Estimation of Shallow S-Wave Velocity Structure in Damascus City, Syria, Using Microtremor Exploration

Hussam Eldeen Zainehe, Hiroaki Yamanaka, Rawaa Dakkak, Ahlam Khalil, Mohamad Daoud

1. Introduction

Damascus city, located in the south-western part of Syria, is a capital city with a large trade, industry, culture and transport activities, and more than five million people live in the city and its suburb. Serghaya Fault, as a branch of Dead Sea Fault System (DSFS), has a length of 200 km and located approximately along 30 km north-west of Damascus [1,2]. Serghaya Fault is considered as the main source of seismic risk potential for the city, and through the last 2000 years, many destructive earthquakes occurred in the region and caused much destructiveness in Damascus city and its vicinity; one of the most destructive events occurred in 1759 with a magnitude of ~7.4 [3]. Historical records suggest that DSFS, which is quiescent at present, is capable of producing relatively large earthquakes [4].

Seismic hazard assessment in Syria started to be a major concern of the government after the PAMERAR program (Program for Assessment and Mitigation of Earthquake Risk in the Arab Region). Consequently, Syrian National Seismological Network was installed and has been operational since 1995. Seismic Design Regulations were officially established in 1995 and revised in 2004. These regulations require an information on S-wave velocity structure for estimating a site classification. Since Syrian cities lack of information on subsurface structure (S-wave velocity structure), it is a so complicated task to define a site classification according to the Syrian codes.

It is well-known that, S-wave velocity has been recognized as one of the important soil properties in earthquake and civil engineering. Therefore, knowledge of S-wave velocity distributions in soil deposits...
and basement is one of the key parameters controlling amplifications of seismic motion. This knowledge is also required for the solution of many significant problems in earthquake engineering such as design earthquake motions and soil-structure interaction. Therefore most of the building codes required the knowledge of S-wave structure. Usually PS-logging or seismic survey are very reliable method to determine the S-wave structure. But, these methods may be too cumbersome to be applied in a crowded city due to the generated noise associated by these methods as well as their high cost. On the other hand, array technique using microtremors becomes very attractive and useful for the estimation of the subsoil structure in urbanized areas. The wide spreading of the microtremor technique is due to its low cost compared with other conventional geophysical prospecting methods, as well as its applicability even in big and crowded cities. This exploration method was established after the pioneering work done by Aki (1957) [5]. Array records of long- and short-period microtremors have been applied successfully to delineate both the deep and shallow S-wave velocity structures of various sedimentary basins [6–12] located in highly populated urban areas. In this exploration method, Rayleigh-wave phase velocities are estimated from vertical components of array records of microtremors, and then a 1-D subsurface structure is estimated by phase velocity inversion.

The main objective of this study is to estimate shallow S-wave velocity structure in Damascus city from the microtremor explorations. We then discuss site effects in the city using S-wave velocity profiles obtained from microtremor data.

2. Topography and geology of the studied area

Damascus city occupies the mostly part of Dimashq basin (Damascus basin), which is located to the south-western part of Syria and extends between 33°00' to 33°50' N and 36°00' to 36°50' E. The north-western part of Damascus was formed after many tectonic evolutions that affected the region and started in Mesozoic period. As a result, many folding structures appear as Mt. Qasyoun and Mt. El-Qalamoun which bounded the basin at the north-west [13]. The south-eastern part of the area is quite different from the folded mountain system. It is a depression zone characterized typically by platform dislocations and intensive basaltic eruption [13]. The eruption of basalts in this area began in the middle Miocene and continued during the Pleistocene and as a result, some basalt flow reaches as far as about 20 km south of Damascus as Mt. El-Mane and Mt. El-Madani which bounded the basin at the south [14,15]. Actually, the basin is filled by deposits of the surrounded heights and deposits carried by Barada River which flows through the basin and forms the lowland of the basin.

Fig. 1a shows the territory of Syria and its neighboring countries with the location of Damascus city, black dashed line represents the boundary of the Arabian plate; while Fig. 1b shows the geological map of Damascus city [16]. The geological map shows different types of geological formations; Cretaceous (Turonian, Cr) and Paleogene (Middle Eocene, Pg) formations appear in the north-west of the city along Mt. Qasyoun and Mt. El-Qalamoun. The outcropping basalt rock (Middle Miocene, Bn) appears in the south along Mt. El-Mane and Mt. El-Madani. While the main part of the city lies on the sedimentary basin (Dimashq basin) represented mainly by the upper Quaternary deposits (Qq) [16] as well as the recent Quaternary deposits (Qr) [17]. The upper Quaternary deposits are represented by Proluvial and Lacustrine formations which are the most dominant exposures; Lacustrine deposits appear in the north-west of Damascus in the intermountain area. The recent Quaternary deposits have very limited areal exposure along Barada River and El-Awaj River [18].

3. Array measurement of microtremors

3.1. Site selection

The site locations for the array measurement of microtremors are shown in Fig. 1b. We conducted the array measurements at 30 sites in the city of Damascus. The selection of these sites is based on the
geological conditions of the city as well as the previous results of microtremor H/V spectral ratios [19]. The array measurements at 26 sites were conducted at Dimashq Basin (Q3 zone). Namely, UNV, MRJ, OD1, OD2, OD3, NEC and ABS sites are located at the central part of Damascus; DAS, HRS and QBN sites in the north; BBL and MDN sites at the south-central part, while LVN, DAR and SEH sites are situated at the western part. It was suggested in the previous work that, all these sites have short-to-medium peak periods of the H/V spectral ratios [19]. The array measurements at JRM, ZML, DOM, BSJ, JSR, ZBD and HTT sites were performed in the eastern part of the basin, while HOS, FJR, SBN and ISS sites are in the south. These sites have medium-to-long peak periods of the H/V [19]. The remaining array measurements (MZH, QSN and SFR) were carried out along Mt. Qasyoun where Paleogene and Cretaceous formations appear (these sites have almost a flat H/V spectral ratio curves), as well as one measurement (TOT) at the south east of the city (location of TOTH seismic station) where young basalt rocks are outcropping. The exact coordinates and geological index of each site are shown in Table 2.

3.2. Array geometry

All measurements were taken using array of circular configuration which consists of 7 recording stations. For each measurement, a 3-components accelerometer (#1 in Fig. 1c) was deployed at the center and 6 vertical accelerometers were distributed along the circumference of two circles. Stations #2, #3 and #4 distributed along the circumference of the inner circle, while #5, #6 and #7 distributed along the outer one. These two circles have the same center and the radius of the inner circle is half of the outer circumference of two circles. Stations #2, #3 and #4 located at the center of the circle, #5, #6 and #7 located at the south-central part of the city. The values of the observed phase velocities for these sites range from 200 m/s to 700 m/s and the phase velocity curves have a narrow period range from 0.03 s to 0.2 s except for the HTT site which has a phase velocity at a wider period range up to 0.5 s (Figs. 2a-2). Group b represents the sites located in the south and south-central parts of the city. The phase velocity curves of these sites comprise a wider period range (0.03 s to 0.5 s) than those in group a (Fig. 2b). The sites in these two groups are located at the same geological formation (Q3 zone). While group c represents the sites located along

\[ \rho(r, \omega) = \frac{1}{2\pi f_0} \int_0^{2\pi} \rho(r, \theta, \omega) d\theta \]  

\[ \rho(r, \omega) = J_0 \left( \frac{\omega}{c_0} r \right) \]  

where \( \rho(r=0, \omega) \) is an average autocorrelation function at a center of the array, \( \rho(r, \theta, \omega) \) is the cross-correlation function between the records obtained at coordinates \((r, \theta)\) and the record obtained at the center of the circle, \( c(\omega) \) is the phase velocity at frequency \( \omega \) at the site, and \( J_0(\cdot) \) is the Bessel function of the first kind and the order zero. In this equation, the only unknown parameter is the phase velocity, \( c(\omega) \), which can be obtained from fitting the correlation coefficients. Further details on the SPAC method can be found in the literatures [21–25].

The observed phase velocity dispersion curves in Fig. 2 show significant differences from site to site, and they can be categorized into three different groups a, b, and c. For easier discrimination of each site in group a, the group is divided into two plots (a-1) and (a-2). Fig. 2a-1, a-2 and b show the variations of the observed phase velocities for the sites located at the same geological formations, while Fig. 2c shows the variation of the observed phase velocities for the sites located at different geological formations. Group a represents the sites located in the central and eastern parts of Damascus. The values of the observed phase velocities for these sites range from 200 m/s to 700 m/s and the phase velocity curves have a narrow period range from 0.03 s to 0.2 s except for the HTT site which has a phase velocity at a wider period range up to 0.5 s (Figs. 2a-2). Group b represents the sites located in the south and south-central parts of the city. Group c represents the sites located along

4. Estimation of phase velocity

For the estimation of phase velocity, each vertical-component record was divided into data with a time segment of 81.92 s in length after removing the transient noise generated locally by some disturbances such as moving vehicles nearby our sensors during the measurement. We estimated the phase velocities of Rayleigh waves by Spatial Autocorrelation (SPAC) method [22]. The SPAC method requires ambient-noise records obtained in a circular array of stations with one station at the center. This geometry allows the computation of cross-correlations between many station pairs at the same inter-station distance, \( r \), and sampling many different azimuths at the recording site. The correlation coefficients, \( \rho(r, \omega) \), as a function of frequency \( \omega \), are computed as the normalized cross-correlations between all station pairs separated at a distance \( r \) and averaged over all azimuths, \( \theta \). Assuming stationary of microtremors, Aki (1957) [5] showed that

\[ \rho(r, \omega) = \frac{1}{2\pi f_0} \int_0^{2\pi} \rho(r, \theta, \omega) d\theta \]  

\[ \rho(r, \omega) = J_0 \left( \frac{\omega}{c_0} r \right) \]  

Fig. 2. Comparison of the observed Rayleigh wave phase velocities for (a) sites in group a located at the central and east, (b) sites located at the south and south-central, and (c) sites c located in the north-west of Damascus along Mt. Qasyoun as well as TOT site in the south-east.
Mt. Qasyoun with different geological formations (Q3, C, and Pg) as well as the TOT site located at the south-eastern part of Damascus in the region of outcropping basalt (BN). The sites of group c in Fig. 2c have high phase velocities (up to 1000 m/s) with a more narrow period range from 0.03 s to 0.15 s than the others. Our results show that the values of the phase velocity decrease from the foothills of Mt. Qasyoun toward the east and the south, while the period range of the observed phase velocity curves increases in the same direction. These clear differences in the observed phase velocities indicate a significant variation in the shallow soil formations in the city.

5. Estimation of s-wave structure

5.1. Inversion of phase-velocity data

The phase-velocity data were inverted to a 1-D S-wave velocity profile using Genetic Simulated Annealing Algorithm technique, which is a hybrid heuristic inversion technique introduced by H. Yamanaka (2007) [26,27] as a global optimizing method. In this technique, a 1-D soil profile is searched by minimizing the misfit function, \( \theta_i \), that is defined as the sum of root means-squares of the differences between the observed phase velocity, \( U_o(T_i) \), and the calculated one, \( U_c(T_i) \),

\[
\theta_i = \frac{1}{N} \sum_{i=1}^{N} \left[ \frac{U_o(T_i) - U_c(T_i)}{\sigma(T_i)} \right]^2,
\]

Where \( N \) is the number of the observed data and \( \sigma(T_i) \) is the standard deviation of the observed phase velocity at a period of \( T_i \). We assumed fundamental mode of Rayleigh wave in the inversion. We fixed the P-wave velocity as well as the density of the layers and chose the shear-wave velocities and thicknesses of the layers as the parameters to be determined. 10 inversions with 100 generations were conducted using different seeds of a random numbers where good model with smaller misfit survive more in the next generation while bad models are replaced by newly generated ones and so on [26,27]. Table 1 reports an example of the upper and lower limits in the search spaces of the parameters assuming a three-layer model used for the case of the sites in group a; as well as the final optimal model obtained at ZML site.

Open circles and solid lines in Fig. 3 show the observed and inverted phase velocities for the models in Fig. 4. The sites are shown in Fig. 3a-1 to a-3, belong to the group a in Fig. 2 and located in the central and eastern parts of the city. The sites in Fig. 3b-1 to b-3 belong to the group b in the south and central-south while the sites in Fig. 3c-1 to c-3 belong to the group c and located in the north-west along Mt. Qasyoun. It is confirmed that the fitnesses between the observed and inverted phase velocities are fairly good for all the sites. Thus we succeeded to estimate the

<table>
<thead>
<tr>
<th>Search limits</th>
<th>Final model at ZML</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_s ) (km/s)</td>
<td>( H ) (m)</td>
</tr>
<tr>
<td>0.15–0.30</td>
<td>1–15</td>
</tr>
<tr>
<td>0.25–0.45</td>
<td>5–30</td>
</tr>
<tr>
<td>0.60–0.80</td>
<td>—</td>
</tr>
</tbody>
</table>

Fig. 3. Comparison between theoretical phase velocities (solid lines) for inverted models and observed ones (circles) for some sites belong to different groups.
shallow structures down to the engineering basement with an S-wave velocity of \( \sim 750 \text{ m/sec} \) for all the sites. The deeper structure (\( 750 \text{ m/sec} \)) was estimated only in few sites that belong to the groups b and c (UNV, QBN, DAS, etc.).

5.2. S-wave velocity structure

As it is mentioned previously, the subsurface structural model corresponding to the minimum misfit between the observed and theoretical velocities was selected as an inverted 1-D soil profile for each site. Fig. 4 shows a comparison between the inverted 1-D soil profiles of a sites located at the central and east, b sites located at the south and south-central, and c sites located in the north-west as well as TOT site in the south-east of Damascus.

Fig. 5 shows contour lines for the depth to the engineering bedrock presented on the elevation map of Damascus city. Circles, squares, and triangles in this figure denote the locations of the a, b, and c groups, respectively. The distributions show that the shallow soils are not uniform in Damascus city and there is a wide variation in the S-wave velocity and thickness of the shallow soil layers. According to our results, the city can be divided into three regions as it is shown in Fig. 4.

Center and east region (a region) (Fig. 4a-1 and a-2), the features of the S-wave velocity structures in this region are as follows:

- The first layer is a shallow soft soil with a very low S-wave velocity (\( \sim 200 \text{ m/s} \)) with a thickness ranged from \( \sim 5 \text{ m} \) in the center (MRJ, OD2 and OD3) and becomes about \( \sim 10 \text{ m} \) in the eastern parts of the city.
- The second layer has a low velocity (\( \sim 350 \text{ m/s} \)) with a thickness ranged from \( \sim 7 \text{ m} \) in the central part and becomes \( \sim 25 \text{ m} \) in the eastern parts (DOM, BSW and ZBD). This layer \( \sim 350 \text{ m/s} \) disappears in OD1, OD2 and OD3 sites while it is replaced by a higher velocity layer (\( \sim 500 \text{ m/s} \)) in HRS and HTT sites.
- The third layer is the engineering bedrock with an S-wave velocity of \( \sim 750 \text{ m/s} \).

Generally, the depth to the engineering bedrock in this region increases from 10 m in the central part along Barada River and becomes to be about 30 m in the eastern part as it is shown in Fig. 5.

South and central-south region (b region) (Fig. 4b), the resulting S-wave profiles in this region have the following features:

- HOS and ISS sites have a very thin soft layer (\( \sim 200 \text{ m/s} \)) and a thick high velocity layer (\( \sim 500 \text{ m/s} \)) overlain the engineering bedrock. The soft layer (\( \sim 200 \text{ m/s} \)) disappears in FJR and SBN sites.
- MDN and LWN sites have a thin low velocity layer (\( \sim 350 \text{ m/s} \)) overlain a high velocity layer (\( \sim 500 \text{ m/s} \)) and the engineering bedrock. The high velocity layer (\( \sim 500 \text{ m/s} \)) disappears in BBL site.

The depth to the engineering bedrock increases from 20 m in the central-southern part (MDN and BBL) towards the southern part and becomes at a relatively deep depth (\( \sim 80 \text{ m} \)) underneath ISS, FJR and HOS sites (Fig. 5).

Foothills region (c region) (Fig. 4c), along Mt. Qasyoun (north-west) and along Mt. El-Madani and Mt. El-Mane (far south), the S-wave velocity structures in this region have the following features:

- QSN, MZH, UNV and DAR sites have the engineering bedrock covered by a low velocity layer (\( \sim 350 \text{ m/s} \)) while the engineering bedrock in SEH site is covered by a very thin soft layer (\( \sim 200 \text{ m/s} \)).
- DAS and SFR sites have a thin low velocity layer (\( \sim 350 \text{ m/s} \)) overlain a high velocity layer (\( \sim 500 \text{ m/s} \)) and the engineering bedrock. The low velocity layer (\( \sim 350 \text{ m/s} \)) disappears in QBN site.
- TOT site in the south-east of Damascus, the engineering bedrock in this site is covered by a very thin low velocity layer (\( \sim 350 \text{ m/s} \)).
Generally, the subsurface distribution of the S-wave velocity revealed the engineering bedrock at a relatively shallow depth (less than 10 m) in this region as it is shown in Fig. 5.

5.3. Horizontal-to-vertical spectral ratio in a short period range

To validate the results of the inversions, the spectral ratios between the horizontal and vertical components of the observed microtremor data \((H/V)_{o}\) were compared with the computed ellipticities of the fundamental-mode Rayleigh-waves \((H/V)_{c}\) for the inverted 1-D soil profiles in Fig. 4. The horizontal-to-vertical spectral ratios \((H/V)_{o}\) at all the measurement sites were determined from the observed microtremor data recorded by the 3-components accelerometer deployed in the center of each array measurement. The spectral ratios were calculated using 81.92-sec time windows. Fourier amplitude spectra were smoothed following the Parzen window with bandwidth of 0.2 Hz. The final H/V ratio was obtained by averaging the H/V ratios from all the windows. The standard deviations on the H/V ratio curves are estimated considering the geometric mean for all H/V ratio computed at each time window. The observed spectral ratios \((H/V)_{o}\) are here compared with the computed ellipticities of the fundamental-mode Rayleigh waves \((H/V)_{c}\) based on the obtained S-wave velocity structure. Solid and dashed lines in Fig. 6 demonstrate the observed spectral ratios \((H/V)_{o}\) of microtremor data and the computed ellipticities \((H/V)_{c}\) assuming fundamental-mode Rayleigh waves.

Fig. 6a-1 to a-8, show the comparisons of the H/Vs at some sites in group \(a\) located in the central and eastern parts of Damascus (region \(a\)). Fig. 6b-1 to b-4, display the results of some sites in group \(b\) situated in the south and central-south (region \(b\)) while Fig. 6c-1 to c-4, show the comparisons of H/Vs for some sites in group \(c\) located in the north-west along the foothills of Mt. Qasyoun (region \(c\)). The comparison of these figures illustrates that the overall peak period characteristics of the observed \((H/V)_{o}\) are in close agreement with the computed \((H/V)_{c}\) in a period

![Fig. 6. Comparison of the observed H/V of microtremor data (solid line) and one standard deviation (gray shading) with the computed H/V of the fundamental-mode Rayleigh waves (dashed line).](image-url)
range from 0.05 s to about 0.5 s. Generally, the sites of \textit{a} group exhibit a dominant peak due to a high velocity contrast in these sites while the observed and calculated H/Vs for the sites of \textit{b} and \textit{c} groups have almost flat characteristics in a period range of 0.05 s to about 0.5 s. As an exception, SEH, ISS, and HOS sites (located in \textit{b} and \textit{c} regions) exhibit a dominant peak in a short period range (less than 0.1 s) because of a high velocity contrast due to the presence of a thin soft layer (~200 m/s) near the surface. The mismatch between the (H/V)\textsubscript{o} and (H/V)\textsubscript{c} in long period range (period > 0.5 s) can be attributed due to the lack of deep soil layers in our models, thereby indicating the limitation of the data used in this study. Since we are focused on shallow Vs profiles and its effects, the effects of deep soil layers will be discussed intensely in different paper. However, to explain the dominant peaks at long period range, we investigate the effects of deep soils in the later discussion.

6. Discussion

6.1. Comparison with geological data

As it is mentioned previously, the basin of Damascus is filled mainly by the deposits of the surrounded heights represented by the Proluvial deposits which form Dimashq fan as well as the Lacustrine deposits which form the basin of El-Oteibeh Lake in the far east of the basin (Fig. 1b). Dimashq fan is characterized by a monotonous lithological composition, i.e., yellow-gray loams with angular intercalations of predominantly limestone pebbles near the mountain ridges. But, further from the mountain ridges and closer to the central part, proluvium is represented by loess-like loams which are laterally replaced by lacustrine deposits. In the outer portion of Dimashq fan, on the boundary with the lacustrine plain, alternation of the lacustrine deposits with proluvial pebble-beds and loams were observed in many wells [18]. In addition, the recent alluvial deposits (Q\textsubscript{4}) have very limited areal

![Fig. 7. Comparison between the inverted 1-D soil profiles (right) and nearest geological borehole profiles (left) at different 4 sites in Damascus city (the locations of these profiles are shown in Fig. 1b); (a) and (b) represent MRJ and NEC sites respectively, located in the center and east region; (c) represents MZH site located in the foothills region along Mt. Qasyoun; and (d) represents SEH site located in the foothills region along Mt. El-Madani.]

![Fig. 8. Comparison of the theoretical amplification factors for (a) the sites in \textit{a} region located in the central and eastern parts, (b) sites in \textit{b} region located in the south and south-central, and (c) sites in \textit{c} group located in the foothills region.]

exposure along Barada River which flows through the basin [17]. This illustrates that the Quaternary deposits in the eastern part of the basin as well as the central part along Barada River are different from other locations near to the mountain ridges. Our results also show that the low S-wave velocity layers were mainly observed in the eastern part of Damascus city as well as the central part along Barada River. Fig. 7 shows the comparison in a general sense between the 1-D soil profiles obtained from the inversion (right) with the nearest geological borehole profiles (left) for different 4 locations in the city. The locations of these profiles are shown in Fig. 1b (squares). The distance between the two profiles in MRJ site (Fig. 7a) is about 200 m; the last layer in the geotechnical borehole profile (Dense Conglomerates with an SPT number of 59) represents the engineering bedrock in our results (with S-wave velocity of ~750 m/s). In NEC site (Fig. 7b), the distance between the two profiles is about 1000 m; the engineering bedrock is represented by the lower Quaternary layer (Clay & Sand) in the geological profile. For MZH site (Fig. 7c), the distance is about 1500 m between the two profiles and the engineering bedrock is represented by the fractured basalt layer and the distance between the inverted 1-D soil profile and the geological one is about 800 m. Although the distance between the inverted models and the geological boreholes are quite big, the comparison between the inverted and geological profiles is so good to confirm the validity of our results.

6.2. Site amplification

6.2.1. 1-D site amplification factor

It is noted that, the site amplification factor is defined by the spectral ratio of S-wave on the surface to input motions in the base layer in this study. It is well known that the H/V of microtremors is more related to the ellipticity of Rayleigh waves. The averaged site amplification for a period range from 0.05 s to 0.5 s and the fundamental predominant period for all the sites are shown in Table 2. Fig. 9a shows the contour lines of the averaged site amplification presented on the elevation map of Damascus city, and Fig. 9b shows the contour lines for the fundamental predominant periods of the site amplification factors. It is noted that, the predominant peak periods longer than 0.5 s (ISS, FJR and HOS sites) are not considered in this discussion.

Regarding our results, the sites in a region (Fig. 8a-1 and a-2) have the highest site amplification among the regions due to the presence of a soft layer (~200 m/s) near the surface which controls the site amplification in this region. On the other hand, the fundamental predominant period of the amplification factors in this region increases from 0.10 s in the central parts of the city to 0.3 s in the east (circles in the Fig. 9). For the b region (Fig. 8b), the overall site amplification in this region is lower than those in the a region. The fundamental periods of the amplification factors in the b region, increase from 0.10 s in the central-south to 0.3 s in the southern parts of the city (squares in the Fig. 9). While the sites in c region (Fig. 8c), have the shortest predominant periods

---

**Table 2**

Site ID, Latitude, Longitude, Elevation (m), \( V_{30} \), \( V_{s10} \), NEHRP Class, Geological index, Fundamental site predominant period (s) obtained from the theoretical amplification factors (Fig. 8), and the averaged site amplification for a period range from 0.05 s to 0.5 s obtained from the theoretical amplification factors (Fig. 8).

<table>
<thead>
<tr>
<th>Site ID</th>
<th>Lat.</th>
<th>Long.</th>
<th>Elev. (m)</th>
<th>( V_{30} ) (m/s)</th>
<th>( V_{s10} ) (m/s)</th>
<th>NEHRP Class</th>
<th>Geology Index</th>
<th>Period (s)</th>
<th>Ave. Ampl (0.05S – 0.5S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRJ</td>
<td>33.513</td>
<td>36.299</td>
<td>691</td>
<td>419</td>
<td>248</td>
<td>C</td>
<td>Q1</td>
<td>0.17</td>
<td>3.4</td>
</tr>
<tr>
<td>OD1</td>
<td>33.512</td>
<td>36.307</td>
<td>694</td>
<td>433</td>
<td>250</td>
<td>C</td>
<td>Q1</td>
<td>0.18</td>
<td>2.9</td>
</tr>
<tr>
<td>OD2</td>
<td>33.510</td>
<td>36.307</td>
<td>697</td>
<td>484</td>
<td>283</td>
<td>C</td>
<td>Q1</td>
<td>0.12</td>
<td>3.1</td>
</tr>
<tr>
<td>OD3</td>
<td>33.509</td>
<td>36.316</td>
<td>683</td>
<td>484</td>
<td>283</td>
<td>C</td>
<td>Q1</td>
<td>0.12</td>
<td>3.1</td>
</tr>
<tr>
<td>ABS</td>
<td>33.522</td>
<td>36.320</td>
<td>690</td>
<td>429</td>
<td>269</td>
<td>C</td>
<td>Q1</td>
<td>0.16</td>
<td>3.6</td>
</tr>
<tr>
<td>NEC</td>
<td>33.527</td>
<td>36.309</td>
<td>697</td>
<td>399</td>
<td>255</td>
<td>C</td>
<td>Q1</td>
<td>0.19</td>
<td>3.3</td>
</tr>
<tr>
<td>JRM</td>
<td>33.487</td>
<td>36.351</td>
<td>665</td>
<td>384</td>
<td>255</td>
<td>C</td>
<td>Q1</td>
<td>0.21</td>
<td>3.3</td>
</tr>
<tr>
<td>ZML</td>
<td>33.525</td>
<td>36.358</td>
<td>682</td>
<td>301</td>
<td>219</td>
<td>D</td>
<td>Q1</td>
<td>0.32</td>
<td>3.0</td>
</tr>
<tr>
<td>HRS</td>
<td>33.553</td>
<td>36.364</td>
<td>701</td>
<td>455</td>
<td>385</td>
<td>C</td>
<td>Q1</td>
<td>0.08</td>
<td>3.6</td>
</tr>
<tr>
<td>DOM</td>
<td>33.564</td>
<td>36.397</td>
<td>657</td>
<td>380</td>
<td>269</td>
<td>C</td>
<td>Q1</td>
<td>0.23</td>
<td>3.5</td>
</tr>
<tr>
<td>BSW</td>
<td>33.537</td>
<td>36.402</td>
<td>649</td>
<td>334</td>
<td>209</td>
<td>D</td>
<td>Q1</td>
<td>0.26</td>
<td>3.1</td>
</tr>
<tr>
<td>JSR</td>
<td>33.512</td>
<td>36.389</td>
<td>652</td>
<td>387</td>
<td>269</td>
<td>C</td>
<td>Q1</td>
<td>0.22</td>
<td>3.5</td>
</tr>
<tr>
<td>ZBD</td>
<td>33.484</td>
<td>36.401</td>
<td>647</td>
<td>304</td>
<td>241</td>
<td>D</td>
<td>Q1</td>
<td>0.36</td>
<td>2.9</td>
</tr>
<tr>
<td>HTE</td>
<td>33.437</td>
<td>36.425</td>
<td>634</td>
<td>338</td>
<td>225</td>
<td>D</td>
<td>Q1</td>
<td>0.43</td>
<td>2.9</td>
</tr>
<tr>
<td>LWN</td>
<td>33.484</td>
<td>36.253</td>
<td>703</td>
<td>455</td>
<td>385</td>
<td>C</td>
<td>Q1</td>
<td>0.14</td>
<td>2.6</td>
</tr>
<tr>
<td>MDN</td>
<td>33.479</td>
<td>36.298</td>
<td>689</td>
<td>503</td>
<td>412</td>
<td>C</td>
<td>Q1</td>
<td>0.07</td>
<td>2.9</td>
</tr>
<tr>
<td>BBL</td>
<td>33.471</td>
<td>36.326</td>
<td>668</td>
<td>574</td>
<td>392</td>
<td>C</td>
<td>Q1</td>
<td>0.09</td>
<td>3.0</td>
</tr>
<tr>
<td>ISS</td>
<td>33.441</td>
<td>36.260</td>
<td>687</td>
<td>417</td>
<td>313</td>
<td>C</td>
<td>Q1</td>
<td>0.67</td>
<td>3.1</td>
</tr>
<tr>
<td>SRN</td>
<td>33.440</td>
<td>36.294</td>
<td>672</td>
<td>500</td>
<td>500</td>
<td>C</td>
<td>Q1</td>
<td>0.36</td>
<td>2.2</td>
</tr>
<tr>
<td>FJR</td>
<td>33.442</td>
<td>36.327</td>
<td>659</td>
<td>500</td>
<td>500</td>
<td>C</td>
<td>Q1</td>
<td>0.59</td>
<td>2.1</td>
</tr>
<tr>
<td>HOS</td>
<td>33.419</td>
<td>36.353</td>
<td>654</td>
<td>400</td>
<td>386</td>
<td>C</td>
<td>Q1</td>
<td>0.63</td>
<td>2.9</td>
</tr>
<tr>
<td>DAS</td>
<td>33.585</td>
<td>36.368</td>
<td>714</td>
<td>495</td>
<td>385</td>
<td>C</td>
<td>Q1</td>
<td>0.17</td>
<td>2.9</td>
</tr>
<tr>
<td>QBN</td>
<td>33.545</td>
<td>36.342</td>
<td>723</td>
<td>570</td>
<td>500</td>
<td>C</td>
<td>Q1</td>
<td>0.15</td>
<td>2.4</td>
</tr>
<tr>
<td>UNV</td>
<td>33.511</td>
<td>36.284</td>
<td>710</td>
<td>592</td>
<td>417</td>
<td>C</td>
<td>Q1</td>
<td>0.08</td>
<td>3.0</td>
</tr>
<tr>
<td>DAR</td>
<td>33.460</td>
<td>36.227</td>
<td>706</td>
<td>515</td>
<td>350</td>
<td>C</td>
<td>Q1</td>
<td>0.14</td>
<td>2.7</td>
</tr>
<tr>
<td>SEH</td>
<td>33.434</td>
<td>36.217</td>
<td>708</td>
<td>588</td>
<td>411</td>
<td>C</td>
<td>Q1</td>
<td>0.06</td>
<td>3.8</td>
</tr>
<tr>
<td>SFR</td>
<td>33.548</td>
<td>36.304</td>
<td>809</td>
<td>542</td>
<td>385</td>
<td>C</td>
<td>C1</td>
<td>0.11</td>
<td>3.0</td>
</tr>
<tr>
<td>QSN</td>
<td>33.533</td>
<td>36.277</td>
<td>1108</td>
<td>592</td>
<td>417</td>
<td>C</td>
<td>P2</td>
<td>0.08</td>
<td>3.1</td>
</tr>
<tr>
<td>MZH</td>
<td>33.505</td>
<td>36.252</td>
<td>740</td>
<td>515</td>
<td>350</td>
<td>C</td>
<td>P2</td>
<td>0.14</td>
<td>2.7</td>
</tr>
<tr>
<td>TOT</td>
<td>33.362</td>
<td>36.429</td>
<td>683</td>
<td>572</td>
<td>372</td>
<td>C</td>
<td>Bn</td>
<td>0.14</td>
<td>3.0</td>
</tr>
</tbody>
</table>
6.2.2. Comparison between site amplification and average S-wave velocity

An average value of shear-wave velocity from the surface to 30 m deep ($V_{S30}$) is adopted as an international standard for soil classification. It was proposed in the United States under the National Earthquake Hazard Reduction Program (NEHRP). In fact, many U.S. building codes now require $V_{S30}$ for soil classification and Syrian building code 2004 which based on UBC97 has the same requirement of $V_{S30}$ for soil classification. Since the NEHRP classification was based on data from the western United States [31,32]; we should confirm the validity of the NEHRP site classification in the case of Damascus city. Therefore, $V_{S30}$ was compared with the averaged site amplification in a period range from 0.05 s to 0.5 s. Fig. 10a and 10b show the contour of the $V_{S30}$ presented on the elevation map of Damascus city and its correlation with the averaged site amplification. Table 2 reports $V_{S30}$ (m/s) and $V_{S10}$ (the average of shear wave velocity for the top 10 m of soils in m/s) for our profiles, with the NEHRP class, geological index, the fundamental site predominant period of the site amplification factor (sec), and the averaged site amplification for a period range from 0.05 s to 0.5 s. A low correlation with a scattered relationship was observed between the $V_{S30}$ and the averaged site amplification as it is shown in Fig. 10b, and almost all our sites belong to the same class (class C) according to the NEHRP classification as it is shown in Table 2. Then, we compared the $V_{S10}$ with the averaged site amplification for the same period range. Fig. 11a displays the contour of $V_{S10}$ presented on the elevation map and Fig. 11b shows a good correlation between the $V_{S10}$ and the averaged site amplification. In the case of the $V_{S10}$, a much higher correlation was observed with the averaged site amplifications than those for the $V_{S30}$. This indicates that the $V_{S10}$ can be a better proxy for the high-frequency site amplification than

Fig. 9. Contour lines of (a) the averaged site amplification for period range (0.05 s–0.5 s) presented on the elevation map, and (b) the fundamental period of the amplification factors (sec). Circles, squares, and triangles denote sites of a, b, and c regions respectively.

Fig. 10. Relationship between elevation and $V_{S30}$, (a) contour of the $V_{S30}$ in m/s presented on the elevation map, and (b) correlation between the $V_{S30}$ and the averaged site amplification for all sites located in the upper Quaternary deposits zone ($Q_3$).

(less than 0.15 s) of the amplification factors among the regions (triangles in the Fig. 9).
Fig. 11. (a) Contour of the $V_{S10}$ in m/s presented on the elevation map, and (b) Correlation between the $V_{S10}$ and the averaged site amplification for all sites located in the upper Quaternary deposits zone ($Q_3$).

Fig. 12. (a) Comparison of the observed spectral ratios ($H/V_o$) of microtremors (solid line) with the computed ellipticities of the fundamental-mode Rayleigh waves for the shallow ($ellp_{S}$) and deep ($ellp_{S&D}$) structures (dotted and dashed lines) for DOM, ISS and MZH sites; (b) the shallow soil structure as well as the deep one (dotted line) for the same sites; and (c) the theoretical amplification factors considering the shallow soil structure (dotted line) and the shallow & deep one (dashed line) for the same sites.
the V_{S30} in the case of Damascus city; this can be interpreted due to the effects of the shallow low velocity layer (~200 m/s) which controls the site amplification as it is mentioned previously.

6.3. Deep soil effects

The shallow structures down to the engineering basement with an S-wave velocity of ~750 m/sec were estimated successfully for all the sites, while the deeper structure (~1300 m/sec) was estimated only in few sites. Considering the shallow structures in Fig. 4, the overall peak period characteristics of the computed ellipticities are in close agreement with the observed spectral ratios of microtremors in a period range from 0.05 s to about 0.5 sec. However, to explain the dominant peaks of the observed H/V of microtremors at periods longer than 0.5 sec, the deep soil layer underlain the engineering bedrock as well as the thickness of the engineering bedrock were assumed by the trial and error method and the computed ellipticities of shallow and deep structures (assuming fundamental-mode Rayleigh waves) were compared with the observed H/V of microtremors.

Figs. 12a-1, a-2, and a-3 show the comparison of the H/Vs at DOM, ISS and MZH sites belong to the a, b, and c groups respectively. Dotted and dashed lines in the figure demonstrate the computed ellipticities for the shallow (elp) and deep structures (elp_{S&D}) while solid lines show the observed spectral ratios (H/V) of microtremors. The results show that the dominant peaks at periods longer than 0.5 s can be explained well by the deep soil layer. Figs. 12b-1, b-2, and b-3 display the shallow soil structure as well as the deep one (dotted line) for the same sites.

To investigate the effect of deep structure on the site amplification, we calculated the site amplification factors considering the deeper soil structure as the half-space. Fig. 12c shows the comparison of the computed site amplification factors considering the shallow structure only (dotted line) with those combining the shallow and deep structures (T.F)_{S&D}. In the figure, it is very clear that the dominant peaks for periods less than 0.5 s are controlled by the shallow structure. On the other hand, the deep structure has major contribution to long period amplification (longer than 0.5 s). This indicates the importance of estimation of the deep S-wave velocity structure for the prediction of long period ground motions in Damascus city.

7. Conclusions

Array measurements of microtremors were performed at thirty sites to estimate the S-wave velocity structures of shallow soil formations in the city of Damascus, Syria. We succeeded to estimate the shallow structures down to the engineering bedrock with an S-wave velocity of ~750 m/sec from the inversion of Rayleigh wave phase velocities in a period range of 0.05 s to 0.5 s. The resultant profiles show that the engineering basement is located at a shallow depth (less than 10 m) for sites located in the foothills region along Mt. Qasyoun in the north-west and along Mt. El-Madani and Mt. El-Mane in the far south. The depth increases gradually toward the center of the basin (~15 m) and toward the east (~30 m) and becomes at a relatively deeper depth (~80 m) underneath ISS, FJR and HOS sites in the south. The shallow structure is not uniform in Damascus city and there is a wide variation in the S-wave velocity and thickness of the shallow soil layers. The results show a shallow soft layer (~200 m/s) appears in the central and eastern regions (a region).

To validate the S-wave structures obtained from the array explorations, the spectral ratios between the horizontal and vertical components of the recorded microtremor data have been compared with the computed ellipticities of the fundamental-mode Rayleigh-waves based on the respective Vs structure. The comparisons show a good agreement between them in a period range from 0.05 s to 0.5 s. However, we cannot explain the peaks of the H/V at periods longer than 0.5 s. The mismatch outside this period range can be attributed due to the lack of deep soil layers in our models.

To validate an application of the NEHRP site classification in the case of Damascus city, the average of shear wave velocity for the top 30 m of soils (V_{S30}) has been compared with the averaged site amplification calculated from the inverted profiles. The comparisons indicate a low correlation between the V_{S30} and the averaged site amplification at periods from 0.05 s to 0.5 s. In the other hand, the V_{S10} shows a much higher correlation with the averaged site amplification suggesting the V_{S10} as a better proxy for the high-frequency site amplification than the V_{S30}; this can be interpreted that the shallow low velocity layer controls the amplification factors in the city.

Acknowledgment

The comments of Dr. Claus Milkereit and an anonymous reviewer helped to improve the manuscript. We are really indebted to Prof. Sasano, Prof. Seo as well as Drs. Foujita and Morita at Tokyo Institute of Technology for their highly intensive support in the preparation and execution of the field survey. Also we like to express our thanks to Syrian team who participated in the field survey, especially, Mr. Ibrahim R. and Miss. Nkshnbndy D. for their efforts. This research is a part of the cooperative project between Tokyo Institute of Technology and National Earthquake Center in Syria with a financial support from Grants-in-Aid for Scientific Research by Ministry of Education, Culture, Sports, Science and Technology (MEXT) in Japan No. 21254004. Furthermore, we acknowledge a financial support of Center for Urban Earthquake Engineering (CUEE) under the G-COE program of the MEXT. Some of the figures in this paper were made using GMT software [33].

References


