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ORIGINAL ARTICLE

Microtremor measurements in Yanbu city of Western Saudi Arabia: A tool for seismic microzonation

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Abstract Microtremor measurements are one of the most popular world-wide tool for estimation of site response especially within the urban area. This technique has been applied over 85 sites distributed regularly through Yanbu metropolitan area with an ultimate aim of seismic hazard microzonation for ground-shaking site effects. The horizontal to vertical spectral analysis (H/V) was carried out over all the sites to estimate both the fundamental resonance frequency and its corresponding amplification for the ground vibration. In most sites, H/V curve for amplitude spectra display a clear peak suggesting the presence of a soil-bedrock impedance contrast. Other sites, however, show more than one peak indicating the presence of more than one impedance contrast through sedimentary cover. The estimated values of fundamental frequency range from 0.25 Hz up to 7.9 Hz increases with decreasing depths of basement rock. It has lower values at the central zone extending from north to south compared to the eastern and western parts of Yanbu area. On the other hand, the estimated values of amplification factor ranges from the value of 2 to 5, where the higher values prevailing through the central zone with increasing thickness of sediments. Analyses of the acquired data set have clearly shown that, both of two parameters vary considerably through Yanbu city. This could be due to lateral variations in soil thickness and/or variations in the soil type at Yanbu area. These results show the 2D and 3D effect of basin geometry. The estimated values for the fundamental frequency from microtremor data are compared with that from shear-wave velocity structure within the area of interest and show an excellent agreement.

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1. Introduction

Yanbu city represents one of marine ports of western Saudi Arabia where it is located along the Red Sea eastern coast. It belongs to Al-Madinah province about 350 km north of Jeddah city (Fig. 1).

The central part of the city refers to the old town, while modern Yanbu is a short distance away. In 1975, the Saudi government selected both Yanbu and Al-Jubail, both small

Figure 1 Location map for Yanbu city.

towns on the Persian Gulf coast, to be developed as modern industrial cities and established the Royal Commission for Jubail and Yanbu. The town is expanding as an industrial and commercial center with three large oil refineries, a petrochemical complex, and a large desalination plant that plays an important role in diversifying Saudi Arabia's economic base.

The behavior of the ground motion during an earthquake is generally well explained by the geological surface structure in the place where the phenomenon is studied. Past and recent observations have shown that the damage caused by strong earthquakes is more important in sedimentary basins than on hard rock structures. Unfortunately, Yanbu city lies within the Red Sea's active tectonic environment and is affected by the present-day geodynamic processes acting in the Red Sea region. The resulting structures either normal or transform faults run parallel to and/or across the Red Sea. Some of these faults extend inland over tens or hundreds of kilometers (Al-Shanti, 1966; Pallister, 1984). The relative movements along such faults can cause large and damaging earthquakes. Historical information (Poirier and Taher, 1980; Ambraseys and Milville, 1983; Ambraseys et al., 1994) in association with the recent studies (Merghelani, 1981; El-Isa and Al-Shanti, 1989; Al-Amri, 1995) around Yanbu have revealed its significant level of earthquake activity which should be taken into account for the strategic plans in the future. Recently, the city was affected by the occurrence of the moderate earthquake at Harat Lunayyir (M_w 5.7) earthquake swarm on May 19, 2009 (Al-Amri and Fnais, 2009). Earthquake ground-shaking intensity has been participated at Yanbu city (MMI = 5) in spite of 130 km distance from the earthquake location.

It is well known that, local site effects play an important role in the damage occurring during a destructive earthquake (Singh et al., 1988; Graves, 1993; Bakir et al., 2002; Sørensen et al., 2006). The lateral variation in the site effects are mainly due to the local site conditions such as type and nature of sediments, water saturation, basin geometry, and thickness of sediments. In addition, it is realized that the presence of sharp lithological boundaries between the bedrocks and the overlying sediments cause strong impedance contrasts that affect the local site responses. Different approaches have been carried out to evaluate the local site response (Nakamura, 1989; Lermo and Chavez-Garcia, 1993; Field and Jacob, 1995). In this study, the evaluation of the local site effects for Yanbu metropolitan city was conducted according to the most popular and world-wide approach through the calculation of the horizontal to vertical spectral ratio (HVSR) for the recorded ambient vibrations. These spectral ratios show the fundamental frequency and the associated amplification factor. As proved through the intensive investigations, thick sedimentary cover usually generates amplitude spectra with peaks at low frequencies (< 3 Hz) while thin sediments generate peaks at high frequencies (> 10 Hz). The broad spectrum with constant amplitude is usually associated with the crystalline outcrops (Nakamura, 1989, 2000; Bard, 1994; Bard et al., 2004). Then, the estimated fundamental frequencies and the corresponding amplifications are compared with the surface geology.

2. Geological and tectonic setting

The available geological information for Yanbu city and the surrounding area comes from the geologic map of Yanbu (Fig. 2) with scale 1:250,000 (Pellaton, 1979). Most of the area is occupied by outcrops of tertiary–quaternary marine and continental coastal plain sediments. Marine quaternary deposits are represented mainly by reef terraces which lie several meters above sea level. Sand and mud in the lower zones are intermixed with contemporaneous alluvial material. While continental quaternary deposits are represented by: (1) sandy mantle covering a wide area which has a composite origin incorporating fluviatile and Aeolian transport; (2) gravely or sandy spreads dissected by very close drainage; and (3) gravely spreads related to the degradation of the older terraces.

The distribution of tertiary sediments was controlled by the syndepositional section across the coastal plain from the Precambrian basement in the east to the coast in the west would be: (1) beds of shale and conglomerate sandstone alternating with siltstone, (2) thin tertiary reefal limestone with the Miocene coral, rising above the coastal plain and alternating with sandstone and silts, (3) shale covered by sand and gravel, and (4) raised reef limestone terraces of quaternary age.

Depending on the lithological variations through 106 boring logs in the city of Yanbu (Al-Haddad et al., 2001), the subsurface soil column at Yanbu city can be classified as an extremely variable complex and is composed of the following profiles:

(1) Extremely loose to loose fine to medium sand deposits from the surface to 15 m depth with a very shallow groundwater table (less than 1 m).
(2) Thin top layer of compact shattered coral (2–5 m with SPT-N values from 20 to 50) underlain by thick layer of very loose to loose fine sand with some gravel and/or silt (6–8 m with SPT-N values between 5 and 25) below the ground level.
(3) A dense to very dense layer of silty sand with gravel and cobbles.
(4) Coral limestone interbedded with coralline sand and fines. It is of medium dense to very dense especially at deeper depths (35 km south of Yanbu).

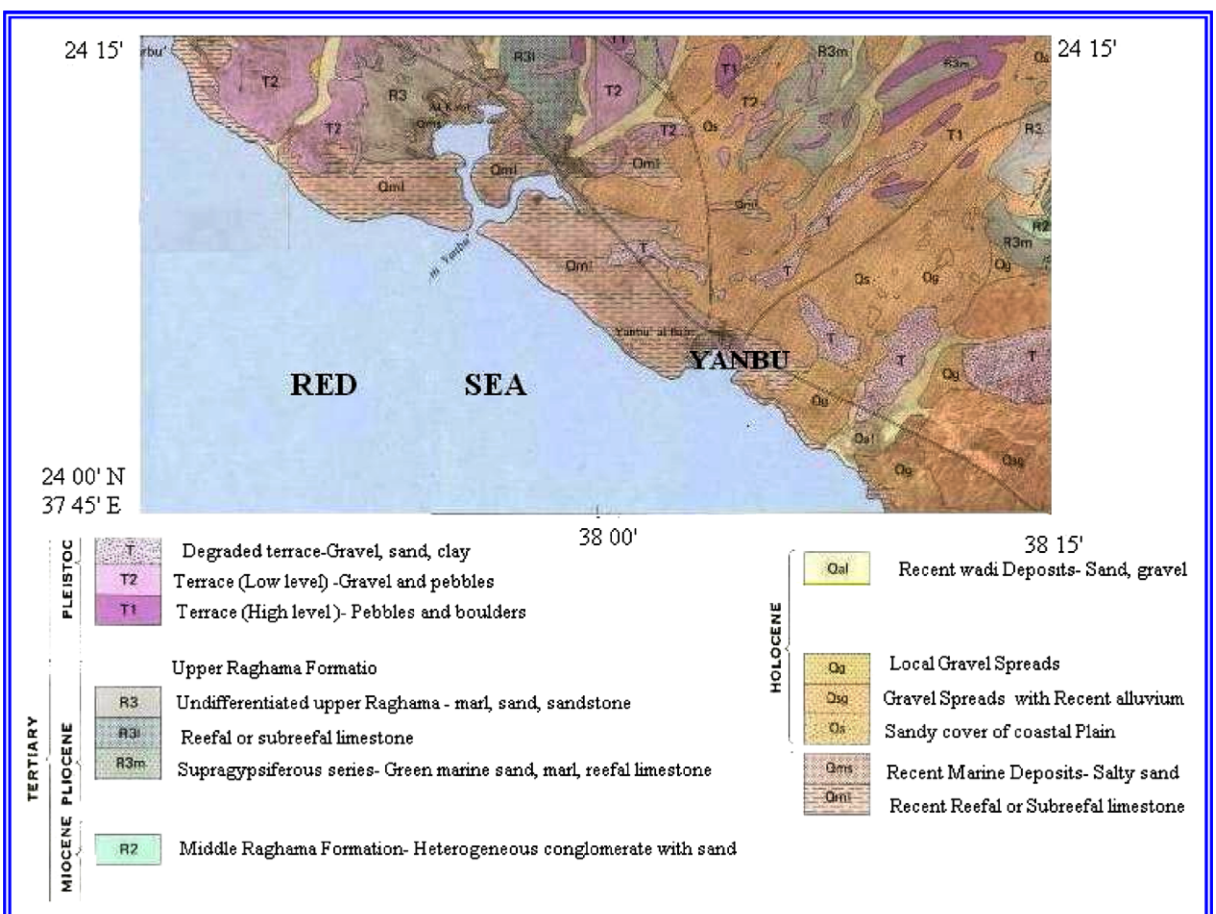


Figure 2 Geologic map for Yanbu area.

3. Data acquisition and processing

Seismic noise measurements were acquired at 85 sites during the period from 3rd to 20th August 2009 at the intersected points of two mutually perpendicular sets of profiles covering the metropolitan zone of Yanbu city (Fig. 3 and Table 1).

Noise measurements were collected (Fig. 4) using five digital stations of 24-bit Quanterra Q_{330} digitizer equipped with high-performance portable Very Broad-Band (VBB) triaxial Streckeisen STS-2 velocimeter (with flat response from 8.33 mHz up to 50 Hz) with GPS timing. Generally known is the fact that man-made seismic noise represents a problem for seismic noise survey especially within densely urbanized areas in the form of traffic or industrial activities. To avoid recording of such transient signals into the measurements, special precautions should be taken whenever possible to measure as far as possible away from sites close to heavily traffic streets, boulevards and heavy-duty machines. In some cases, there are no possibilities in finding an appropriate site, then the measurements should be acquired in the early morning when there is relatively little human activity throughout the city. During the acquiring period of data the used seismometers have been installed in the early morning to collect the desired data after twenty-four hours of continuous recording. The measuring points are spread out within a range of 450 m vertically and 900 m horizontally forming a regular grid to achieve good quality of the contour maps for the fundamental frequency and amplification factor (Fig. 3).

Throughout the current work, all the sensors used were calibrated, installed in good coupling with soil, isolated thermally well against temperature changes using thick foam box and covered to reduce the interference of wind. Then, these sensors were oriented horizontally and vertically leveled. Ambient seismic noise was recorded with 200 Hz sampling rate for 24 h of continuous recording. This long duration of recording guarantees the statistical stabilization of the signal (Picozzi et al., 2005, 2008). All the experimental conditions for the current work were controlled mainly by the precautions of European SESAME research project (Chatelain et al., 2008; Guillier et al., 2008). Keeping in mind, higher fundamental resonance frequencies would be observed on sites having thin sediments, whereas the lower values of fundamental frequencies would be observed over the thick sediments (Nakamura, 1989; Atakan 1995; Lacave et al., 1999; Bard et al., 2004).

The collected data have been processed using the J-SESAME software developed within the framework of the great European project SESAME. The H/V spectral ratios were computed according to the following methodology: (1) baseline correction; (2) band-pass filtering to retain the frequencies in the range from 0.2 to 20 Hz; (3) windows of 50 s length were automatically selected using an anti-STA/LTA trigger algorithm and tapered with a 5% cosine function before the computation of spectra; (4) Fourier spectra were calculated for each noise component and smoothed using Konno–Omachi window having a smoothing constant *b*-value of 30; (5) the

Figure 3 Distribution of microtremor measurements at Yanbu area.

Table 1 Parameters of measuring stations for seismic noise at Yanbu City.

Station code	Date	Latitude (°)	Longitude (°)	Location
Y1	3 August 2009	38.1082	24.0581	Empty Land
Y2	3 August 2009	38.1083	24.0628	Empty Land
Y3	3 August 2009	38.1097	24.0683	Balbeed Company
Y4	3 August 2009	38.1094	24.0730	Empty Land
Y5	3 August 2009	38.1080	24.0790	Empty Land
Y6	4 August 2009	38.1084	24.0836	Holiday Inn Hotel
Y7	4 August 2009	38.1079	24.0885	Empty Land
Y8	4 August 2009	38.1088	24.0930	Empty Land
Y9	4 August 2009	38.1087	24.0975	Empty Land
Y10	4 August 2009	38.1076	24.1019	Empty Land
Y11	5 August 2009	38.0996	24.0580	Jeddah Road
Y12	5 August 2009	38.0997	24.0627	Empty Land
Y13	5 August 2009	38.0997	24.0665	Empty Land
Y14	5 August 2009	38.1000	24.0708	Empty Land
Y15	5 August 2009	38.1000	24.0750	Almajd Club
Y16	6 August 2009	38.0997	24.0790	Empty Land
Y17	6 August 2009	38.0997	24.0833	Empty Land
Y18	6 August 2009	38.1000	24.0875	Empty Land
Y19	6 August 2009	38.1000	24.0916	Empty Land
Y20	6 August 2009	38.0999	24.0958	Empty Land
Y21	7 August 2009	38.09261	24.05833	Empty Land
Y22	7 August 2009	38.09156	24.06236	Empty Land
Y23	7 August 2009	38.09192	24.05	Empty Land
Y24	7 August 2009	38.09183	24.07111	Empty Land
Y25	7 August 2009	38.09164	24.075	Playground
Y26	8 August 2009	38.0915	24.0791	Jeddah Road
Y27	8 August 2009	38.0919	24.083	Empty Land
Y28	8 August 2009	38.0917	24.0877	Empty Land
Y29	8 August 2009	38.0917	24.0914	Empty Land
Y30	8 August 2009	38.0914	24.0957	Empty Land
Y31	9 August 2009	38.0832	24.0666	Radison Sas Hotel
Y32	9 August 2009	38.0833	24.0708	Empty Land
Y33	9 August 2009	38.0833	24.075	Empty Land
Y34	9 August 2009	38.0833	24.0791	Mercury Exhibit
Y35	9 August 2009	38.0831	24.0836	Jeddah Road
Y36	10 August 2009	38.0838	24.0875	Empty Land
Y37	10 August 2009	38.0834	24.0916	Empty Land
Y38	10 August 2009	38.0832	24.0959	Empty Land
Y39	10 August 2009	38.0832	24.1003	Empty Land
Y40	10 August 2009	38.0832	24.1041	Empty Land
Y41	11 August 2009	38.0749	24.0751	Yanbu Port
Y42	11 August 2009	38.0752	24.0791	Yanbu Port
Y43	11 August 2009	38.0749	24.0835	Yanbu Port
Y44	11 August 2009	38.0750	24.0873	Danat Yanbu Hotel
Y45	11 August 2009	38.0752	24.0918	Empty Land
Y46	12 August 2009	38.0751	24.0957	Empty Land
Y47	12 August 2009	38.0750	24.1001	Sabhkat area
Y48	12 August 2009	38.0751	24.1041	Sabkhat area
Y49	12 August 2009	38.0748	24.1081	Empty Land
Y50	12 August 2009	38.0750	24.1124	Empty Land
Y51	13 August 2009	38.0666	24.0791	Yanbu Port
Y52	13 August 2009	38.0667	24.0833	Al-Maktaba
Y53	13 August 2009	38.0667	24.0874	Empty Land
Y54	13 August 2009	38.0668	24.0917	Empty Land
Y55	13 August 2009	38.0667	24.095	Empty Land
Y56	14 August 2009	38.0666	24.1000	Empty Land
Y57	14 August 2009	38.0665	24.1042	Empty Land
Y58	14 August 2009	38.0664	24.1080	Empty Land
Y59	14 August 2009	38.0666	24.1126	Empty Land
Y60	14 August 2009	38.0668	24.1167	Empty Land
Y61	15 August 2009	38.0581	24.0790	Old City
Y62	15 August 2009	38.0582	24.0834	Historical Gate

(*Continued on next page*)

Table 1 (*continued*)

Station code	Date	Latitude (°)	Longitude (°)	Location
Y63	15 August 2009	38.0581	24.0873	Schools compound
Y64	15 August 2009	38.0581	24.0916	Playground zone
Y65	15 August 2009	38.0583	24.0957	Empty Land
Y66	16 August 2009	38.0584	24.0999	Empty Land
Y67	16 August 2009	38.0583	24.10422	Empty Land
Y68	16 August 2009	38.0585	24.1084	Empty Land
Y69	16 August 2009	38.0583	24.1125	Empty Land
Y70	16 August 2009	38.0583	24.1165	Empty Land
Y71	17 August 2009	38.0563	24.0763	Empty Land
Y72	17 August 2009	38.0498	24.0826	Empty Land
Y73	17 August 2009	38.053	24.088	Empty Land
Y74	17 August 2009	38.0499	24.096	Empty Land
Y75	17 August 2009	38.0501	24.1001	Empty Land
Y76	17 August 2009	38.0823	24.0446	Governorate Build
Y77	18 August 2009	38.05	24.1086	Water Authority
Y78	18 August 2009	38.0499	24.1125	Empty Land
Y79	18 August 2009	38.0516	24.0807	Educational Build
Y80	19 August 2009	38.0416	24.0827	Empty Land
Y81	19 August 2009	38.0416	24.0791	Al-Shate School
Y82	19 August 2009	38.0375	24.0833	Obeida School
Y83	20 August 2009	38.0326	24.0856	Empty Land
Y84	20 August 2009	38.0304	24.0913	Al-Waleed School
Y85	20 August 2009	38.0387	24.1792	

resulting spectral amplitudes of horizontal components were geometrically averaged and divided by the vertical spectra to calculate the H/V function. Moreover, stability of the peak in the H/V curve have been checked through three tests conducted at every measuring point, where the same frequency peaks were picked for each site at different times. Sensitivity

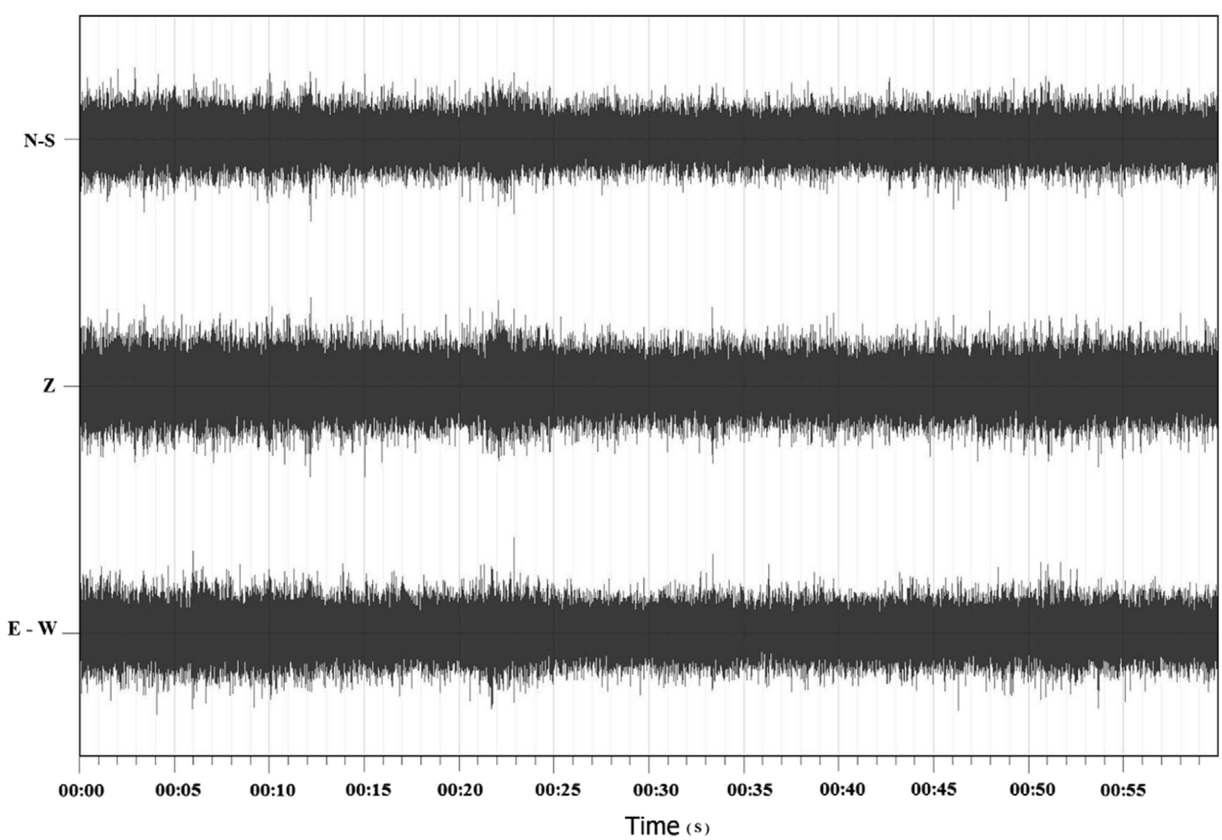


Figure 4 Microtremor record at Yanbu city.

tests were also carried out on the selected time window lengths during the data processing; the results declared low dependence of the window length and therefore, a high stability was achieved.

The reliability of the actual H/V curve obtained with the selected recordings should be tested throughout the following consequences: (i) for a peak to be significant, it is recommended checking that the following condition is fulfilled: $f_0 > 10/l_w$ (window length). This condition means that, at the frequency of interest, at least 10 significant cycles in each window should be present, (ii) large number of windows and of cycles is needed. The total number of significant cycles: $n_c = l_w \cdot n_w \cdot f_0$ be larger than 200, and (iii) an acceptably low level of scattering between all windows is needed. Large standard deviation values often mean that ambient vibrations are strongly non-stationary and undergo some kind of

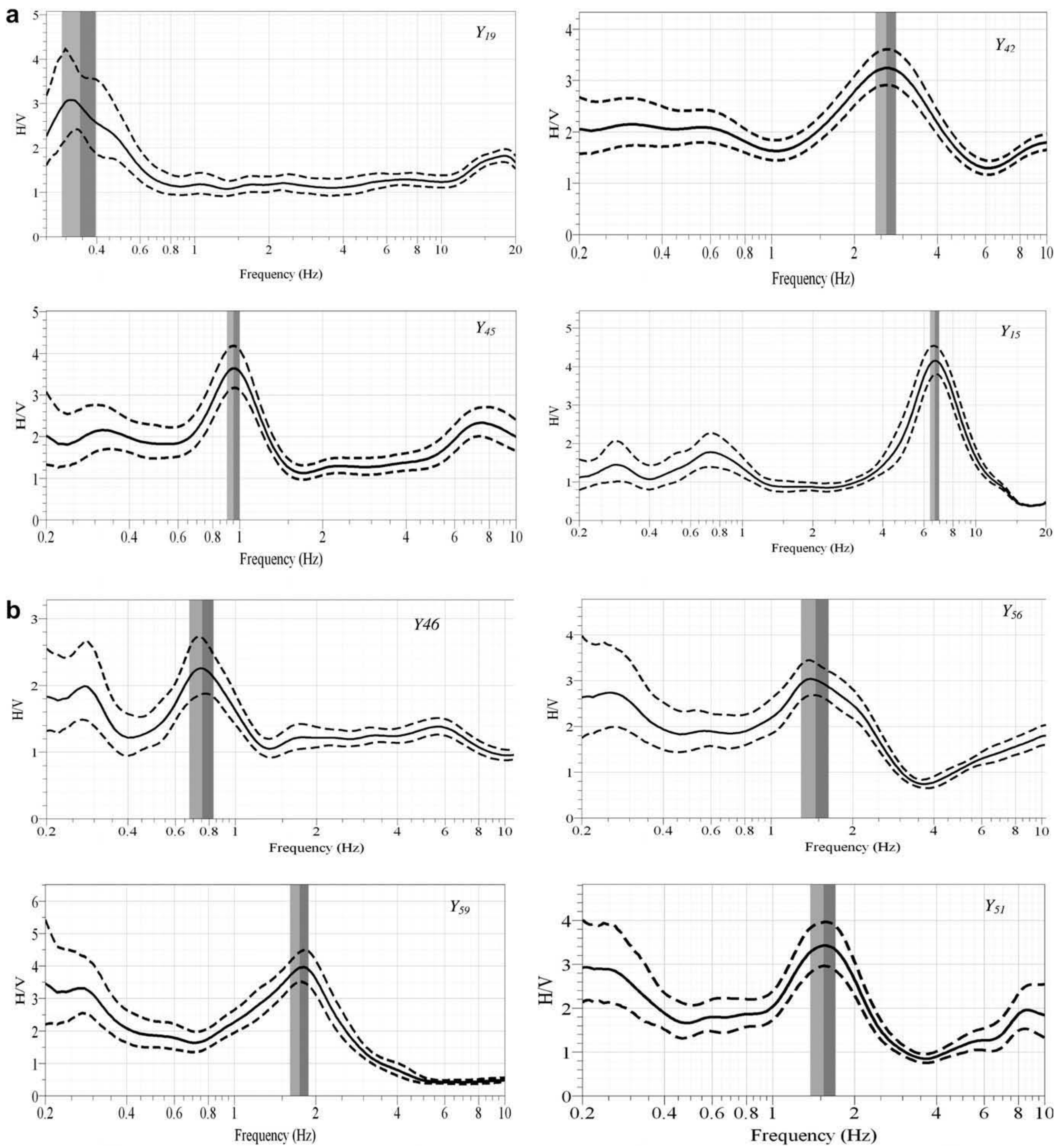


Figure 5 (a) Examples of clear peak of spectral ratio (H/V) curves. (b) Examples of two peaks of spectral ratio (H/V) curves. (c) Examples of multiple and broad peaks of spectral ratio (H/V) curves.

perturbations, which may significantly affect the physical meaning of the H/V peak frequency. Therefore it is recommended that $\sigma_A(f)$ be lower than a factor of 2 (for $f_0 > 0.5$ Hz), or a factor of 3 (for $f_0 < 0.5$ Hz), over a frequency range at least equal to [$0.5f_0$ and $2f_0$].

Generally, as noticed in urban environments that, the H/V curves exhibit local narrow peaks – or troughs of industrial origin, related to some kind of machinery (turbine and/or generators). Such perturbations are recognized by the following general characteristics: (i) they may exist over a significant area (in other terms, they can be seen up to distances of several kilometers from their source), (ii) as the source is more or less "permanent" (at least within working hours), the original (non smoothed) Fourier spectra should exhibit sharp narrow peaks at the same frequency for all the three components, (iii) reprocessing with less and less smoothing: in the case of industrial origin, the H/V peak should become sharper and sharper (while this is not the case for a site effect peak linked with the soil characteristics), (iv) if other measurements have been performed in the same area, determine whether a peak exists at the same frequencies with comparable sharpness (the amplitude of the associated peak, even for fixed smoothing parameters, may vary significantly from site to site, being transformed sometimes into a trough), and (v) another very effective check is to apply the random decrement technique (Dunand et al., 2002) to the ambient vibration recordings in order to derive the "impulse response" around the frequency of interest: if the corresponding damping (z) is very low (below 1%), an anthropic origin may be assumed almost certainly, and the frequency should not be considered in the interpretation.

4. Results and discussion

H/V spectral ratios for the selected windows have been computed at 85 of surveyed sites (Fig. 5a–c). The presence of clear peak of H/V curve (Fig. 5a) is considered as an indicative of the impedance contrast between the uppermost surface soil and the underlying hard rock, where large peak values are generally associated with sharp velocity contrasts (Bard et al., 2004) and is likely to amplify the ground motion. Fig. 5b illustrates two of peaks that reflect the presence of two large impedance contrasts while, Fig. 5c present some of broad peak or plateau-like curve and this could be related to the presence of an underground sloping of the interface between softer and harder layers. These results declared that the underground structure of the site exhibits significant lateral variations in thickness and dynamic properties, which lead to a significant 2D or 3D effects.

According to Fig. 6, the resonance frequency f_0 varies from 0.25 to 7.9 Hz within the study area. The central part has lower values of f_0 (less than 1 Hz) where 50% of f_0 values lie in this area (Fig. 7). These low values indicate large thickness of sediments. While, there are some localized areas that have higher values of f_0 (up to 6.7 Hz) distributed throughout the southeastern, southern, and southwestern parts of the area. The presence of high f_0 at the southern part is limited to Al-Majd Sporting Club, Al-Maktaba, and Al-Shati secondary school sites. Parolai et al. (2001) stated that, the resonance frequency becomes lower in areas where the basement depth is greater and higher where it is shallower. Accordingly, the presence of higher and lower values reflect variation in the thicknesses of sediments through the area suggesting 2D or 3D basins in-between (Fig. 8). In general, the values of f_0 increase due north.

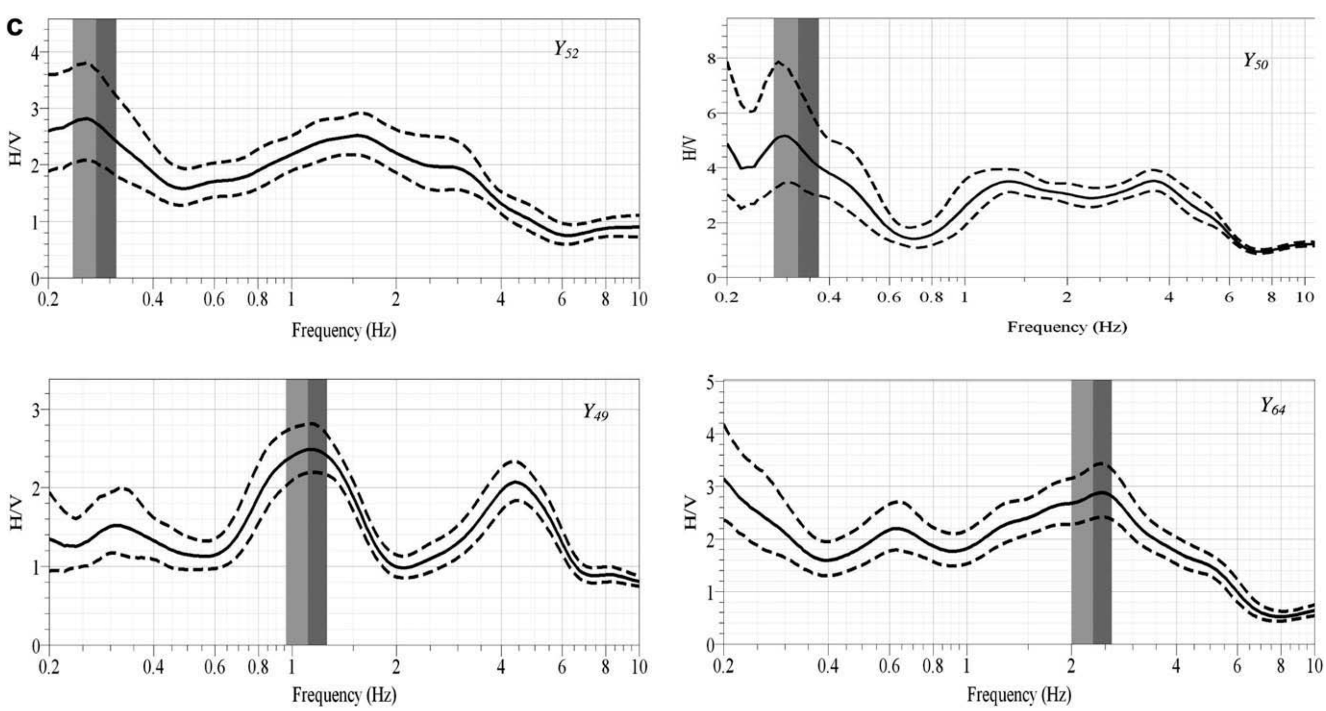


Figure 5 (*continued*)

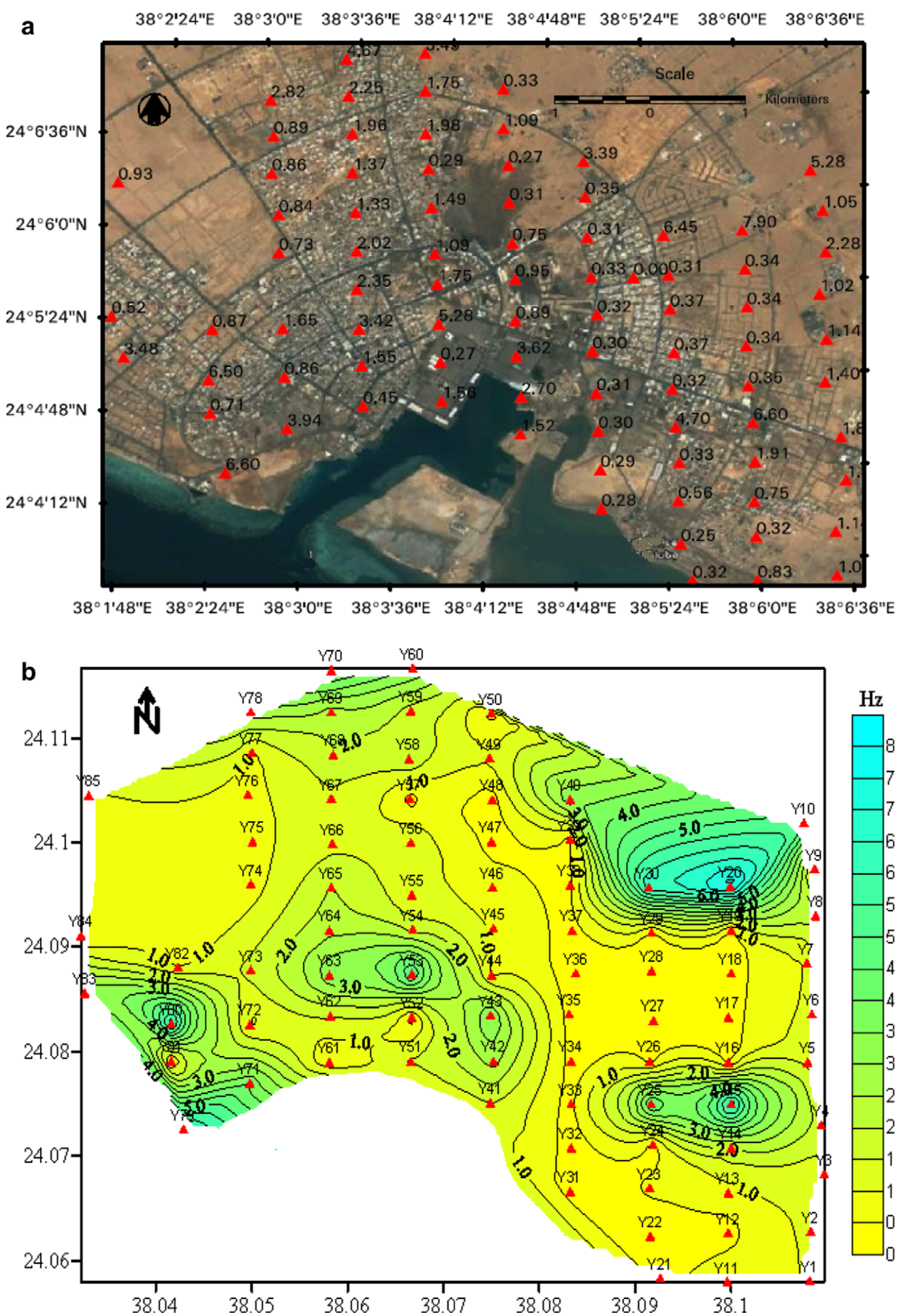


Figure 6 Contour map for f_0 for Yanbu city.

Contour map for H/V amplitude ratio A_{max} (Fig. 9) illustrated that, the eastern part of the area has values less than 2.5 while the western part has values less than 3. Whereas these values increases towards the central zone of Yanbu metropolitan where it has a value of 5. By referring to the surface soil distribution it can be observed that the central part

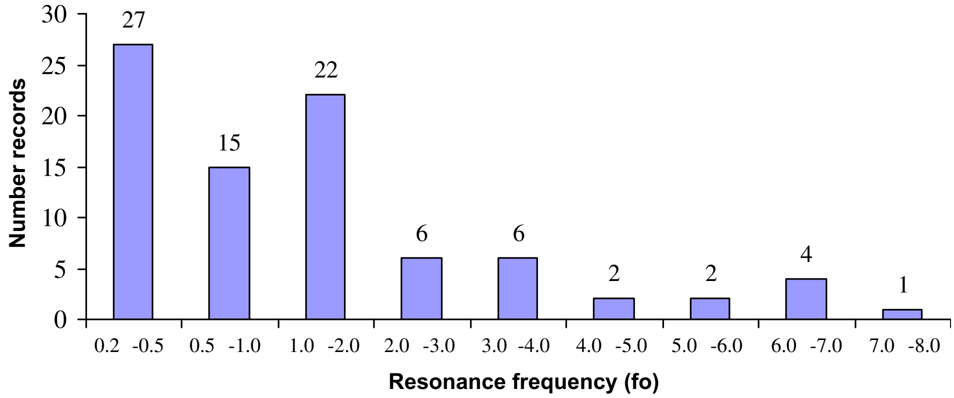


Figure 7 Relation between number of records and their values of f_0.

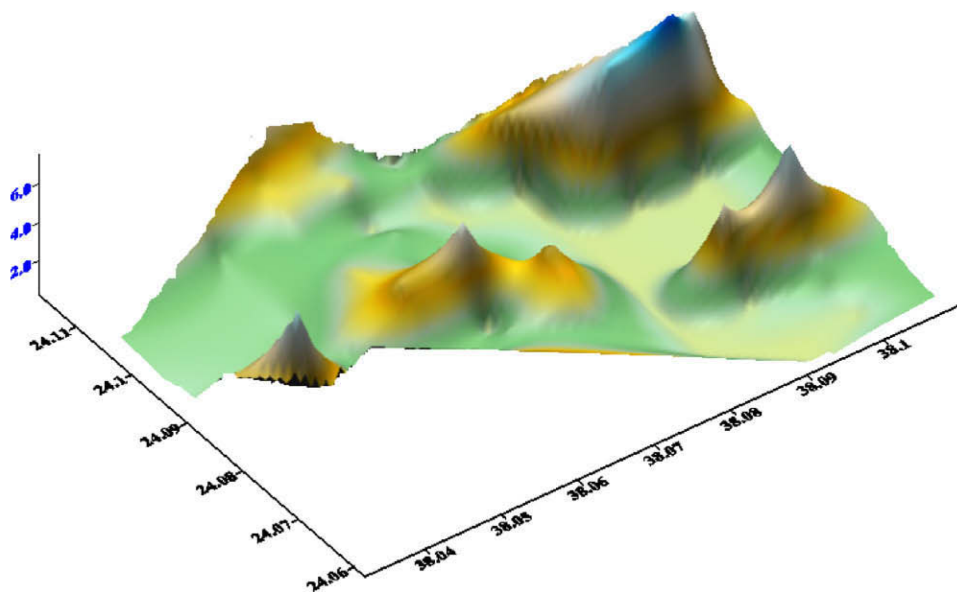


Figure 8 3D model for the subsurface basement at Yanbu city.

characterized by the thick section of soft sediments (sabkhat) amplifies the ground-shaking intensity five times more than that of basement rocks. However, it is to be noted that these values give the lower bound estimates of amplification of H/V ratio for a given site. Generally, it could be mentioned that, there is significant variation in this parameter within the study area.

Several studies show the relationship between the velocity structure beneath the recording site and the fundamental frequency obtained from HVSR (horizontal-to-vertical spectral ratios of microtremors) analysis (Ibs-von Seht and Wohlenberg, 1999; Parolai et al., 2002; Motamed et al., 2007). We used the sedimentary layer parameters obtained by Al-Haddad et al. (submitted for publication) through shear-wave velocity profiles, where a sample of ten boreholes have been drilled through the study area. Three of these boreholes are presented within the area of interest (Table 2). The weighted shear-wave velocities were computed according to the following formula:

$$V_{s(av)} = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \frac{d_i}{V_{si}}}$$

where d_i and v_{si} denote the thickness (in m) and the shear-wave velocity (in m/s) of the ith layer, in a total of n layers, existing in the same type of stratum (d_i and v_{si} were determined by borehole measurements).

Then, the values of fundamental resonance frequency can be computed at these three localities through the application of the following equation (Bard, 2000):

$$f = \frac{V_{av}}{4H}$$

where H is the total thickness (in m) of the sediments overlying the half-space and V_{av} is the average shear-wave velocity (in m/s) in the sediments. Using the above equation and the velocity model in Table 2, the resonance frequency f_0 at these sites is estimated to be equal to 6.7 Hz at Al-Shati secondary school; 4.8 Hz at Al-Maktaba, and 6.3 Hz at Al-Majd Sporting Club where V_{av} values are 467.83 m/s; 566.04 m/s and 752.74 m/s respectively. On the other hand, the resonance frequency f_0 estimated using the microtremor measurements, close to these boreholes, are 6.7 Hz, 5.2 Hz, and 6.5 Hz, respectively (Fig. 10) that reflects an excellent agreement between the estimated values for f_0 from two independent techniques.

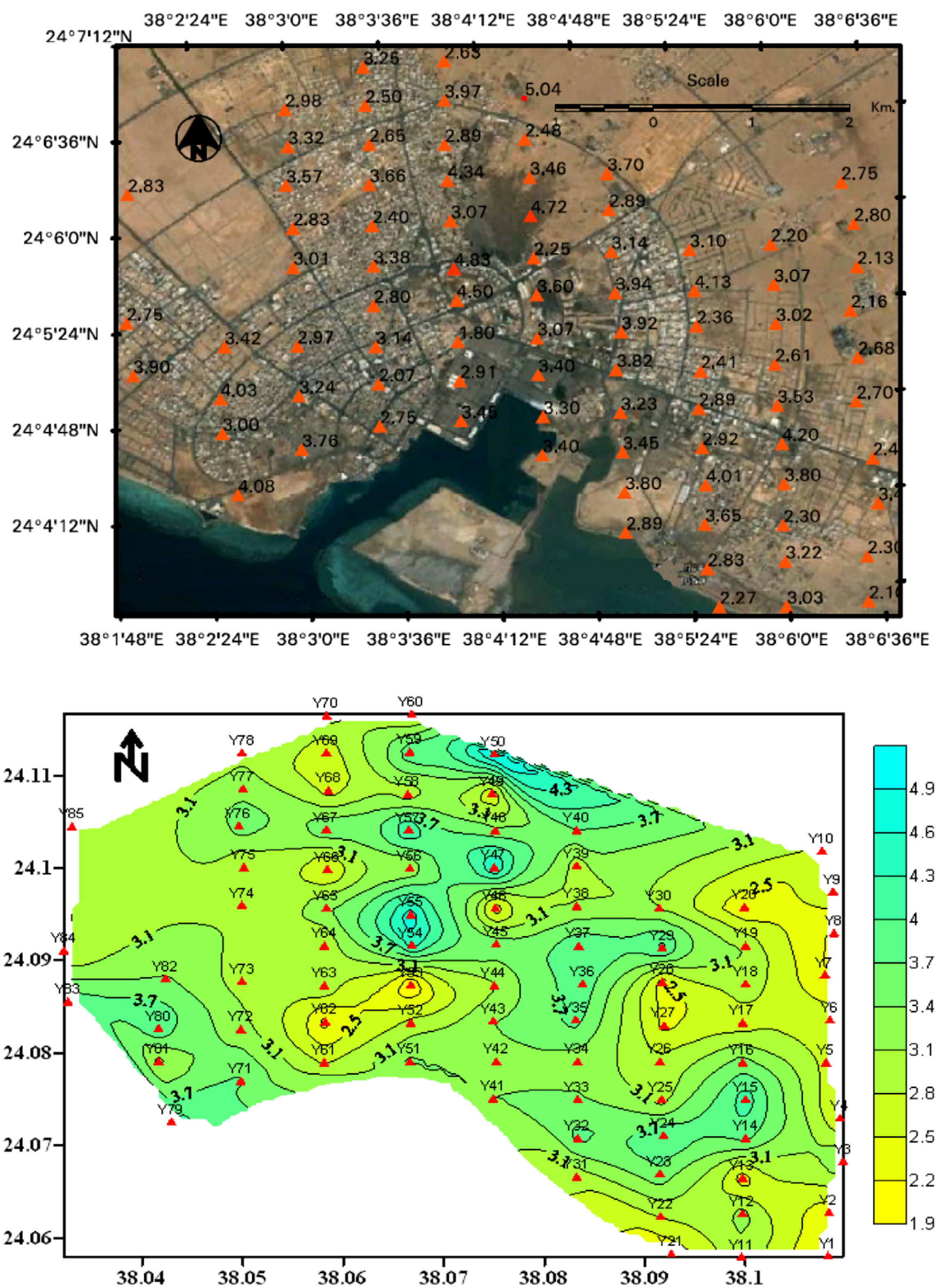
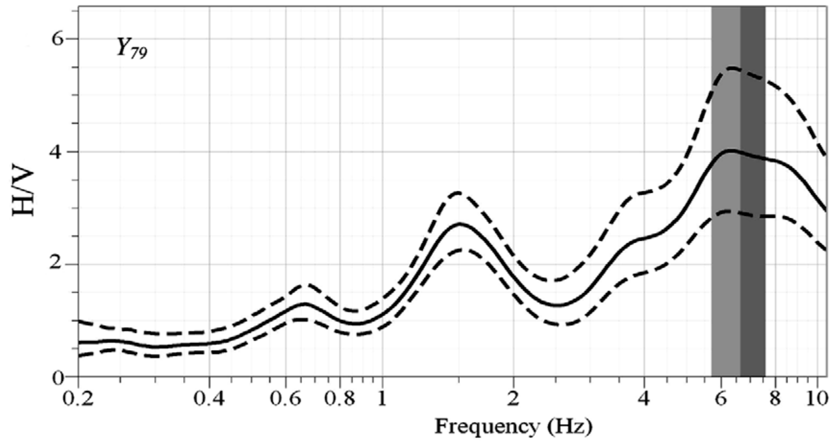


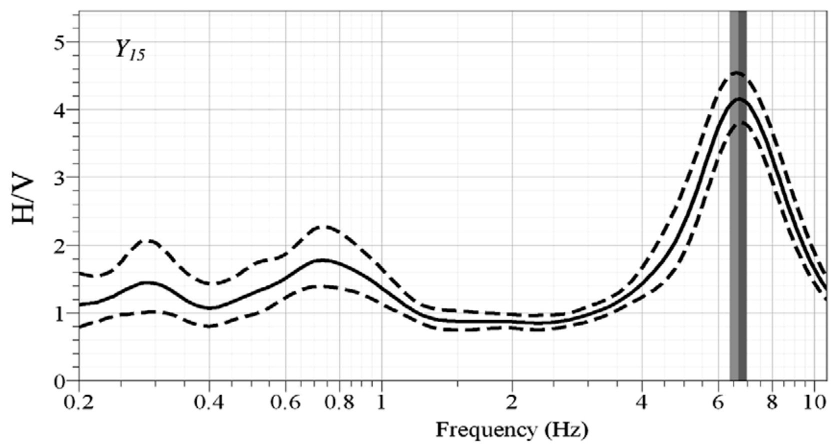
Figure 9 Contour map for H/V amplitude ratio A_{max} for Yanbu city.

5. Conclusions

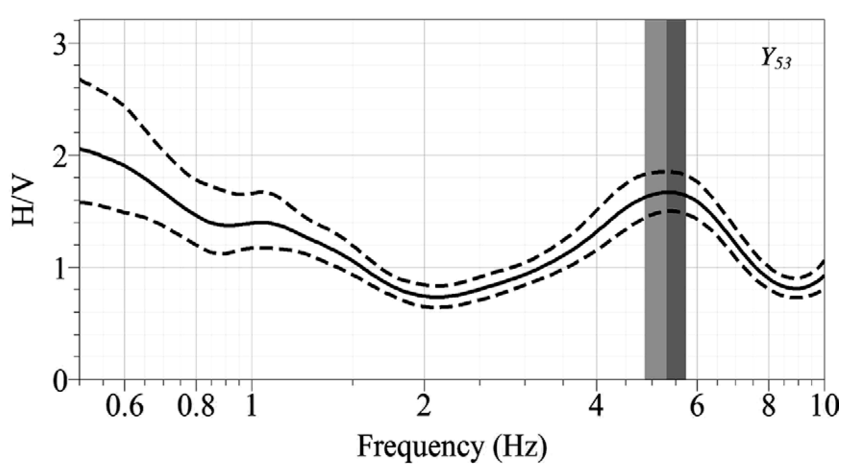
Although Yanbu city is located close to Red Sea floor spreading active zone; it is not affected by recent instrumentally strong earthquakes. Moreover, most of the city is built on thick soft sediments, which could reasonably amplify the earthquake ground motion in the case of an event. No site effects analyses have been carried out in the city, therefore, it is believed that a detailed study of the local response of Yanbu city should be of some concern in terms of seismic hazard.



a) Al-Shati Secondary School site



b) Al-Majd Sporting Club site



c) Al-Maktaba site

Figure 10 H/V results at three of geotechnical boreholes at Yanbu city.

The current work represents the first attempt to derive useful information on local ground motion amplification in the urban area of Yanbu.

Analysis of microtremor measurements show that the resonance frequency varies considerably through Yanbu city. Values of resonance frequency increase as the basement depth decreases. The central part of the city has low values of f_0 as compared to other parts of the city suggesting basinal shape with great thickness of sediments. The results of microtremor data are in congruence with the shear-wave velocity profiles through Yanbu city.

Finally, it is declared that, the using of microtremor measurements represents a powerful tool for microzonation studies in spite of their tendency to underestimate the level of ground

Table 2 Shear-wave velocity profiles within the city of Yanbu.

Al-Ahati secondary school			Al-Maktaba			Al-Majd sporting club		
Depth (m)	V_s (m/s)	Thickness (m)	Depth (m)	V_s (m/s)	Thickness (m)	Depth (m)	V_s (m/s)	Thickness (m)
0.9	205.53	0.9	1.21	225.69	1.21	0.73	180.7	0.73
1.82	301.02	0.92	1.71	315.76	0.5	1.47	332.69	0.74
2.59	427.26	0.77	3.35	491.59	1.64	2.91	474.57	1.43
3.4	421.26	0.81	5.7	750.08	2.35	5.39	804.79	2.49
4.75	385.39	1.35	7.66	835.94	1.96	8.29	798.79	2.89
6.34	427.4	1.58	8.17	929.94	0.5	11.27	763.53	2.98
8.23	575.5	1.89	9.43	610.52	1.26	15.66	757.53	4.39
10.95	624.84	2.72	10.31	446.4	0.88	19.28	884.37	3.62
14.16	618.84	3.21	16.63	446.85	6.33	23.45	1069.09	4.17
17.56	691.27	3.4	20.88	640.83	4.25	30	1063.09	6.55
			30	772.11	9.12			
$V_{s(av)}$ = 467.83			$V_{s(av)}$ = 566.04			$V_{s(av)}$ = 752.74		

motion amplification when compared with earthquake records.

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