velocities are more indicative of soil properties and can be used as a diagnostic tool for engineering properties. Seismically, shear-wave velocity (Vs) is the best indicator of shear modulus that is directly linked to a material’s stiffness which is one of the most critical engineering parameters. There are several methods of Vs measurements in laboratory conditions and in in-situ conditions. Each method has its advantages and disadvantages. 

Laboratory methods include (1) the resonant column test; (2) the cyclic torsion tests, and (3) the Bender element tests (ASTM D3999, 1991(1996); Schneider, et al., 1999; Stokoe and Santamarina, 2000; Terzaghy, et al., 1996). These tests should be carried out on undisturbed samples, but sometimes they are carried out on compacted or reconstructed (remolded) ones. Laboratory tests allow measurement of shear-wave velocities at controlled conditions and different shear deformations, affecting shear modulus (G) and velocity (Vs). These methods enable taking into account Vs decrease in accordance with shear deformations increase (Vucetic and Dobry, 1991). 

Recently, similar tests were carried out for in-situ conditions (Stokoe II, et al., 2006). Deformations used in calculations are derived for a typical earthquake. However, Vs values measured for soil samples are strongly different from in-situ velocities. The laboratory testing is relatively expensive.

In-situ geotechnical methods. Recently, S-wave velocities are being calculated from correlations between Standard Penetration Tests (SPT) parameter and Vs velocities (DeJong, 2007). The SPT
is carried out in accordance with ASTM D1586 (2008). Interpreting data is based on Terzaghi et al. (1996) and DIN 4094-2 (1980). SPT testing is carried out in Israel using standard equipment of 63kg weight falling from the height of 76cm. The number blows required to insert the SPT device 30.5cm (12 inches) is determined. This value is reported as the raw (uncorrected) Standard Penetration Test (SPT) blow-count \( N_{SPT} \). The correlation between \( N \) and \( V_s \) is explained by dependence of SPT blow-count \( N_{SPT} \) on relative density of soils (Carter, 1983; Iyisan R., 1996; Terzaghi, et al., 1996). Comprehensive review of \( N_{SPT} \)-\( V_s \) correlations has been carried out by DeJong (2007). The following example shows correlations between \( N_{SPT} \) and \( V_s \) for Dead Sea lime carbonate (Fig. 1a).

Figure 1. Shear wave velocity (\( V_s \)) based on Standard Penetration Test \( N \) blows. (a) \( V_s \) versus \( N \) relationship for the Dead Sea lime carbonate. Relationships of other researchers presented from DeJong review (2007) obtained in similar soils and are presented for comparison (referenced by Sykora 1987); (b) \( V_s \) versus depth graphs calculated for fine and medium sands from SPT log using Ohta-Goto estimator (Ashkelon area). Graphs are compared with \( V_s \) versus depth graph calculated at the same site using MASW technique.

Analysis shows that correlation for lime carbonates is high enough. However, it is significantly higher than that for sandy-gravel sediments (Ezersky and Livne, 2013). One can see from Fig. 1a that relationships derived by different researches for similar lithology are close to the Dead Sea Lime carbonate, whereas sandy-gravel sediments show essential scatter. Ohta and Goto (1978) suggested a method to calculate \( V_s \) based on properties of soils. It was utilized as a \( V_s \) estimator calculating \( V_s \) versus \( N_{SPT} \) blows and taking into account soil type, geological epoch of soil and a combination of other factors (Software for estimation, 1999). Example of \( V_s \) distribution calculated for fine and medium sands from SPT log using Ohta-Goto estimator are shown in Fig. 1b. One can see that \( V_s \) calculated from \( N_{SPT} \) is strongly dependent on the lithology, whereas the MASW
methods nicely approximates both calculated graphs; showing that upper Vs values are determined by fine sand, whereas lower part of the graph coincides with medium sand. Another Vs calculation method based on Hadrin and Drnevich (1972) model allows calculation of Vs as function of void ratio (e), confining pressure (kPa), specific gravity and soil conditions (dry or saturated).

In situ geophysical methods include borehole and surface measurements. The most accurate among them is the cross-hole method (ASTM D4428/D4428M, 2007). This method requires at 3 or at least 2 highly parallel boreholes (accuracy of measurement of distance between 2 boreholes can be computed to within ±2% to a depth of about 30m. [4.2.1]. The inclinometer is also required to perform accurate measurement of distances between borehole source and geophone position. Another method is the downhole one (ASTM D7400, 2007) allowing Vs measurement of a single borehole. The borehole is encased by a PVC pipe or filled with bentonite to stabilize the borehole walls. In the first case, measurements can be affected by the quality of the borehole walls and fill geometry. In addition, soil characteristics in borehole can differ from those in the site located 100m away.

Surface methods measurements include seismic refraction SH-measurements (Palmer, 1986) and Surface Wave prospecting (SWP) methods (Park, et al., 1999; Socco and Strobia, 2004; Stokoe, et al., 2006). If refraction method is based on direct measurements, SWP method is based on the nature of Rayleigh waves whose phase velocity depends on Vs and its distribution with depth. Latter waves are of dispersive origin that testifies possibility to penetrate to different depths. Although methods like shear-wave refraction, downhole, and cross-hole surveys can be used, they are generally less economical than Multichannel Analysis of surface Waves (MASW) in terms of field operation, data analysis, and overall cost.

### 2.2. SEISMIC VELOCITIES OF SOILS AND ROCKS IN ISRAEL

Numerous surveys carried out in Israel allow estimating the range of seismic compression wave (Vp) and shear-wave (Vs) velocities of the sediments and rocks of the shallow subsurface (down to 100m deep). The schema of seismic velocities in the soils and rocks of Israel is presented in Fig. 2a and b, respectively.

Analysis of Figs. 2a and 2b allows us to conclude that (a) ranges of both Vp and Vs seismic in soils and rocks conform to those measured by other researchers (Jakosky, 1950; Press, 1966; Reinolds, 1997); (b) shear-wave velocities measured throughout Israel vary by a wide range: from 100 m/s in sands and lime carbonates to more than 600 m/s in gravels and from 400 m/s in conglomerates to more than 2400 m/s in basalts and dolomites. Variability of Vs and thickness of soft sediments overlying hard rock on the one side and very limited availability of densely distributed geotechnical information such as Vs at depth calls for the use of less expensive and time consuming methods providing required parameters for site effect assessment. Data presented in Figs. 2a and 2b, allows consideration of approximate the range of Israeli sediments and rocks velocity for preliminary evaluation of possible site response and modeling. Separately, we consider velocities in the salt constituting firm layers along the Dead Sea coastal area.
Figure 2. Range of $V_p$ and $V_s$ in soils (a) and rocks (b) measured in Israel in-situ and in laboratory (in brackets) conditions

3. METHODS

3.1. HVSR METHOD

3.1.1. General

Nakamura (1989) hypothesized that site response could be estimated from the spectral ratio of horizontal versus vertical component of noise observed at the same site (site of interest). The HVSR technique has become the primary tool of choice in many of the ambient noise related studies; and it has been successful in seismology to estimate the local transfer function in the site response problem in Israel and worldwide (Lermo and Chávez-García, 1994; Mucciarelli and Gallipoli, 2004; Seekins et al., 1996; Zaslavsky et al., 2005, 2008, 2009). The Nakamura's method is based on the assumption that microtremors consist of body waves. Enomoto et al. (2000) and Mucciarelli and Gallipoli (2004) claim that the $H/V$ spectrum of ambient noise is dominated by the upward propagation of SH wave through the layered media. On the other hand, an explanation based on the opposite assumption that microtremors mainly consist of surface (Rayleigh) waves is also successful (see e. g. Fäh et al., 2001; Lachet and Bard, 1994). Both models agree that the $H/V$ spectra and the site response function for SH wave are the results of the velocity structure of the media, that both exhibit the same fundamental resonance frequencies with similar amplitudes at least when considering small motions.

It was demonstrated through many studies (Zaslavsky et al., 2005, 2008, 2009), when noise measurements are made near boreholes and/or near refraction surveys, the fundamental frequency and its corresponding $H/V$ amplitude are practically the same as the fundamental frequency and amplification derived from the computed transfer function of SH-waves at low strains propagating through a relatively simple 1-D model of the site, known from geotechnical and geophysical surveying. Computer code SHAKE (Schnabel et al., 1972) is used to analytically evaluate site response function. The specific parameters required for this analysis are:
- S-wave velocity, thickness, density and damping of each layer in unconsolidated sediments;
- S-wave and density of the hard rock (reflector).

3.1.2. Data acquisition

The methodology of HVSR data acquisition and processing is considered in details in Zaslavsky, et al. (2009). Ambient noise measurements are conducted using portable instruments (Shapira and Avirav, 1995) consisting of a multi-channel amplifier, Global Positioning System (GPS) for timing and a laptop computer with 16-bit analogue-to-digital conversion card to digitize and store the data. (Fig. 3).

![Figure 3. Photographs of noise measurements: (a) 3-component 1Hz seismological station; (b) recording of seismic noise; (c) Field records.](image)

Each seismograph station consists of three (one vertical and two horizontal) L4C velocity transducers (Mark Products) with a natural frequency of 1.0Hz. The sample rate is of 100 samples per second and filter band-pass is between 0.2Hz and 25Hz. All the equipment: sensors, power supply, amplifiers, personal computer, and connectors are portable allowing performing of measurements in autonomous mode (Fig. 3b). Examples of 3-component noise records are shown in Fig. 3c. Presented pattern of measurements is typical and repeated from site to site.

3.1.3. Data processing

Data processing is explained in Fig. 4. For each site, the average H/V spectral ratios and their corresponding standard deviations are determined by applying the following process: (1) time windows, each of 30-60 seconds long depending on fundamental frequency, are selected. (2) A Fourier transform is applied on the time windows, using cosine-tapering (1 second at each end) before transformation and then smoothed with a triangular moving Hanning window. (3) For each site a set of up to 50 time windows is selected, records within these time windows are compiled, each window provides an H/V spectral function.

Data processing is carried out using "SEISPECT" software developed in the Geophysical Institute of Israel (Perelman and Zaslavsky, 2001). SEISPECT is a MATLAB application for spectral analysis and processing of ground motion including seismograms recorded by short-period and broad-band seismic stations, as well as strong motion accelerometers. The main modules realized
in the program are: visualizing and editing of the input data; selecting time window and computing Fast Fourier Transform (FFT) and H/V spectral ratios; saving and displaying results. The average spectral ratio for each of two horizontal components is computed; if the curves of average spectral ratios of the two components are similar then the average of the two horizontal-to-vertical ratios is defined as:

$$A(f) = \frac{1}{2n} \left[ \sum_{i=1}^{n} \frac{S_{NS}(f)_{i}}{S_{V}(f)_{i}} + \sum_{i=1}^{n} \frac{S_{EW}(f)_{i}}{S_{V}(f)_{i}} \right]$$  \hspace{1cm} (1)

where $S_{NS}(f)_{i}$ and $S_{EW}(f)_{i}$ are individual spectra of the horizontal components and $S_{V}(f)_{i}$ is individual spectrum of the vertical component.

Figure 4. (a) Example of individual (1) and average (2) spectral ratios obtained on the Dead Sea shore; (b) Analytical transfer function (4) in comparison with observed H/V spectral ratio (3). Arrows denote the resonance frequencies.

3.2. MASW METHOD

3.2.1. General

Surface-wave dispersion inversion (SWDI) is a standard approach for inferring a 1D Vs structure. Surface waves, commonly known as ground roll, are always generated in all seismic surveys, have the strongest energy, and their propagation velocities are mainly determined by the medium’s shear-wave velocity.

The development of multichannel equipment has led to exploiting the methodology known as Multichannel Analysis of Surface Waves (MASW) (Park, et al., 1999; Xia, et al., 1999). The MASW method is basically an engineering seismic method dealing with frequencies mainly 3-30Hz recorded by using a multichannel (24 or more channels) recording system and a receiver
array deployed over a 2-200m distance. The active MASW method generates surface waves actively through an impact source like a sledge hammer, whereas the passive method utilizes surface waves generated passively by cultural (e.g., traffic) or natural (e.g., thunder and tidal motion) activities (Park, et al., 2007).

**Active MASW.** Active-source surface-wave dispersion measurements are made with typical seismic shot gatherers that are a collection of seismic traces, which share some common geometric features. The wave field is transformed into a frequency-wave number (or frequency-slowness) domain in which the maxima should correspond to surface-wave signatures (Fig. 5a). Several modes can be picked out for such dispersion curves if the propagation mode signatures are well separated. The dispersion curves are then inverted for a 1D Vs profile with depth. When data are collected in a roll-along mode, each 1D profile is represented at its corresponding midpoint spread, allowing a pseudo-2D Vs section to be drawn.

![Dispersion images and extracted curves](image)

**Figure 5.** Examples of dispersion images (DI) and extracted curves from the Ein Boqeq site (Dead Sea). (a) Active MASW; (b) passive MASW; (c) Combined (active + passive) image.

The inverse problem formulation imposes that the investigated medium is assumed as one-dimensional under the spread. Long spreads are required to record wavelengths large enough for increasing the investigation depth and for mitigating near-field effects (Bodet, et al., 2005; Socco, et al., 2009).

**Passive MASW.** The passive surface waves generated from natural (e.g., tidal motion) or cultural (e.g., traffic) sources are usually of a low-frequency nature with wavelengths ranging from a few kilometers (natural sources) to a few tens (or hundreds) of meters (cultural) (Okada, 2003), providing a wide range of penetration depths and therefore a strong motivation to utilize them. The ambient noises are recorded using receiver arrays (antennae) arranged as different geometrical figures (linear, circular, cross layout, etc. arrays). The dispersion image and extracted dispersion curve are extracted (Fig. 5b). The most accurate estimation is obtained through a survey using a true 2D receiver array (Park, et al., 2006). However, because the true 2D receiver array, such as a circular and cross-layout ones are not a practical or possible mode of survey in built-up urban areas, a method that can be implemented with the conventional 1D linear receiver array can be effective in this case (Louie, 2001). The data processing scheme can be found in Park, et al. (2004).

**Combination of active and passive MASW measurements.** Dispersion images processed from active and passive data sets should be combined to obtain improved dispersion curves (Fig. 5c). The active MASW method generates signals in the range of 5-30Hz, whereas a passive one allows for widening that to the low frequency range down to geophone frequency. Combining two signals, we widen the range of frequencies from 2.5-30Hz, and sometime even up to 50Hz. Thus, the
penetration depth can be increased to a deep range (low frequencies) and the uppermost depth can be decreased (high frequencies) (Park, et al., 2004).

3.2.2. Data acquisition

3.2.2.1. Practical aspects of data acquisition

Although methods like shear-wave refraction, downhole, and cross-hole surveys can be used, they are generally less economical than any other seismic methods in terms of field operation, data analysis, and overall cost. The great advantage of the surface wave method in comparison with the refraction one is quality of the field records. We illustrate it comparing two above acquisition methods in Fig. 6.

Figure 6. Comparison of seismic methods for S-wave acquisition. (a) Excitation of S-waves in the seismic refraction technique using horizontal stroke on metallic beam by a 30 kg hammer; (b) excitation of surface wave of R (Rayleigh) type using vertical stroke by 200 kg hammer forced by slingshot; (c) raw data obtained at such stroke complicated by strong noise; and (d) field records of surface waves.

Surveys were carried out along the same length line by different hammers. The data acquisition of S-waves with the refraction method is carried out using a horizontal stroke of the 30kg sledge hammer (Fig. 6a) allowing a most clear excitation of SH waves at the background of other waves. However, because of weak source, S-wave records are complicated by ambient noise (Fig. 6b) allowing penetration of S-wave as a rule to 25-30m. On the other hand, surface waves, because of strong vertical stroke by 200kg-hammer (in our case, forced by slingshot) (Fig. 6c) are characterized by the strongest energy, and their propagation velocities are mainly determined by the medium’s shear-wave velocity. Quality of the field records is significantly higher (Fig. 6d) and
allows penetrate down to depths determined by wavelength (that is usually some tens to hundreds of meters).

### 3.2.2.2. Modified data acquisition

**Active MASW.** Conventional seismic data (i.e., the vertical component of the wave field from common shot records obtained in shallow refraction surveys) were used. To increase penetration depth of surface waves we used vertical low frequency 2.5Hz geophones (Fig. 7a) implemented to seismic profile (Fig. 7b).

![Image](image_url)

Figure 7. Modified MASW data acquisition. (a) 1 - 2.5Hz geophone and 2 - 10Hz geophone (for comparison); (b) MASW profile comprised of 32 of 2.5 Hz geophones, signal is excited by Digipulse seismic source (is seen at the end of line). The wave exciting is shown in Fig. 6c and field records are presented in Fig. 6d.

Receiver spacing was varied with respect to necessary penetration depth from 2.5-10m; shot location was 5-10m away from nearest trace (off-end shooting). Data excitation was carried out using power Digipulse hydraulic source mounted on a Chevrolet pickup truck (Fig. 6). Both geophone frequency and power source facilitate recording raw data of high quality and more penetration depth. A Summit II plus seismic recorder was used with a 24-48 geophone spread (vertical 2.5Hz geophones). The number of geophones as well as line length were selected in accordance with the depth of target.

At first, P-wave seismic refraction study was carried out along study line using 2.5Hz vertical geophones. Record length for P-wave refraction was as 500 ms. Then record length was increased to 2000 ms and surface waves were recorded.

**Passive MASW.** Passive MASW measurements were carried out using linear system located along the roads (roadside schema) with 2.5Hz geophone separation of 5m. Other arrays used in Israel were circular arrays with 5-10m separation between geophones (Ezersky and Gorstein, 2013). Then active and passive records were combined using SurfSeis v3 software.


**3.2.3. Data processing**

Data processing is applied to (a) P-wave refraction data, and (b) surface wave data.

(a) P-wave refraction processing is intended for constructing of Vp depth layered model and determination depth to firm layer (reflector). These data are used for generating an initial model for surface wave inversion.

(b) Surface wave data are used for: (1) generation of dispersion image; (2) extracting dispersion curve; and (3) its inversion. All these are carried out using SurfSeis v3. Software of Kansas Geological survey (KGS). Software allows any combining of active and passive dispersion images with different parameters of measurements (different frequency, separation of geophones etc.).

An inversion of the dispersion data is carried out using *linearized inversion* with a gradient-based iterative method (Park, et al., 1999, Xia, et al., 1999) implemented to commercially available SurfSeis v.3 software (Park and Brohammer, 2003). The Root Mean Square Error (R.M.S.E.) between the theoretical dispersion curve and the measured one is usually used as an indicator of the closeness between measured and iteratively calculated dispersion curves. Usually, in linearized inversion methods, constraints are applied to the solution in order to reduce the degree of non-uniqueness. Constraints are obtained from available independent geological and geophysical information, such as longitudinal (compression) wave velocity (Vp), depth to reflector layer or half space, firm layer thickness and composition, geological section of the site under investigation. For instance, seismic refraction Vp depth section is shown in Fig. 8a. From this section one can see that bedrock is located at a depth of 25m and is characterized by Vp = 3100m/s. The bedrock is overlain by water saturated sediments with Vp = 2460m/s in a depth range of 5-25m. These data are intended to confine the result of inversion by possible parameters. The dispersion equation depends mainly on Vs, and thickness value in the layers. An appropriate choice of these parameters (the initial model) is considered as a fundamental issue for the successful application of inversion (Socco and Strobia, 2004).

The most important part of the MASW data processing is constructing an initial layered model for inversion. Inversion is carried out at constant Vp values (in our case Vp = 3100 m/s), whereas Poisson’s Ratio varies (Ezersky et al., 2013a). Such inversion procedure allows stabilizing of the inversion results. Result of inversion of the combined dispersion curve presented in Fig. 5 is shown in Fig. 8b as Vs – depth section. Note that number of layers should be not so large (usually, 5-7 layers) to avoid equivalency problem (Cerato et al., 2009; Renalier et al.2010).

Generally bounds of wave velocities are presented in Fig. 2. Some parameters can be selected using well-known rules of thumb (Xia, et al. 2003): (a) Vp versus Vs ratio can be considered bounded for near surface materials, assuming Poisson’s ratio, with values ranging from 0.20-0.48; (b) The Rayleigh-wave velocity in a uniform half-space is very close to the Vs of the layer. As a reference model for inversion, Vs can be approximated by the phase velocity multiplied by a correction factor (less than unity for fundamental-mode data). The examples of field records and data processing will be considered in continuation.
3.3. COMBINATION OF HVSR AND MASW METHODS

Data collected from a few seismic profiles provide information on the S-wave velocities and thickness of shallow sediments (down to 50-100m) within the accuracy and resolution of the geophysical technique. Seismic MASW profiles are normally designed to obtain maximum information on Vs of the lithological units represented in the study area and in the vicinity of boreholes. Measurements of ambient vibrations are also carried out either very close to or directly at drilling sites where detailed information on the subsurface is available. The logging data are incorporated to obtain more detailed and reliable information about the subsurface. Then, the borehole and geophysical information are combined with the observed spectral ratios to estimate the depth S-wave velocity profile. The iterative procedure based on the stochastic optimization algorithm (Storn and Price, 1995) is applied in order to fit an analytical transfer function (4 in Fig. 4b), estimated using SHAKE code (Schnabel et al., 1972) to an observed H/V spectral ratio (3 in Fig. 4b), focusing mainly on the resonance frequencies (arrows in Fig. 4b) and considering the shape H/V curve. Thus, combining the borehole and geophysical information with the observed spectral ratios 1-4 the depth – Vs velocity profile is derived.

3.4. RESOLUTION OF MASW METHOD.

The resolution of MASW method is considered usually as a rule of thumb (Bodet, et al., 2005, Richart, et al., 1970, Park, et al., 1999, O’Neill, 2003, Shtivelman, 1999). Many conclusions are based on experimental results. Some issues should be considered: (1) The maximum and minimum penetration depth; (2) their relationships with seismic line length, and (3) reliability of measured
velocities. This section is based on literature data and our experience (Ezersky, et al., 2013a, 2013b).

Maximum penetration depth. At the beginning of our study, we examined the main concerns and possibilities in increasing penetration depth. The normally accepted axiom (Richart, et al., 1970) is that the penetration depth ($Z_{max}$) of ground roll is approximately equal to its wavelength ($\lambda$) and may be up to $2\lambda$.

Rayleigh waves are surface waves that propagate close to the surface, affecting a limited depth depending on the wavelength. This depth–wavelength relationship is not linear in vertically heterogeneous media. There is no radiation towards the earth’s interior and wave fronts are cylindrical in laterally homogenous media. The propagation velocity depends mainly on the shear-wave velocity $Vs$: in a homogeneous half-space the Rayleigh-wave velocity $V_R$ is slightly lower than $Vs$ ($0.87Vs<V_R<0.96Vs$), depending on Poisson’s ratio (Fig. 9 from Richart et al.1970).

Then the question arises, what is the maximum penetration depth ($Z_{max}$) for which $Vs$ can be reasonably calculated? Park, et al. (1999) evaluates it using a $0.5\lambda_{max}$ criterion. Rix and Leipski (1991) evaluate it using a $(0.5-1.0)\lambda_{max}$ criterion. The maximum depth depends on the maximum reliably estimated wavelength. Different authors suggest $Z_{max}$ as a rule of thumb. Some estimations are suggested. As a rule, it is estimated as $0.25\lambda_{max}$ (Bodet, 2005), $0.5\lambda_{max}$ (Shtivelman, 1999) to $(0.5-1)\lambda_{max}$ (Rix and Leipski, 1991). The latter authors affirm that the results indicated that the best overall accuracy and resolution is obtained when the dispersion data is evenly distributed between the minimum and maximum wavelengths and the maximum wavelength is one to two times the maximum desired depth of the shear-wave velocity profile.

It is important that in principle, penetration depth can reach $\lambda_{max}$ (and even, more). This depends on some factors such as shear-wave velocity of overburden, frequency, and signal quality.

Our experience (Ezersky, et al. 2013a) shows that in most cases (with 2.5Hz geophones) criterion of $Z_{max}=0.5\lambda_{max}$ is enough to estimate properties ($Vs$) of the foundation down to 40-60m deep. However, in rare cases of deeper reflector penetration depth should be checked as an exception.

Example of such a case is presented here for Ramat Hakovesh site presented in this article, where active and passive MASW measurements were carried out:

$$c_{max} = 708m/s \quad f_{min} = 2.96Hz \quad \lambda_{max} = c_{max} / f_{min} = 239m$$

Where, $f_{min}$ = minimum frequency measured in combined image, $c_{max}$ = maximum phase velocity, measured at this frequency, and $\lambda_{max}$ = maximum wave length. Thus, accepting the criterion of Rix and Leipski (1991) maximum penetration depth can be evaluated as between 120 and 239m. However, it is reasonably to accept maximum penetration depth as 120m at least.
Figure 9. Variation in normalized particle motions with normalized depth for Rayleigh Waves propagating along a uniform half space (from Richart et al., 1970).

**Relationship between $\lambda_{\text{max}}$ and length of geophone line (array).** This issue is debated by different researchers. It is generally considered that length of receiver spread ($L$) is directly related to the longest wavelength ($\lambda_{\text{max}}$) that can be analyzed; e.g., $L = \lambda_{\text{max}}$ (Park, et al., 1999). $L = X_1 \ast (N-1)$, where $X_1$ is separation between geophones and $N$ is number of geophones in spread. Parameter $X_1 = H_1$ is connected with a minimum measured depth in limits of which $V_s$ can be considered as a reliable value (Stokoe, et al., 1994); e.g., $H_1 > 0.5 \lambda_{\text{min}} = 0.5C_{\text{min}} / f_{\text{max}}$, where $f_{\text{max}}$ is the highest frequency at which minimum phase velocity $C_{\text{min}}$ can be measured. Thus, in all parameters of measurements ($\lambda_{\text{max}}, L, N, H_1, Z_{\text{max}}$) it seems to be mutually connected and based on experimentally revealed rules of thumb that are often determined by required depth of investigation i.e. 30m and available geophones of 4.5Hz. However, Socco and Strobia (2004) concluded that in fact, wavelengths longer than the array can be observed, and the maximum wavelength depends mainly on quality of the dispersion image. Our experience agrees with this conclusion. Our concept is to use the lowest frequencies possible and thus reach a maximum penetration depth. To improve the quality of signal (S/N ratio) we have used in this study: (1) low frequency geophones, (2) power Digipulse source based on Chevrolet pickup truck (Fig.6b), (3) long seismic line, and (4) all available information (borehole data, refraction seismic and TEM measurement).

The increase in penetration depth is reached also by a combination of active and passive sources (Park, et al., 2004). That is why we also consider (0.5-1.0) $\lambda_{\text{max}}$ criterion as determining $Z_{\text{max}}$ suggested by Rix and Leipski (1991). This criterion corresponds to our conditions and data. We have checked it with passive MASW, which has a penetration depth $Z_{\text{max}} = \lambda_{\text{max}}$. 
Resolution in uppermost subsurface. The thickness $H_1$ of the uppermost (irresolvable) layer limiting the resolution of sub-surfaces is determined by the wavelength and parameters of the data acquisition according to the half-wavelength criterion (Rix and Leipsky 1991). The normally accepted criterion is that the minimum penetration $H_1$ is determined by (Stokoe et al., 1994):

$$H_1 \geq 0.5\lambda_{\text{min}} = 0.5V_{p\text{min}} / f_{\text{max}}$$  \hspace{1cm} (2)

where $V_{p\text{min}}$ is the minimum phase velocity of the fundamental mode and $f_{\text{max}}$ is corresponding frequencies at the phase velocity measured. Note that $\lambda_{\text{min}}$ relates to the minimum distance ($2dx$) between geophones (O’Neill, 2003).

The problem can be resolved in two ways. The first way is varying the geophone separation at active MASW. The second way is to use high frequency array. The real example of data acquisition with separations of 10m and 2.5m (both, 2.5Hz geophones) and separation of 5m and 10Hz geophones show:

- 2.5Hz geophones, 10m apart: $c_{\text{min}} = 219m/s$, $f_{\text{max}} = 15Hz$, $Z_{\text{min}} = \lambda_{\text{min}} / 2 = 7.3m$
- 2.5Hz geophones, 2.5m apart: $c_{\text{min}} = 219m/s$, $f_{\text{max}} = 23Hz$, $Z_{\text{min}} = \lambda_{\text{min}} / 2 = 4.7m$
- 10Hz geophones, 5m apart: $c_{\text{min}} = 256m/s$, $f_{\text{max}} = 59Hz$, $Z_{\text{min}} = \lambda_{\text{min}} / 2 = 2.2m$

It is clearly seen that a more effective way to improve the resolution of MASW at small depth is to increase geophone frequency instead of decreasing separation.

### 4. PARAMETRIC STUDY

Within the framework of this paper, we consider two typical subsurface structures forming conditions for site effect. In the first model, one or two hard layers are over- and underlain and by soft soil ("Layer model"). This case is presented by salt layers of 5-30m thickness located at a depth of 20-50m along the Dead Sea coastal area that is a national and international resort area. The subsurface structure in the second case is widespread in the Israel plain, and is formed by soft sediments overlaying rigid rock ("Half-space model"). With respect to the surface waves prospecting method, the penetration depth depends on geophones natural frequency. Forward modeling carried out for the two above models of subsurface (Fig.10b dashed and solid lines) has shown that dispersion curves are significantly differed (dashed and solid graphs in Fig. 10a, respectively).
Figure 10. Forward modeling. (a) Two dispersion curves corresponding to subsurface models shown in (b). Dashed line corresponds to firm salt layer of 20m thickness located under alluvial sediments at a depth of 25m. Salt layer is also underlain by alluvial sediments. Vs of half space is of also 1650 m/s.

Fig. 11 shows examples of two combined dispersion images obtained in subsurface of the above structure. Geophones of 4.5Hz are mainly used for Surface-wave prospecting (SWP). Fig. 10a shows that in the frequency range of more than 5.5-6Hz both curves are non-distinguishable. To distinguish between recorded curves frequency should reach the frequency range between 4.5-6Hz. As a rule, to obtain such frequencies the source should be powerful, otherwise, surface waves cannot penetrate overburden. Geophones used in our study (2.5Hz) together with a powerful Digipulse source allowed the registration low frequencies down to 2.5Hz (Fig. 10a).

Figure 11. Examples of combined dispersion images with extracted dispersion curves for subsurface models discussed above. (a) Ein Boqeq site. “Layer model” (dashed line in Fig. 10b); (b) Ramat Hakovesh site - the “Half space” (solid line in Fig. 10b) located at 74m deep under alluvial sediments. In both cases dark zone near 2.5Hz is an anomaly associated with maximum energy near resonant frequency.

The use of a powerful source and low frequency geophones, together with proper line length allow penetration of both overburden and solid layers down to a depth of 70-100m and more (Ezersky, et al., 2013a; 2013b). Thus, the MASW method with our modification resolves the objectives formulated in Section 1.
5. TEST SITES

5.1. NAVOT SITE

5.1.1. Geological outline

The Navot site is located in the Hordos valley, between Afula and Bet Shean (Fig. 12a). According to the borehole information, lithological section at this location is represented by clay layers with different content of conglomerates overlying basalt at a depth of about 25 meters (Fig. 12b). The study area is situated close to crossing two roads #rout 675 and rout 71 (see Fig. 12a and 12c).

Figure 12. Navot site. (a) Site location map; (b) borehole 38 lithological section (Zaslavsky et al., 2012); (c) Geophysical measurements layouts.

To construct analytical model for the subsurface of the site a Vp refraction line (no. 2) was shoot along with MASW measurements (Fig. 12c). Noise was measured at three 3-component stations shown in Fig. 12c. In this report, results of measurements along line 2 located close to Route #71 are presented.

5.1.2. MASW measurement results

Passive MASW measurements. Passive MASW measurements were carried out using roadside technique along 32-channel line located 35-45 m from a Route #71 (Figs. 12a and 13a). Example of ambient noise record from traffic is shown in Fig. 13b. Noise was recorded during 1 min with sample rate of 4 ms. Dispersion image with extracted dispersion curve is depicted in Fig. 13c. The frequency range is between 2.5 to 8 Hz.
Figure 13. Navot site results. (a) Passive MASW roadside array, 4m separation, (b) field records 30 min length, sample rate of 4 ms, and (c) dispersion image (See Fig. 12c for location). Traffic noise is intense.

**Active MASW measurements.** Results of active MASW measurements along Line 2 (see Fig. 12c for location) are shown in Fig. 14. Active signal is noisy (Fig. 14a). However, still allows extraction of a good quality dispersion image (S/N Ratio is in limits of 1.0 – 0.9) in a frequency range between 4 to 10 Hz (Fig. 14b).
Figure 14. Active MASW data along line 2 in the Navot site. (a) Field records acquired using active source; (b) Dispersion image (DI) generated from active record: squares are points of the extracted dispersion curve. The DI comprises mainly the fundamental mode and allows extracting the fundamental mode dispersion curve.

**Combined MASW measurements.** Combined image shown in Fig. 15a integrates the dispersion images of passive and active MASW surveys presented in Figs. 13c and 14b, respectively. The refraction P-wave depth velocity section used as constraint for inversion is shown in Fig. 15a. Velocity $V_p=1610\text{m}$ characterizes water saturated sediments. Combined inversion of the dispersion curve for 6-layered model is presented in Fig. 16 (R.M.S.E. = 13.6%) and in Table 1. The depth to the top of basalt layer is accepted as 26m.

Figure 15. Navot site. (a) Seismic refraction depth velocity section along line 2 (reflector is located at a depth 25m); (b) Dispersion image generated from combined record: squares are points of the extracted dispersion curve. The combined image is confined by frequency of 10 Hz.
Inversion of the dispersion curve. Velocity versus depth function obtained by inversion of combined dispersion curve shown in Fig. 15b for 6-layered model. Denoted: Initial model (thin blue dashed line), corresponding initial dispersion curve (thin blue dotted line), experimental points (blue circles) and fitted dispersion curve (blue thin solid line), inverse depth velocity model (blue thick layered graph). Lower horizontal axis is frequency (Hz) and top axis is depth (m).

Table 1. Parameters of the inversion procedure for 6 layered model (Navot site Line 2).

<table>
<thead>
<tr>
<th>Layer No</th>
<th>Depth, m</th>
<th>Initial model, m/s</th>
<th>Inverted model, m/s</th>
<th>R.M.S.E of Vs, %</th>
<th>Vp, m/s</th>
<th>Density, kg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0 – 6</td>
<td>245</td>
<td>135</td>
<td>1.97</td>
<td>600</td>
<td>1550</td>
</tr>
<tr>
<td>2</td>
<td>6.0 – 14.0</td>
<td>300</td>
<td>320</td>
<td>9.07</td>
<td>966</td>
<td>1600</td>
</tr>
<tr>
<td>3</td>
<td>14.0 – 20.0</td>
<td>400</td>
<td>530</td>
<td>13.2</td>
<td>1408</td>
<td>1650</td>
</tr>
<tr>
<td>4</td>
<td>20.0 – 26.0</td>
<td>500</td>
<td>250</td>
<td>4.9</td>
<td>1600</td>
<td>1800</td>
</tr>
<tr>
<td>5</td>
<td>26 – 31.0</td>
<td>1600</td>
<td>1550</td>
<td>13.62</td>
<td>3200</td>
<td>3200</td>
</tr>
<tr>
<td>6</td>
<td>Under 31</td>
<td>2050</td>
<td>2000</td>
<td>13.61</td>
<td>3200</td>
<td>3200</td>
</tr>
</tbody>
</table>

5.1.3. **HVSR measurement results**

Location of ambient noise measurement points are shown in Fig. 12c. The Fourier spectra and spectral ratios obtained from ambient noise measurements using HVSR method along the Line 2 are presented in Fig. 17a and 17b. The site effect is clearly seen in the Fourier spectra, i.e. while
the vertical spectral component is almost flat, amplitudes of the horizontal spectra significantly increase in the frequency range 1.5-5 Hz; and the spectral ratios yield amplification of about 6 at frequency of 3 Hz.

5.1.4. Constructing of the subsurface model using HVSR and MASW

The subsurface model for Navot site is elaborated in accordance with the ambient noise and MASW measurements results. All the geotechnical data contributing to model constructing are collected in Table 2.

In order to specify the subsurface model which should approximate the spectral ratios by analytical function in the best way, we used the MASW Vs-depth section. Four layers are identified in this section down to a depth of 25 m that is top of the basalt layer and is detected by all the information sources including borehole and refractions. Inhomogeneity of the clay layer over the basalt layer is confirmed by borehole data about different content of conglomerates. The velocity of 250 m/s at 20-25m depth for the layer directly overlying the basalt is confirmed by Standard Penetration Test (SPT) data in the borehole 38 that shows low SPT N blow of 17.5 at depth range of 18 – 18.5 m; N=18 at the depth range of 19-19.95m, N=16 (in the depth range 21-21.45m), N=37 at depth range of 22.5-23m, whereas background N value is more than 50 (and even 100). The upper part of the basalt layer characterized by Vs of 1550 m/sec has limited thickness and is not fundamental reflector but an intermediate hard layer. Again, it agrees quite well with the borehole data. We note that neither inhomogeneity of the clay layer nor different Vs in the basalt are reflected in results of the refraction survey.

In Fig. 18 the analytical transfer function (black dashed line) is compared with HVSR one averaged for three measurement points along the MASW line (red solid line) and shows good agreement. Optimal 1-D subsurface model for determination of analytical site response function in the Navot site is given in Table 3.
Figure 17. (a) Average Fourier spectra and (b) individual and average horizontal-to-vertical spectral ratios (HVSR) of ambient noise obtained at measurement points 1, 2 and 3.
Table 2. Geotechnical parameters used for determination of analytical site response function in the Navot site.

<table>
<thead>
<tr>
<th>Borehole data</th>
<th>P-wave refraction survey</th>
<th>MASW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithology</td>
<td>Depth, m</td>
<td>Depth, m</td>
</tr>
<tr>
<td>Clay fat, brown</td>
<td>0-6</td>
<td>0-6</td>
</tr>
<tr>
<td>Clay fat, brown with limestone (5-15%)</td>
<td>6-13</td>
<td>6-25</td>
</tr>
<tr>
<td>Clay fat, brown with limestone (15-40%)</td>
<td>13-25</td>
<td>1610</td>
</tr>
<tr>
<td>Basalt fractured</td>
<td>25-30</td>
<td>Below 26</td>
</tr>
<tr>
<td>Basalt massive</td>
<td>Below 30</td>
<td>4500</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 18. Analytical transfer function (black dashed line) in comparison with HVSR averaged for three measurement points along the MASW line (red solid line).
Table 3. Optimal 1-D subsurface model for determination of analytical site response function in the Navot site.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness, m</th>
<th>Vs, m/sec</th>
<th>Density, kg/m$^3$</th>
<th>Damping %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>6</td>
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<td>5</td>
<td>5</td>
<td>1550</td>
<td>1900</td>
<td>1</td>
</tr>
<tr>
<td>Half-space</td>
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<td>2000</td>
<td>2300</td>
<td>$\infty$</td>
</tr>
</tbody>
</table>

5.2. RAMAT HAKOVESH, (THE TOWN OF TIRA, CENTRAL ISRAEL)

5.2.1. Geological outline

The investigated area is situated close to the town of Tira, a few kilometers west of the Shomron Mountains slope represented by hard carbonates of the Judea Gr. (Turonian-Cenomanian age). The plain is filled by heterogeneous sediments of the Pleistocene age, mainly represented by clayey and sandy soils of 70-100m thick.

5.2.2. Schema of measurements

The measurement schema is presented in Fig. 19d. Two seismic refraction lines (P-wave line of 320m long and S-wave line of 250m long) were shot in 2007. MASW lines SS-10, SS-5, and SS-2.5 of 250m long, 150m long and 72.5m long, respectively, comprised of 2.5Hz geophones (with separation 10m, 5m, and 2.5m, respectively) were shot in 2014. HVSR of ambient noise is obtained at point 11w situated close to borehole 1A.

5.2.3. MASW results

Dispersion images obtained for different data (different separation between geophones, active and passive sources, combined images) are presented in Fig. 20. Note that active dispersion curves for 10m separation (Fig. 20a) are in the range of 4-12Hz, similar images for 2.5m separation wide, the frequency range to 3-23Hz (Fig. 20b), and passive image extends the low-frequency range to 2.5Hz, whereas high-frequency decreases to 9Hz (Fig. 20c). Combining the different images allows getting a frequency range between 2.5Hz and 23Hz and to reach resolution (penetration of waves) of $1\lambda_{max}$ in the deep part of section and the resolution in shallow depth to 2.5m from surface.
Figure 19. General map of Ramat Hakovesh site location. (a) Israel map and test site location; (b) Geological map showing the study area relative to the Tira town; (c) Lithological section of 1A borehole (see Fig.19d for location); (d) measurement layouts. RF (top of dolomite) is located at a depth of 73.5m in borehole 1A (test well).
Figure 20. Four dispersion curves extracted from surface wave records from different MASW measurements: (a) active source along 26 channel line with geophone separation of 10m (250m length); (b) active source along 31 channel line with separation 2.5m between geophones (77.5m length); (c) ambient noise (passive source) along 26 channel line 10m separation; (d) combined dispersion curve combined from (a) – (c) images; (e) and (f) are field records of active and passive sources, respectively.

Inversion has been carried out with the following constraints: top of reflector is located at a depth of 73.5m, $V_p = 3230$ m/s based on seismic refraction section (Fig. 21a). Inversion has been carried out with $V_p$ fixed and Poisson’s Ratio varying. 5-layered model with half space located at 73.5m gives best result with R.M.S.E. = 9.9%. $V_s$ of half space is evaluated as 1480 m/s. Inversion results for 5-layered model are shown in Fig. 21b and in Table 4.

Figure 21. Ramat Hakovesh site. Velocity versus depth function obtained by inversion of combined dispersion curve shown in Fig. 11b for 5 layered model with half space as foundation. Denoted: as Fig. 15. Vertical axis is $V_s$, upper horizontal axis is depth and lower one is the frequency.
5.2.4. HVSR results

Measurements of ambient vibrations were carried out close to the experimental borehole 1A where detailed information on the subsurface down to a depth of 75m is available. The prominent feature of the individual and average spectral ratios shown in Fig. 22a is two inseparable peaks at frequencies of 1.4 and 1.9Hz. While the first resonance peak is related to the hard rock at depth, the second peak is caused by intermediate hard layer directly overlying the deep reflector.

![Figure 22](image)

Figure 22. (a) Example of H/V spectral ratios (individual, average and standard deviation) obtained at 1A borehole location. Arrows show the fundamental and second resonance frequencies; (b) Comparison between H/V curves (red solid line) and analytical function (dashed line) based on Vs model derived from combination of HVSR and MASW methods; blue solid line is analytical function calculated on the base of MASW results solely.

5.2.5. Combination of HVSR and MASW methods

In the velocity-depth section obtained from MASW measurements (Fig. 21b), four layers could be identified. According to the lithological section of the borehole 1A (Fig. 19c) layered Vs may be correlated with sandy loam (Vs = 205 m/sec); sand (Vs = 300 m/sec); clay and sandy loam (Vs = 500 m/sec) that overlies the broken dolomitic limestone (Vs = 1440m/sec). Slightly different section was extracted from refraction survey along P-S lines, shown in Fig. 21a. The response function calculated using solely geophysical data and the broken dolomitic limestone at a depth of 73m as a fundamental reflector is shown in Fig. 22b (blue solid line). It is clearly seen that there is no satisfactory consent between the calculated function and HVSR neither in amplitude nor in shape. In particular, the calculated function exhibits a single resonance peak with amplitude of 3.5 at resonance frequency 1.6Hz, when HV spectral ratio yields two resonance peaks at 1.4 and 1.9Hz with associated amplitudes of 7 and 5.5 respectively. Therefore, in the second step, we supposed
the subsurface model in which the broken dolomite-limestone is an intermediate hard layer and overlays the fundamental reflector (dolomite) at a depth which should be estimated. The result of the optimization procedure is shown in Fig. 22b. The optimal model providing the best fit between HVSR and calculated response function is given in Table 4.

Table 4. Vs model obtained from MASW measurements and optimal soil column model for Borehole 1.

<table>
<thead>
<tr>
<th>Lithology</th>
<th>MASW</th>
<th>MASW+HVSR optimal model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Depth, m</td>
<td>Vs, m/sec</td>
</tr>
<tr>
<td>Alluvium</td>
<td>0-5</td>
<td>205</td>
</tr>
<tr>
<td>Sand, loam, clay, calcareous sandstone</td>
<td>5-30</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>30-50</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>50-73</td>
<td>490</td>
</tr>
<tr>
<td>Broken dolomite, limestone</td>
<td>73-240</td>
<td>1440</td>
</tr>
<tr>
<td>Dolomite</td>
<td>Under 240m</td>
<td>--</td>
</tr>
</tbody>
</table>

6. DISCUSSION AND CONCLUSIONS

Any analytical procedure (making use of a computer code) needs a model of the site’s subsurface to facilitate the computations. Based on numerous investigations it can be concluded that there is no one single technique that will provide a model good enough for site response evaluations. The spectral ratio method reveals key information about the dynamic characteristics of the subsurface and should be used to help construct the subsurface model. In recent researches carried out in Israel, the reliable subsurface models could be reached by integrating information from empirical HVSR, and available geological, borehole, and geophysical data (Zaslavsky, et al., 2009). Such combination of seismic methods provide the Vs model for the uppermost tens of meters while, HVSR method adds information and constraints for the development of a subsurface model at significantly greater depths. In this study, we applied the Multichannel Analysis of the Surface Wave (MASW) method to reveal shallow Vs models for two sites where seismic refraction or downhole methods were performed in the earlier investigations. Noting the high quality of the S-wave refraction method in constructing subsurface models (Palmer, 1986) we have to resume very shallow, as a rule, Vs sections derived from this survey (Fig 12). Deeper penetration of surface waves enables constructing deeper Vs sections and facilitates their optimization in combination with the HVSR method. Moreover, the system of shooting used in the MASW method enables us to also simultaneously carry out a seismic
refraction line at the same disposition, geophones and stroke to get the Vp section used as a constraint.

MASW is usually performed in 3 modifications: (1) passive, (2) active, and (3) combined (passive + active). Our experience testifies that generally, all three MASW modifications would give similar Vs sections when the signal is strong enough (Signal-to-Noise Ratio = 0.8-1.0) and the same initial layered model is used for inversion procedure. In this case, frequency range can be very similar. Such a case is the Dam 5 study in the south of the Dead Sea (Ezersky, et al., 2013b). However, in many of the cases passive and active MASW modes differ by the frequency range. Passive MASW is shifted to the low-frequency range, while active MASW has been shifted to the relatively high-frequency range.

In the Navot site the passive MASW signal was measured in the range of 3.5 - 8.0 Hz (Fig. 21c), whereas active signal was measured in the range of 4.0 - 9 Hz (Fig. 22b). Combining these methods enables slight widening the frequency range between 3.5 – 9 Hz. Giving a maximum wavelength at low-frequency of 3.5 Hz and maximum phase velocity of $V_{ph}=700 \text{ m/s}$ and estimated maximum penetration depth is between $Z_{max}=100-200\text{m}$. At the same time, at higher frequencies of 9 Hz and minimum $V_{ph}=250\text{m/s}$ minimum wavelength $\lambda_{min}=27.7\text{m}$ and the minimum penetration depth is as $Z_{min}=\lambda_{min}/2=14\text{m}$. Table 2 shows that seismic (P-wave) refraction method allows constructing the Vs section down to 25m deep (Vs section was not calculated because of very noisy data). At the same time MASW enables constructing Vs section below 31 m deep.

A common feature of H/V spectral ratios obtained at Navot site is the amplification effect by a factor 6 at a frequency of 3Hz. (Fig. 17b). This frequency is related to the top basalt, which is confidently identified in the both borehole #38 and P-wave refraction at a depth of 26m (Figs. 20b and 23a). Analytical function calculated on the base of such model does not match the measured H/V spectral ratio. The situation changes when MASW method detects an intermediate rock layer with Vs=1550 m/s in a depth range between 26m and 31m deep underlain by harder layer with Vs=2000 m/s. In this case the analytical model matches well to H/V Ratio function (Fig. 16). We note that this observation as well as heterogeneity of the clay layer (shown in Fig. 16) is beyond the resolution of the refraction survey. The latter is explained by water saturation of soil and rock foundation decreasing the resolution of the P-wave refraction method. At the same time Vs is not affected by water saturation and, thus, is more sensitive to heterogeneity of the layer (Stokoe II and Santamarina, 2000).

We considered the Navot case is an example of successfully using the MASW and HVSR methods to estimate the subsurface model down to the depth of about 50m when the site is very noisy (S/N ratio is so low).

In the Ramat Hakovesh site the following geophysical measurements were carried out close to 1A borehole at different times: P and S-wave refraction survey, downhole and MASW measurements (Fig. 19d). The MASW survey was performed in passive, active, and combined modifications. All the Vs versus depth graphs, namely S-wave refraction section (thin solid line), downhole (thick dashed line) and MASW based ones (thick dashed line) derived from combine dispersion curve (Fig. 11b) are shown in Fig. 23. The optimal model calculated from a combination of MASW and HVSR methods is also shown by a thick solid line. General Vs depth trend is presented by a circle dashed line.
From the comparative graph presented, it is clearly seen that the depth of the Vs section obtained from different methods varies significantly. The Vs refraction model based on 250m line with separation of 10m between geophones reaches the depth of about 75m. The downhole characterizes Vs structure down to a depth of 68-70m, which is the depth where it met a karstified carbonate and was stopped. The extraction of the drilling instrument from the borehole caused a collapse and the lowermost part of borehole was filled with sediment. MASW penetration depth is evaluated from wavelength; that is \( \lambda_{\text{max}} = c_{\text{max}} / f_{\text{min}} = 239m \) and penetration depth is evaluated within the range of 120-240m (accepting \( Z_{\text{max}} = (0.5 - 1.0) \cdot \lambda_{\text{max}} \)).

Comparing the different Vs section with the optimal one derived from MASW and HVSR methods one can see that the Vs versus depth trend shows the gradual increase of Vs with the depth from 200 m/s near surface to 550 m/s at a depth of the refractor (70-73m). Along with the general similarity, graphs are slightly differed from the optimal graph in the shallow (down to 40m) part (by 50-100 m/s). The largest deviation is observed between the refraction and downhole sections. At depths greater than 40m, all graphs are converged. Finally, shear-wave velocity of half space measured by S-wave refraction method as 1400 m/s has been evaluated by MASW method as 1480 m/s. Optimization of the Vs-depth graph lead to Vs = 1440 m/s and overlain soil velocities as shown in Fig. 23 (thick solid graph).

The discrepancy between the Vs for shallow subsurface sediments can be caused by several reasons. The downhole located at approximately 70m north of the refraction and MASW lines is affected, evidently, by features of shallow subsurface properties. In addition, the downhole is also affected by the construction of the borehole walls, quality of drilling, cementation and properties of the cement, required by the ASTM D4428/D4428M, (2007)). It requires an experienced drilling crew. Deviation of refraction Vs section can be caused by the large separation (10m) between geophones that provides low depth resolution at shallow depths and more than that at greater depths.

As seen from the comparison of penetration depths, S-wave refraction section characterizes only uppermost part of rock foundation (~ 73-80m), whereas the MASW method characterizes depths down to 120m at least. No variations of Vs were revealed in this depth range. We also note that quality of the MASW signal is significantly higher than the refraction one (Fig. 6d and 6c, respectively). This provides a more reliable velocity-depth section obtained from the MASW method. A good match between the analytical function and experimental spectral ratio was reached when we extended the intermediate hard layer down to a depth of 250m while retaining Vs profile obtained from MASW (Fig. 22b) and added fundamental reflector composed of dense dolomite with Vs = 2400 m/s. This velocity value agrees well with Vs measured in samples at the Technion laboratory (Frydman, 2007).

In 2007, the Geophysical Institute of Israel (Zaslavsky et al., 2007) has carried out the research in cooperation with the National Building Research Institute at the Technion (Frydman, 2007) and the Geological Survey of Israel (Dr. Z. Gvirtzman) in the Ramat Hakovesh site. The goal of this study was to evaluate the site response function using linear (based on Nakamura’s technique) and non-linear approach used by Prof. S. Frydman. Frydman (2007) writes: “It is found that there is variance between the site response prediction based on geophysical and geotechnical studies”.

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\( Z_{\text{max}} = (0.5 - 1.0) \cdot \lambda_{\text{max}} \).
Comparing the results of the geotechnical study (Frydman, 2007[1]) to those presented by the Geophysical Institute, has shown that there is a difference in parameters of site response. According to the GII study, the frequency of the site effect is about 1.5 Hz and a maximum $H/V$ spectral value (related to the amplification) of up to 7.5 was obtained (see Fig. 22b of this report). On the basis of the geotechnical tests performed in the present investigation, the average shear wave velocity of the profile is 268 m/s, and for a 76 m deep profile, a site frequency of 0.88 Hz is indicated. The dominant site response frequency under the action of various rock input motions was less than 1 Hz, and site amplifications were found to be less than 4.5.

Such difference of site parameters should be better understood in order to select the most reliable approach to analysis and prediction. Here we discuss this issue. Let us briefly consider at first two mentioned above methodologies for site response evaluation.
Geotechnical (non-linear) methodology is based on borehole data and laboratory testing.

1. Execution of a drill hole down to and into bedrock, while obtaining the maximum possible information regarding the geotechnical properties of all layers constituting the profile (Drilling data, lithological description, performing of SPT, sample collection and laboratory test. Samples should be of undisturbed origin. If no, samples are collected from SPT tests and should be compacted).
2. In-situ tests (generally SPT and vane shear strength) are performed at close depth intervals during the drilling, and soil samples (disturbed and undisturbed) are extracted for later laboratory testing. The soil samples extracted from the drill hole are used to perform monotonic, cyclic, and resonant column triaxial tests for definition of mechanical/dynamic soil properties, as well as classification and consolidation tests for definition of soil type and state. From the results of these tests, the geotechnical parameters of the site profile are defined.
3. On completion of the borehole, downhole shear wave velocity is measured.
4. Measured parameters are used in numerical analyses to estimate the site response.
5. Required parameters are shear modulus \( G \) and the damping ratio of every layer. Borja (1999, 2002) found that analysis were very sensitive to the assumed strain dependent degradation function of these parameters. Soil behaves non-linearly under load, showing decreased rigidity and increase damping ratio with increasing strain (deformation) used in the analysis. Approach used in the analysis is the Equivalent-linear Earthquake Response Analysis (EERA) (Bardet et al., 2000), that operates in the frequency domain iteratively, modifying the shear modulus and damping ratio between iterations in order to account for non-linearity.

Comment: Site response is analyzed assuming one-dimensional upward propagation of shear (SH) waves from bedrock to the soil surface (soil is laterally infinite with horizontal layering); Only horizontal component of soil motions is considered.

Again, semi-empirical approach used in GII to estimate site response includes:

1. Ambient noise measurements and estimation of horizontal-to-vertical spectral ratio observed at the same site (HVSR or Nakamura’s technique).
2. Determination of Vs section (seismic S-wave refraction, Surface wave prospecting, Downhole)
3. Using HVSR and Vs section from geophysics, borehole data etc.to specify subsurface model which best characterizes the site. Calculation of an analytical function (site response) using SHAKE code (Schnabel et al., 1972). Vs, thickness of layer, density and damping of every soil layer; Vs and density of the hard rock are the input parameters.
4. Finally, the analytical function is fitted to an observed H/V spectral ratio using stochastic optimization algorithm (Storn and Price, 1995). The fitted analytic function is considered as Site Response Function for linear behavior of soils.

Site response determination is an important stage in the overall process of seismic hazard assessment despite the fact that the function itself has no direct engineering application. In order to estimate the ability of structures at a certain site to withstand seismic activity, we need to obtain the site-specific acceleration spectrum.

Since seismic activity in areas such as Israel is low, local acceleration data from strong earthquakes is insufficient to estimate directly the design acceleration spectrum; therefore, we must resort to
the use of synthetic data. For this purpose Shapira and van Eck (1993) developed the SEEH method (*Stochastic Estimation of the Earthquake Hazard*), which is based on the generation of synthetic strong ground motions by means of stochastic simulations (e.g. Boore, 2000) of events assembled in simulated earthquake lists. These simulations adopt local seismological characteristics such as mechanism and strength of the event, epicenter location, dynamic characteristics and characteristics of the propagation paths. The ensemble of thousands of synthetic acceleration response spectra are statistically analyzed in order to assess the spectral amplitude level that should at least once in certain exposure time with certain probability. The *uniform site-specific acceleration response spectrum for structural models* is computed for 10% probability of exceedance in an exposure time of 50 years and damping ratio 5%.

It was found (Borja et al., 2002, Frydman, 2007) that both 1D and 3D approaches predicted recorded ground acceleration response satisfactorily, but they are extremely sensitive to the soil parameters used in the analyses. The soil parameters required for site response analysis are shear modulus \( G \) (associated with \( Vs \) via density) and the damping ratio \( \beta \) for each layer in the profile. Borja et al. (1999, 2002) found that the analyses were extremely sensitive to the assumed strain-dependent degradation functions of these parameters. The results of these studies affirm that natural variations in soil properties can significantly influence the predictions of even the simplest codes such as *SHAKE* and *SPECTRA*. Thus, the \( Vs \) structure of the subsurface should be determined with high reliability.

In this sense the **geophysical (linear) methodology** is based on the combination of two independent techniques (MASW and HVSR). The methods are complementary to each other and provide characteristic (\( Vs \) profile) using waves of different origin, i.e. surface and body (\( S \) or \( SH \) respectively). Their combination provides us with reliable information on the subsurface \( Vs \) structure.

The **geotechnical (non-linear) methodology** is based on the laboratory testing of soil samples of undisturbed and compacted structure. \( Vs \) is derived either indirectly from shear modules or recently directly from very expensive Bender element tests. As it is noted by different investigators (Barja et al., 2002; Stokoe II and Santamarina 2000) unlike the elastic moduli of the soil which can be estimated reliably from geophysical seismic tests, accurate moduli ratio and damping ratio curves are difficult to develop in practice because they are usually inferred from laboratory test results, which, in turn, are influenced to a great extent by sample disturbance effects (samples are artificially compacted) and bias in the laboratory testing procedures. For example, sudden jumps in the moduli and damping ratio values from those obtained by resonant column testing to those obtained by cyclic triaxial testing are not uncommon (Tang et al. 1990; Borja and Amies 1994). These uncertainties have led to the development of a technique to back-figure material properties from the earthquake site responses themselves (Zeghal et al. 1995), but even this procedure naturally produces scattering of data points. This suggests that when performing site response analyses, one should deal with a band of possible material property values, and not a unique curve. In this aspect, we have to analyze the initial \( Vs \) model used by S. Frydman for the calculation of the site effect. The author constructed his section using all the data available including (a) downhole measurements (from Ezersky, 2007); (b) correlations SPT N blow – \( Vs \) (Ohta-Goto, 1976; Imai and Tonouchi, 1982), (c) resonant column tests and small-strain cyclic torsional tests; from
empirical relations developed, for instance, by Hardin (1978) which is based on a large collection of laboratory test results on different soils taking into account void ratio (e), OCR (over consolidation ratio of clay), plasticity index PI etc. After the laboratory tests, the author suggested a simple two layered $V_s$ model shown in Fig. 24 (dashed line 4): sediments with average velocity $V_s = 268$ m/s are underlain by rock foundation with $V_s=1400$ m/s. The SPT-$V_s$ correlations (curve 1), downhole profile (curve 2) and MASW-HVSR profile (curve 3) are presented for comparison. One can see in Fig. 24 a significant difference between the $V_s$ profile from geophysical measurements (curves 1-2), SPT test (curve 3) and from laboratory derived $V_s$ profile (curve 4). Latter velocity values are significantly (almost twofold) less than geophysical ones at depths of 30-76m. We suggest that initial subsurface $V_s$ profiles used for calculation should be substantiated better. Then, difference in applied algorithms and results can be understandable.

![Figure 24. Comparison of SPT-$V_s$ correlation (1), $V_s$ profile derived from downhole measurements (2), MASW-HVSR profile (3), and $V_s$ from geotechnical study (4)](image)

Finally, we have to emphasize that the analytical transfer functions calculated in this study are only associated with weak motions in the range where the behavior of the soils is linear (Zaslavsky et al., 2005). Therefore these functions do not represent the site effects under strong ground motion. The nonlinear characteristics of different sites are currently beyond the scope of this study. Nevertheless, based on the result of the linear behavior of soils nonlinear site response can be
determined by different mathematical models of soil nonlinearity, making use of the models developed for each zone.

In this study, we substituted S-wave seismic refraction by MASW method in its active and passive modes using 2.5Hz geophones, modified data acquisition and processing that enabled constructing Vs section to a depth of 100m and over.

The MASW method has the following main advantages: (1) It is not limited by reverse velocity structure; (2) It is based on highly energetic surface waves that provide good quality records; (3) It is a low-cost, efficient, and relatively fast method. At the same time, constructing initial Vs model and applying constraints bounding the results of inversion are necessary.

The methodology of joint use of HVSR (based on ambient noise) and Multichannel Analysis of Surface Waves (MASW) based on surface wave records excited by seismic source (active MASW) or ambient noise (passive one) has been elaborated and tested in the different geological conditions of Israel. Obviously that each of two MASW methods can be used independently. However, in some cases passive MASW expands frequency range toward the low frequencies allowing deepening of the Vs profile, whereas active MASW allows registration of higher frequencies increasing resolution of the Vs profile at smaller depths. The main issue discussed is: whether resolution of the MASW method is enough to adequately replace the refraction techniques.

After the Dead Sea coast last year (Ezersky et al. 2013), two characteristic sites in Hasharon and in the north of Israel were selected as test sites. The geological structure of these sites is characterized by presence of the intermediate hard layer underlying the soft sediments, while a fundamental reflector is directly beneath it. The results of this year of the study could be briefly summarized as follows:

1. In the Navot site (North of Israel) under conditions of strong noise from heavy traffic on the road, MASW method enabled detecting intermediate 5-6m thick layer (fractured basalt) overlying the bedrock (massive basalt) at a depth of about 35m. Account of this layer while calculating the analytical response function significantly improved the match to the observed H/V ratio and thereby increased the reliability of the subsurface model;

2. In the Ramat Hakovesh site (plain area in the Centre of Israel), as a result of the joint use MASW and HVSR, a subsurface model in which the fundamental reflector is a compact high velocity dolomite located at a depth of 260m, while fractured limestone at a depth of 74-76m directly overlying the dolomite is an intermediate layer was constructed. This model differs significantly from that which is based on geotechnical and borehole data solely. unlike the geophysical and geotechnical data,

7. ACKNOWLEDGEMENTS

This publication was made possible through support provided by the Ministry of Energy and Water Resources of Israel (Contracts No. 211-17-007 and 213-17-004). Special thanks to Eldad Levi and Oz Dror for useful comments. We are grateful also to V. Giller and P. Portnov who acquire the data in complicated climate conditions. We thank G. Rix for cooperation.
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**Combination of active and passive MASW with HVSR method for improving the accuracy and reliability of Vs model (in site response assessment. (First year of the study)**

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Estimating possible site effect is an integral part of evaluation of the seismic hazard and reduction of earthquake damages. In regions with low or moderate seismicity as in Israel, the site response should be determined by analytical tools. These computations require the knowledge of the subsurface geological structure in terms of shear-wave velocity (Vs) profile down to seismic bedrock. Conventionally, this problem is resolved by joint implementation of Horizontal-to-Vertical Spectral Ratios (HVSR or Nakamura’s) technique, which is based on ambient noise measurements and seismic methods such as S-wave refraction or Multichannel Analysis of Surface Waves (MASW) method. The first one does not permit deep penetration of seismic waves because of its weak source. The MASW method using 4.5Hz geophones is restricted in penetration depth of surface waves because of frequency (wavelength) limitations. In this study, we have applied 2.5Hz geophones and special data processing to provide constructing Vs section down to bedrock located at 100m deep and over. In combination with HVSR measurements enables constructing reliable subsurface model, which could be integrated into the seismic hazard assessment. Testing combined methodology was carried out at a number of sites with different geological structures in Israel: the Navot site (North of Israel) and Ramat Hakovesh site (the town of Tira, Central Israel).

**Keywords:** ambient noise, HVSR method, shear-wave velocity subsurface structure, surface waves.