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ORIGINAL PAPER

Site effect evaluation for Yanbu City urban expansion zones, western Saudi Arabia, using microtremor analysis

K. Alyousef · A. Al-Amri · M. Fnais · Kamal Abdelrahman · Oumar Loni

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Abstract Recently, Yanbu City has been greatly growing; great developmental projects, urban community settlements, and petrochemical industries have been established. Historical and instrumental earthquakes were felt by this city, such as the earthquake on 19 May 2009 which was a moderate earthquake (moment magnitude (M_w) 5.7) whose ground motions have affected some building structures. Yanbu City has been divided by a grid of points separated by about 500 m, and microtremor measurements have been conducted at 141 measuring sites. The acquired data have been processed using worldwide Geopsy software package to calculate the fundamental frequency peaks and their corresponding amplification factors. The natural origin of these peaks has been confirmed. Based on fundamental frequency (f_0), Yanbu City has been classified into three zones—from 0.13 to 1.0 Hz in the first zone, from 1.0 to 4.0 Hz in the second zone, and from 4.0 to 7.6 Hz in the third zone. The coastal zone of Yanbu illustrates smaller values of f_0 that reflect great thickness of soft sediments while the eastern zone presents an opposite phenomenon. Accordingly, high-rise buildings in the coastal zone will be affected greatly by low frequencies originating from distant earthquakes. Most of Yanbu City has f_0 values in the range of 1.0–4.0 Hz. Furthermore, bedrock ground motion could amplify as much as three times. This indicates that one- to three-story buildings in Yanbu City are vulnerable to hazardous resonant shaking from local and near earthquakes.

Keywords Soft sediments · Microtremor · Predominant frequency · Amplification factor · Yanbu City

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Introduction

Yanbu City is one of the oldest marine ports along the western coast of Saudi Arabia (Fig. 1) and lies at latitude 24°0.5′ 07.27″ N and longitude 38°03′28.47″ E. In recent times, this city attracted several projects for development and urban expansion. In 1068, Yanbu was affected by a historical earthquake of intensity VI (El-Isa and Al-Shanti 1989; Ambraseys et al. 1994). Furthermore, on 19 May 2009, the city was affected by an earthquake of moment magnitude (M_w) 5.7, with an epicenter located about 100 km northeast of the city, followed by a huge number of aftershocks with a maximum magnitude of 4.2. Some structures at Yanbu City have been affected, and slight damage was documented for two and/or three building structures. Therefore, the evaluation of local site response effects of the earthquake ground motion in the urban expansion zones of Yanbu City is of utmost importance.

Borcherdt's approach (Borcherdt 1970), in which the ambient seismic noise instead of earthquake is used, has been applied to several studies (Ohta et al. 1978). The main advantage of this approach is the fact that the spectral characteristics of a microtremor have been recognized to be associated with the site conditions (Katz 1976; Katz and Bellon 1978; Kagami et al. 1986; Bard 2000; Gosar 2007). It has been accepted that microtremor measurements are capable of identifying the fundamental frequency of the near-surface soil deposits.

Nakamura (1989) suggested a method that requires only one recording station. Nakamura hypothesized that site

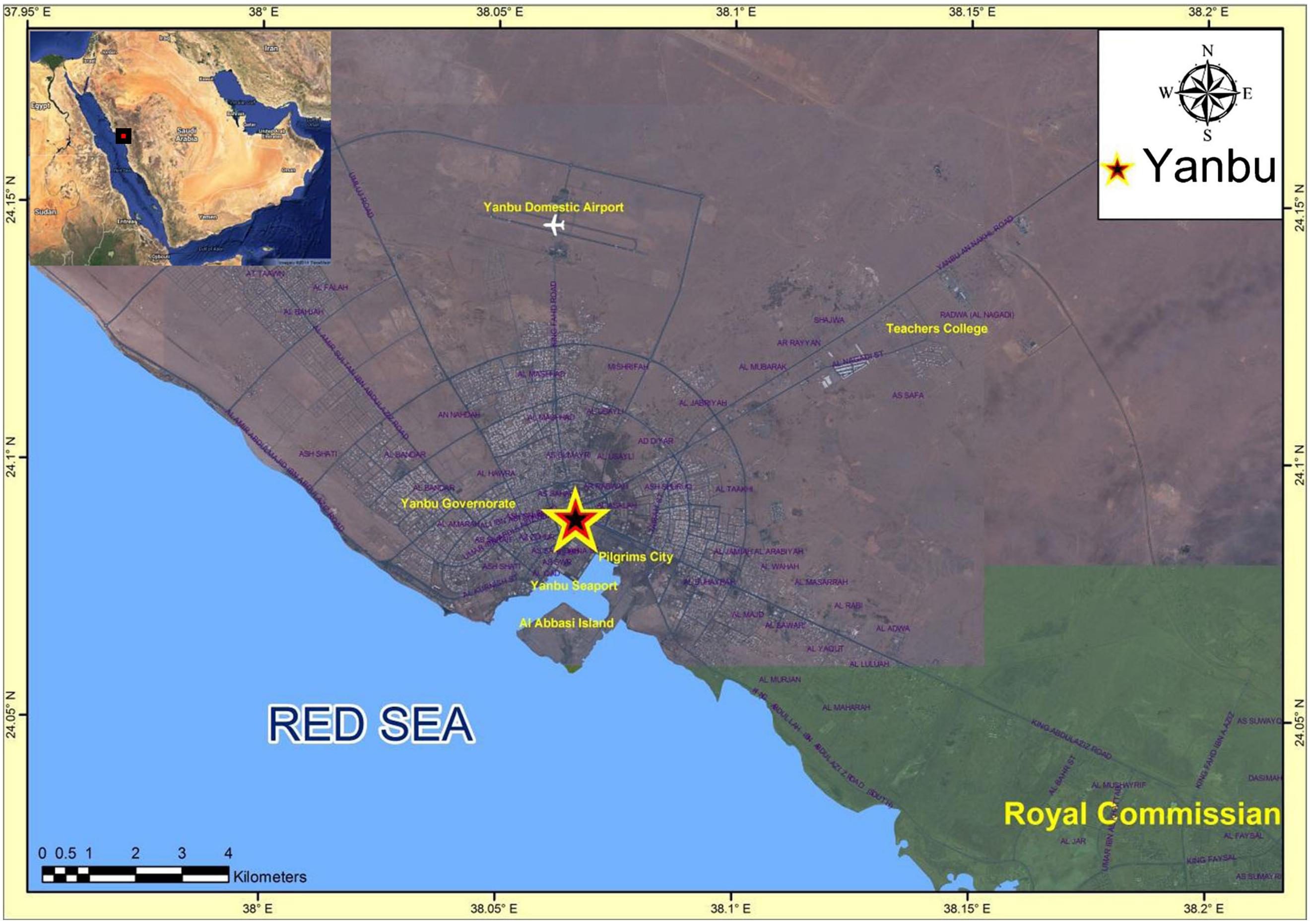


Fig. 1 Location map for Yanbu City

response could be estimated from the horizontal-to-vertical ratio of a microtremor. Numerous authors around the world (Lermo and Chavez-Garcia 1993, 1994; Lachet and Bard 1994; Field and Jacob 1995; Malagnini et al. 1996; Seekins et al. 1996; Teves-Costa Matias and Bard 1996; Theodulidis et al. 1996; Konno and Ohmachi 1998; Mucciarelli 1998; Mucciarelli et al. 1998) tested this technique, experimentally and theoretically. Results obtained by implementing Nakamura's technique support such use of microtremor measurements for estimating the site response of surface deposits. Lermo and Chávez-García (1993) applied Nakamura's technique to seismic recordings of earthquakes and concluded that this approach is able to reliably estimate the frequency of the fundamental resonant mode and correctly predict the amplification level. Other studies (Field and Jacob 1993; Wakamatsu and Yasui 1996; Lachet and Bard 1994) indicate that the Nakamura method has already proved to be one of the cheapest and most convenient techniques to estimate the fundamental frequency.

Fnais et al. (2010a, b), conducted microtremor measurements for the downtown of Yanbu City, where they conducted 85 measurement points, while in the present work, 56 points of microtremor measurements are acquired in the northern and southern urban expansion zones of the city.

Geological setting

The surface geology of Yanbu City consists of Tertiary and Quaternary deposits (Fig. 2), where these sediments crop out along a narrow coastal plain of the Red Sea with an average width of 5–10 km (Pellaton 1975). The total thickness of sediments ranges between 2.0 and 5.0 m with considerable variations. The distribution of the Tertiary sediments that is essentially controlled by syndepositional faulting and graben formation is related to the development of the Red Sea. Quaternary deposits of the coastal plain are represented by (1) sandy sediments covering a wide area; these sediments have a composite origin incorporating fluviatile and eolian transport, and erosion of in situ rock; (2) gravelly or sandy spreads dissected by a very close drainage network where they are intimately mixed with Recent alluvium; and (3) gravel spreads related to the degradation of the older terraces.

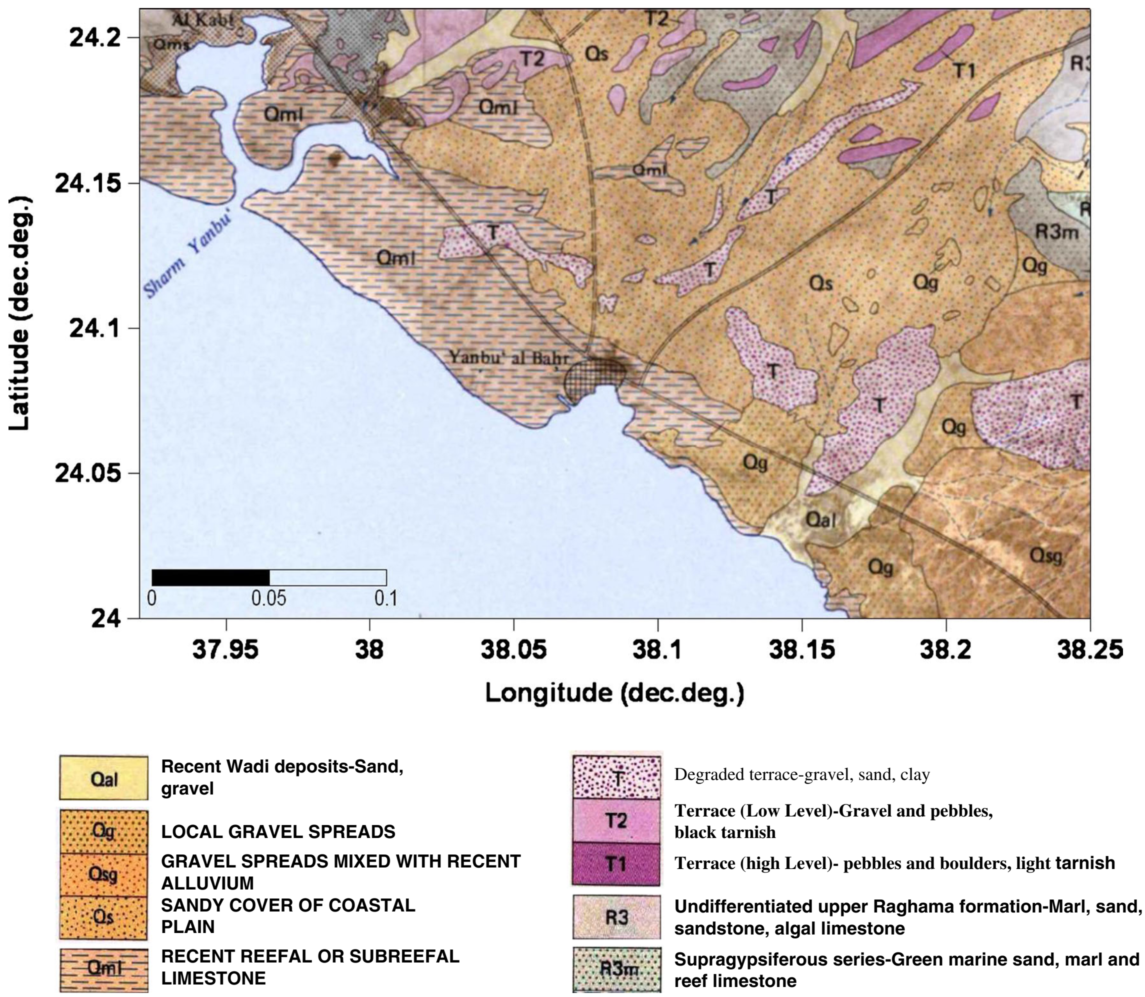


Fig. 2 Geological map of the study area (Pellaton 1975)

Data acquisition

Yanbu City is divided by a grid of points with spacing of 500 m×500 m, each comprising a discrete measurement site. Some of the measuring points are not accessible at 500 m, so this distance was increased a little bit and sometimes reached 700 m especially in the new expansion zones of Yanbu because some projects extend over a great distance. Microtremor measurements have been acquired in two separate time intervals; the first period is from 9 to 20 August 2009 (Fnais et al. 2010a, b), while the second period is from 25 March to 10 April 2012. Figure 3 illustrates the locations of 141 observation points. At each site, the microtremors were recorded continuously for almost 1 h with the following recommended precautions of Nakamura (1996), Mucciarelli et al. (1998), Mucciarelli (1998), and Bard and SESAME Team (2004): (1) Measurements were carried out using a 1-s (or higher) triaxial velocimeter, for analysis at periods longer than 1 s carried out measurements; (2) avoid long external wiring, to reduce any mechanical and electronic interference; (3) avoid measurements in windy or rainy days, which can cause large and unstable distortions at low frequencies; and (4) avoid recordings close to roads with heavy vehicles, which cause strong and rather long transients.

Digital records have been acquired with a band-pass filter in the range of 0.1–20 Hz with a sampling rate of 100 samples per second. Table 1 presents the parameters of 2012 measurement points.

Data processing

The collected data of microtremors have been processed by Geopsy software developed within the framework of the great European Site Effects assessment using Ambient Excitations (SESAME) project. All the necessary and recommended information about the recorded signals were applied according to the following criteria.

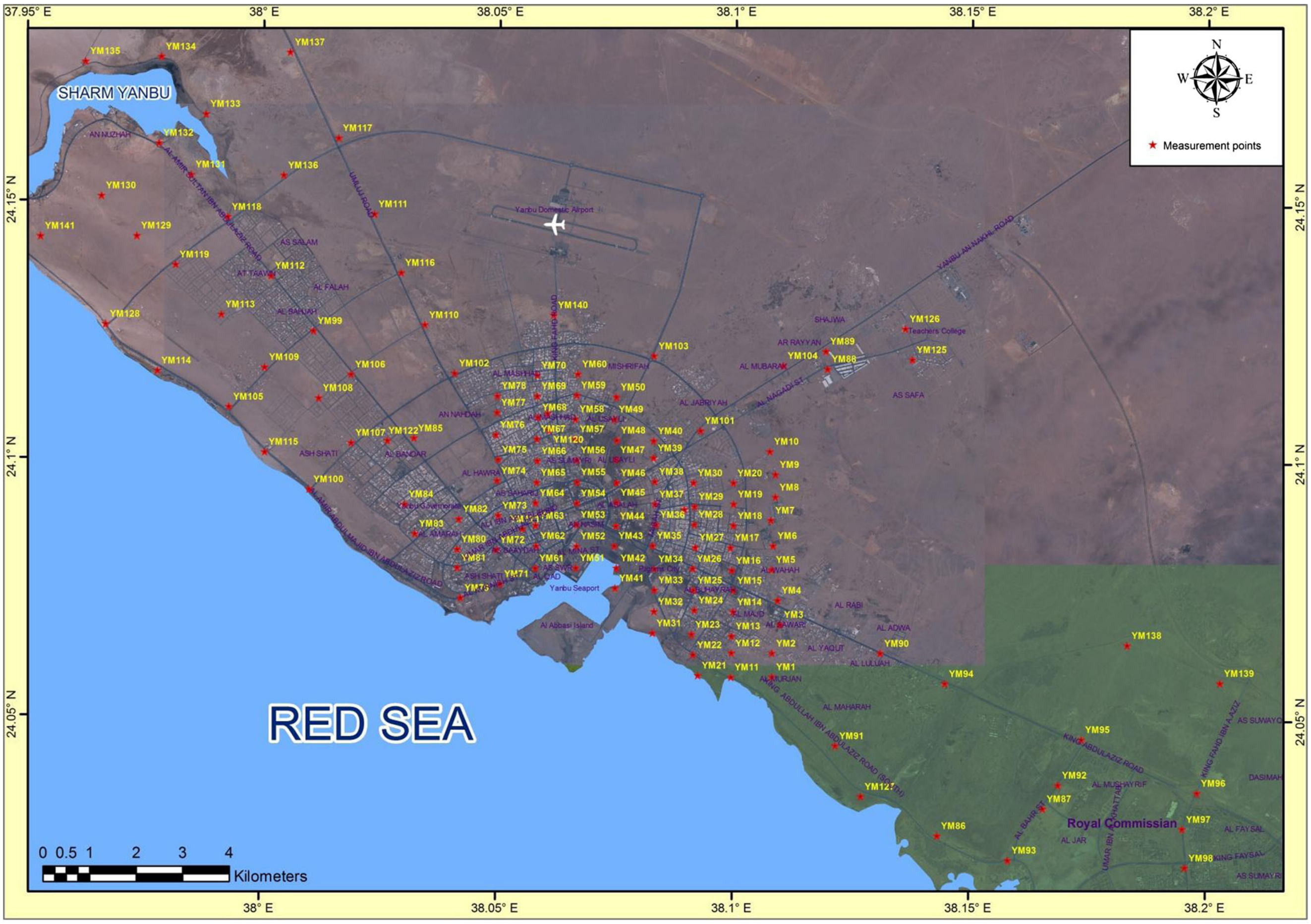


Fig. 3 Microtremor measurement points in the Yanbu area

Criteria for reliability of results

The SESAME project recommended several criteria for reliability of results as follows:

$$f_{0>}\ 10\ (\ I_{\mathrm{w}}$$

where I_w is window length.

According to this condition, at the frequency of interest, there are at least ten significant cycles in each window. Although not mandatory, but if the data allows, it is always fruitful to check whether a more stringent condition (f_0>20/I_w) can be fulfilled, which allows at least ten significant cycles for frequencies half the peak frequency and thus enhances reliability of the whole peak.

According to this condition, a large number of windows are needed. The total number of significant cycles, $n_c = I_w \cdot f_0$, is larger than 200 (which means, for instance, for a peak of 1 Hz, there are at least 20 windows of 10 s each or, for a peak of 0.5 Hz, ten windows of 40 s each). In case no window selection is considered, all transients are taken into account.

$$\sigma A(f) < 2 \quad \text{for } 0.5f_0 < f < 2f_0 \quad \text{if } f_0 > 0.5 \text{ Hz}$$

or

$$\sigma A(f) < 3 \quad \text{for } 0.5f_0 < f < 2f_0 \quad \text{if } f_0 < 0.5 \text{ Hz}$$

This condition takes into account an acceptably low level of scattering between all windows.

Criteria for a clear H/V peak

According to the SESAME guidelines, at least five of the following criteria must be achieved for the clarity of H/V peaks:

$$\exists\ f^{-} \in \left[\frac{f_0}{4}, f_0\right] | A_{H\ V}(f^{-}) < A_0\ 2$$

Table 1 Characteristics of the sites of the microtremor measurements in the study area for the second period, 2012

Site code	Latitude	Longitude	Date	Start time	End time	Duration	Sensor type	Sampling frequency
YM-86	24.02748	38.14337	27 Mar 2012	11:45	12:32	50	T.C.	100
YM-87	24.03285	38.16567	27 Mar 2012	10:17	11:01	40	T.C.	100
YM-88	24.11808	38.11967	27 Mar 2012	15:20	16:25	65	T.C.	100
YM-89	24.12153	38.11933	27 Mar 2012	13:40	14:20	40	T.C.	100
YM-90	24.0629	38.13117	27 Mar 2012	13:24	14:24	60	T.C.	100
YM-91	24.04492	38.12175	27 Mar 2012	12:05	12:45	40	T.C.	100
YM-92	24.03747	38.16887	27 Mar 2012	09:50	10:30	40	T.C.	100
YM-93	24.02285	38.15833	27 Mar 2012	10:55	11:35	40	T.C.	100
YM-94	24.05707	38.14487	27 Mar 2012	13:25	14:05	40	T.C.	100
YM-95	24.04637	38.17375	27 Mar 2012	08:50	09:42	50	T.C.	100
YM-96	24.03605	38.19825	27 Mar 2012	06:45	07:25	40	T.C.	100
YM-97	24.02902	38.19518	27 Mar 2012	07:00	07:40	40	T.C.	100
YM-98	24.02153	38.19572	27 Mar 2012	08:35	09:15	50	T.C.	100
YM-99	24.1249	38.0109	28 Mar 2012	05:30	06:18	50	T.C.	100
YM-100	24.09413	38.01017	28 Mar 2012	07:20	08:13	50	T.C.	100
YM-101	24.10597	38.09288	28 Mar 2012	11:50	12:37	45	T.C.	100
YM-102	24.1168	38.04083	28 Mar 2012	09:45	10:17	32	T.C.	100
YM-103	24.12042	38.083	28 Mar 2012	09:20	10:02	40	T.C.	100
YM-104	24.11867	38.11033	28 Mar 2012	12:05	12:26	25	T.C.	100
YM-105	24.1101	37.9931	28 Mar 2012	07:45	08:25	40	T.C.	100
YM-106	24.11647	38.01888	28 Mar 2012	05:45	06:18	40	T.C.	100
YM-107	24.1032	38.019	3 Apr 2012	18:29	19:09	40	T.C.	100
YM-108	24.11188	38.01207	3 Apr 2012	19:35	20:15	40	T.C.	100
YM-109	24.11777	38.0006	4 Apr 2012	20:45	21:25	40	T.C.	100
YM-110	24.12618	38.03447	4 Apr 2012	14:10	14:50	40	T.C.	100
YM-111	24.14765	38.02365	4 Apr 2012	15:10	15:50	40	T.C.	100
YM-112	24.13558	38.00182	4 Apr 2012	17:47	18:30	40	T.C.	100
YM-113	24.128	37.99137	4 Apr 2012	19:55	20:35	40	T.C.	100
YM-114	24.117	37.97792	4 Apr 2012	21:05	21:45	40	T.C.	100
YM-115	24.10133	38.00072	4 Apr 2012	22:05	22:45	40	T.C.	100
YM-116	24.13633	38.02935	4 Apr 2012	14:10	14:50	40	T.C.	100
YM-117	24.16242	38.01598	4 Apr 2012	15:15	15:55	40	T.C.	100
YM-118	24.14695	37.9926	4 Apr 2012	16:26	17:05	40	T.C.	100
YM-119	24.13765	37.98162	4 Apr 2012	19:25	20:05	40	T.C.	100
YM-120	24.1059	38.06088	26 Mar 2012	08:50	09:30	40	T.C.	100
YM-121	24.08662	38.0553	26 Mar 2012	10:20	11:07	40	T.C.	100
YM-122	24.10367	38.02665	26 Mar 2012	11:50	12:34	40	T.C.	100
YM-123	24.10912	38.06053	26 Mar 2012	13:35	14:15	40	T.C.	100
YM-124	24.09062	38.0896	26 Mar 2012	14:15	14:55	40	T.C.	100
YM-125	24.11997	38.13762	26 Mar 2012	15:30	16:10	40	T.C.	100
YM-126	24.12598	38.1361	26 Mar 2012	15:55	16:35	40	T.C.	100
YM-127	24.03506	38.12719	29 Mar 2012	15:05	15:45	40	T.C.	100
YM-128	24.12601	37.96688	29 Mar 2012	16:00	16:40	40	T.C.	100
YM-129	24.14318	37.97337	29 Mar 2012	16:55	17:35	40	T.C.	100
YM-130	24.15094	37.96586	29 Mar 2012	17:45	18:30	40	T.C.	100
YM-131	24.15514	37.98482	29 Mar 2012	19:00	19:40	40	T.C.	100
YM-132	24.16125	37.97795	29 Mar 2012	19:55	20:35	40	T.C.	100
YM-133	24.16697	37.98787	29 Mar 2012	20:50	21:30	40	T.C.	100

Table 1 (continued)

Site code	Latitude	Longitude	Date	Start time	End time	Duration	Sensor type	Sampling frequency
YM-134	24.17803	37.97833	29 Mar 2012	21:45	22:30	40	T.C.	100
YM-135	24.17702	37.9623	30 Mar 2012	14:45	15:30	40	T.C.	100
YM-136	24.15512	38.00439	30 Mar 2012	15:45	16:30	40	T.C.	100
YM-137	24.17904	38.00562	30 Mar 2012	16:50	17:30	40	T.C.	100
YM-138	24.0647	38.18338	30 Mar 2012	17:55	18:35	40	T.C.	100
YM-139	24.0574	38.20301	30 Mar 2012	19:00	19:40	40	T.C.	100
YM-140	24.12826	38.06167	30 Mar 2012	19:55	20:35	40	T.C.	100
YM-141	24.143	37.953	30 Mar 2012	20:45	21:30	40	T.C.	100

T.C. Trillium compact seismometer (Nanometrics Inc.)

One frequency, f^{-}, should be lying between $f_0/4$ and f_0, such as $A_0/AH/V\,(f^{-})>2$.

$$\exists\ f^{+}\ \in[f_0, 4f_0]\ |A_{H\ V}(f^{+}) < A_0\ 2$$

Another frequency, f^{+}, should be lying between f_0 and $4f_0$, such as $A_0/A_{H/V}\,(f^{+})>2\ A_0>2$.

$$f_{\text{peak}}[A_{H\ V}(f) \pm \sigma_A(f)] = f_0 \pm 5\ \%$$

The peak should appear at the same frequency (within a percentage ±5 %) on the H/V curves corresponding to the mean ±1 standard deviation.

$$\sigma f < \varepsilon(f_0)$$

σf should be lower than the frequency-dependent threshold $\varepsilon\,(f_0)$, as in Table 2.

$$\sigma A\quad (f_0) < \theta(f_0)$$

$\sigma_A(f_0)$ should be lower than the frequency-dependent threshold $\theta\,(f_0)$, as in Table 2.

where

I_w Window length
n_w Number of windows selected for the average H/V curve
n_c $I_w \cdot n_w \cdot f_0$ is the number of significant cycles
f Current frequency
f_{sensor} Cutoff frequency
f_0 H/V peak frequency
σ_f Standard deviation of H/V peak frequency ($f_0 \pm \sigma_f$)
$\varepsilon_{(f_0)}$ Threshold value for the stability condition $\sigma_f < \varepsilon(f_0)$
A_0 H/V peak amplitude at frequency f_0
$A_{H/V(f)}$ H/V curve amplitude at frequency f
f^{-} Frequency between $f_0/4$ and f_0 for which $A_{H/V}(f^{-}) < A_0/2$
f^{+} Frequency between f_0 and $4f_0$ for which $A_{H/V}(f^{+}) < A_0/2$
$\sigma_A(f)$ "Standard deviation" of $A_{H/V}(f)$; $\sigma_A(f)$ is the factor by which the mean $A_{H/V}(f)$ curve should be multiplied or divided
$\sigma_{\log H/V}(f)$ Standard deviation of the log $A_{H/V}(f)$ curve
$\sigma_{\log H/V}(f)$ Absolute value which should be added to or subtracted from the mean $\log_{A_{H\ V}}(f)$ curve
$\theta_{(f_0)}$ Threshold value for the stability condition $\sigma_A(f) < \theta_{(f_0)}$
$V_{s,\ av}$ Average S-wave velocity of the total deposits
$V_{s,\ surf}$ S-wave velocity of the surface layer
H Depth to bedrock
$H_{\min}$ Lower-bound estimate of h

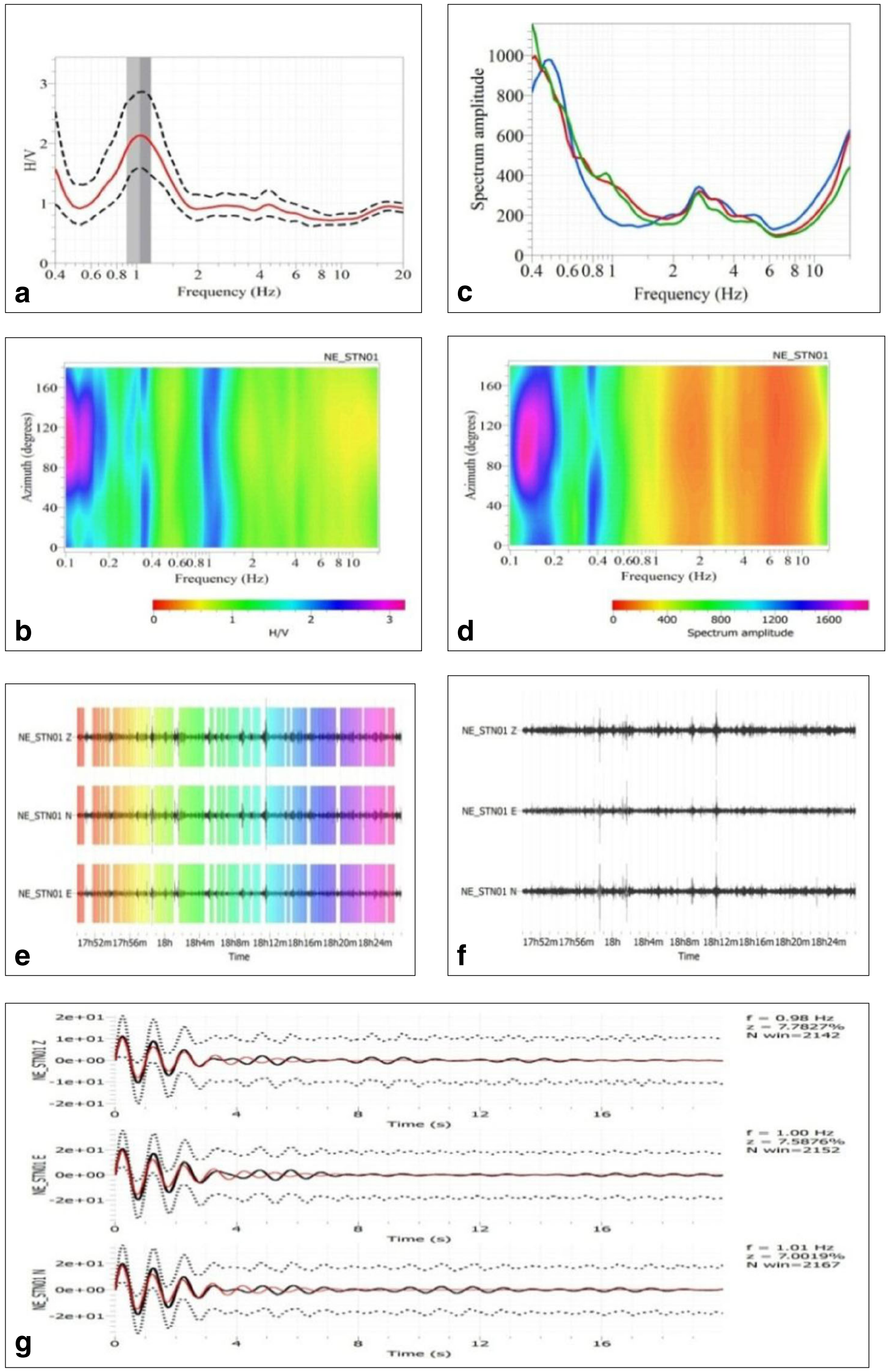
Criteria for H/V industrial origin peaks

According to SESAME (2004), in urban environments, H/V curves exhibit local narrow peaks or troughs. In most cases, such peaks or troughs related to some kind of machinery are recognized by the following general characteristics:

- They may exist over a significant area up to a distance of several kilometers from their source in the same localities.
- 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 three components, as seen in Fig. 4.

Table 2 Threshold values for σf and $\sigma A\ (f_0)$

Frequency range (Hz)	<0.2	0.2–0.5	0.5–1.0	1.0–2.0	>2.0
$\varepsilon(f_0)$ (Hz)	$0.25f_0$	$0.20f_0$	$0.15f_0$	$0.10f_0$	$0.05f_0$
$\theta(f_0)$ for $\sigma_A(f_0)$	3.0	2.5	2.0	1.78	1.58
Log $\theta(f_0)$ for $\sigma_{\log H/V}(f_0)$	0.48	0.40	0.30	0.25	0.20



a- H/V spectral ratio. b- The H/V rotation. c- Spectral amplitude.
d- Spectrum rotate. e- Number of windows. f- Wave form.
g- Damping test for the peak amplitude.

Fig. 4 Analysis of microtremor at YM-112 measuring point

Table 3 Results of the second period of microtremor measurements

Site code	No. of samples	No. of windows (n_w)	Window length (I_w)	No. of cycles (n_c)	*H*/*V* peak amplitude (A_0)	Standard deviation $\sigma_A(f)$	Fundamental frequency (f_0)	Standard deviation (σ_f)	Remarks
YM-86	282,000	90	15	229.5	3	0.96	0.17	0.03	Natural
YM-87	264,000	69	25	2,794.5	1.88	2.04	1.62	0.02	Natural
YM-88	390,000	56	25	350	3.43	2.2	0.25	0.02	Natural
YM-89	164,282	23	25	287.5	2.24	1.67	0.5	0.07	Natural
YM-90	338,502	70	20	224	3.1	0.55	0.16	0.03	Natural
YM-91	240,000	38	25	475	5	1.42	0.5	0.06	Natural
YM-92	240,000	30	25	1,050	5.1	1.44	1.4	0.2	Natural
YM-93	240,000	50	20	1,590	7.6	1.44	1.59	0.27	Natural
YM-94	240,000	22	25	280.5	2.3	0.92	0.51	0.17	Natural
YM-95	312,000	77	25	1,193.5	3.12	1.47	0.62	0.09	Natural
YM-96	217,796	66	25	1,006.5	2.71	1.4	0.61	0.1	Natural
YM-97	240,000	56	25	784	2.39	1.36	0.56	0.08	Natural
YM-98	240,000	74	25	943.5	2.4	1.52	0.51	0.055	Natural
YM-99	288,000	49	25	1,310.8	2.21	1.26	1.07	0.16	Natural
YM-100	318,000	12	25	498	4.3	1.46	1.66	0.42	Natural
YM-101	216,020	15	25	555	3.85	1.51	1.48	0.23	Natural
YM-102	192,000	12	25	302.7	3.26	1.4	1.009	0.34	Natural
YM-103	252,000	19	25	760	2	1.22	1.6	1.59	Natural
YM-104	126,000	38	25	361	1.8	1.49	0.38	0.21	Natural
YM-105	240,000	17	25	1,326	3.12	5.24	1.32	0.71	Natural
YM-106	198,000	20	25	1,200	2.4	2.43	1.14	0.16	Natural
YM-107	240,000	20	25	270	2.2	1.35	1.54	0.06	Natural
YM-108	240,000	52	25	2,418	2.75	1.25	1.86	0.34	Natural
YM-109	214,588	48	20	278.4	4	0.49	1.35	0.32	Natural
YM-110	196,837	15	25	387.38	4.91	2.31	1.033	0.003	Natural
YM-111	240,000	14	25	560	2.4	1.43	1.6	1.66	Natural
YM-112	257,603	68	25	1,751	2.1	1.23	1.03	0.14	Natural
YM-113	240,000	76	20	212.8	2.04	0.83	1.45	0.002	Natural
YM-114	183,209	55	15	247.5	2.4	0.94	1.6	0.05	Natural
YM-115	240,000	17	25	709.75	3	0.85	2.36	0.526	Natural
YM-116	240,000	10	25	385	2.2	1.47	1.54	1.54	Natural
YM-117	240,000	42	25	1,711.5	5.4	2.88	1.63	0.11	Natural
YM-118	103,537	15	15	247.5	3	1.33	1.1	0.25	Natural
YM-119	240,000	39	25	975	2.05	1.34	1.35	0.13	Natural
YM-120	240,000	14	25	266	3.8	1.35	0.76	0.105	Natural
YM-121	282,000	21	20	231	3.77	1.75	0.55	0.07	Natural
YM-122	264,000	91	20	1,110.2	1.99	1.41	0.61	0.1	Natural
YM-123	81,200	25	15	371.25	1	0.3	2.97	0.05	Natural
YM-124	33,690	17	15	211.65	3.5	1.68	0.83	0.159	Natural
YM-125	215,637	29	10	481.4	2.1	1.19	1.66	0.25	Natural
YM-126	240,000	95	20	304	2.4	0.83	3.24	0.31	Natural
YM-127	390,000	88	25	286	5.5	1.42	0.13	0.09	Natural
YM-128	164,282	20	25	500	3.5	1.67	1.31	0.12	Natural
YM-129	192,000	22	15	495	3.4	1.65	1.5	0.18	Natural
YM-130	264,000	42	20	336	4.3	1.47	1.44	0.08	Natural
YM-131	240,000	12	20	264	4.2	1.39	1.1	0.28	Natural
YM-132	318,000	33	25	412.5	5	1.42	0.5	0.05	Natural
YM-133	288,000	17	25	255	4.5	1.4	0.6	0.09	Natural

Table 3 (continued)

Site code	No. of samples	No. of windows (n_w)	Window length (I_w)	No. of cycles (n_c)	*H*/*V* peak amplitude (A_0)	Standard deviation $\sigma_A(f)$	Fundamental frequency (f_0)	Standard deviation (σ_f)	Remarks
YM-134	264,000	85	15	637.5	5.2	1.61	0.5	0.16	Natural
YM-135	390,000	90	15	540	5.5	1.53	0.4	0.05	Natural
YM-136	164,282	21	25	735	3.5	1.7	1.4	1.38	Natural
YM-137	318,000	10	20	300	3.5	1.69	1.5	1.03	Natural
YM-138	81,200	20	15	510	2.1	1.2	1.7	0.3	Natural
YM-139	288,000	19	25	950	1.6	0.89	2	0.2	Natural
YM-140	240,000	20	15	630	2	0.99	2.1	0.06	Natural
YM-141	280,000	20	15	260	4.2	1.41	1.41	0.09	Natural

- Reprocessing with less and less smoothing: in the case of industrial origin, the *H*/*V* peak should become sharper and sharper, which is not the case for a site effect peak linked to soil characteristics.
- 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).
- Another very effective check is to apply the random decrement 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

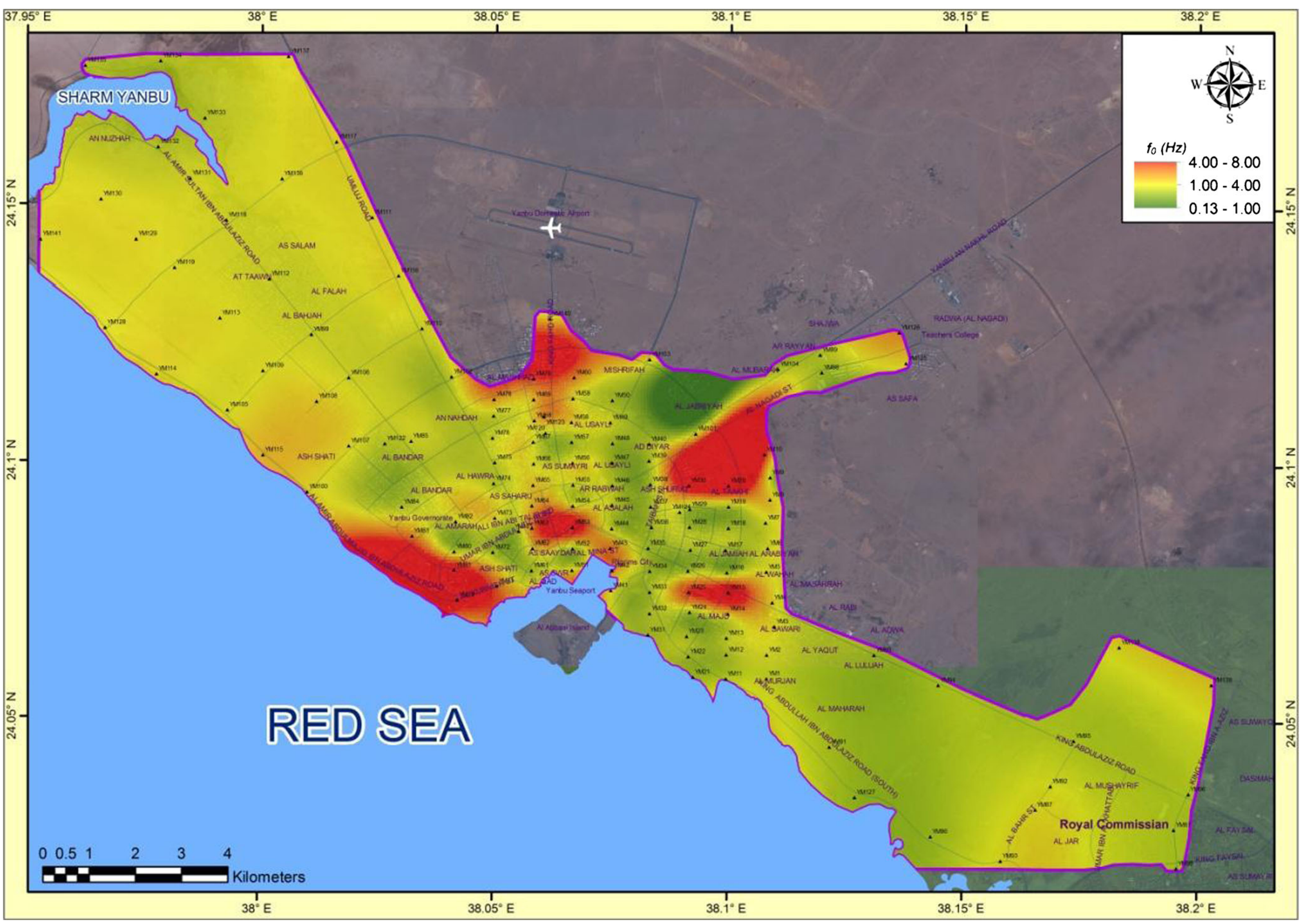


Fig. 5 Distribution of the fundamental frequencies (f_0) throughout Yanbu City

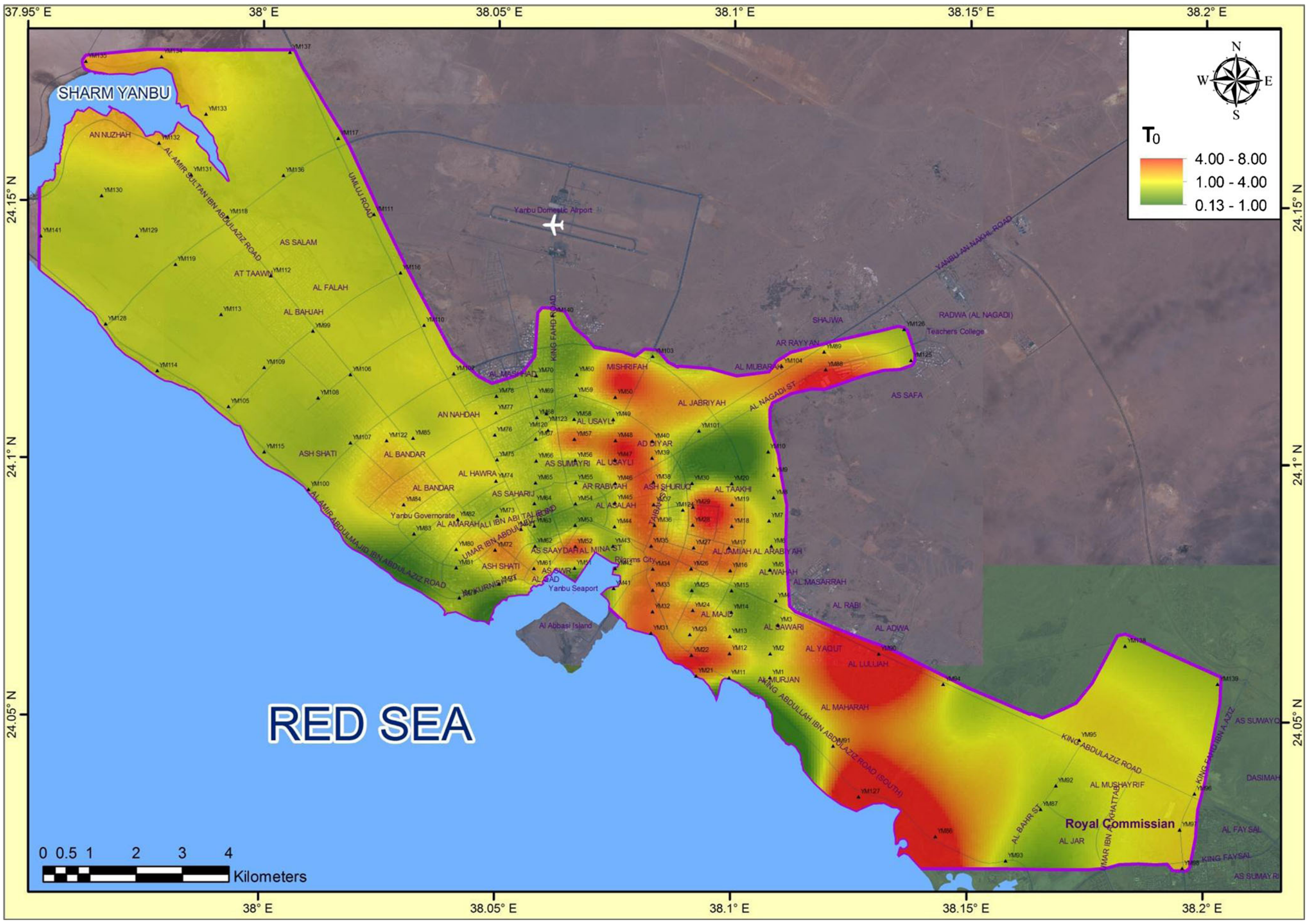


Fig. 6 Distribution of the predominant period (T_0) throughout Yanbu City

(below 1 %), an anthropogenic origin may be assumed almost certainly, and the frequency should not be considered for interpretation purposes (Fig. 4).

At each site, the microtremor data file was divided into several time windows of 15–25 s for spectral calculations (Fig. 4). This time window is proven sufficiently long to provide stable results. The selected time windows were Fourier transformed using cosine tapering before transformation. Then, the spectra were smoothed with a Konno and Ohmachi algorithm (Konno and Ohmachi 1998). After data smoothing, the spectra of EW and NS channels at a site were divided by the spectra of the vertical channel (Nakamura estimate) in order to obtain spectral ratios. The geometrical average of the two component ratios is the site amplification function. However, in most cases, due to the influence of sources like dense population, high traffic, and industrial activities, the resonance frequency cannot be directly identified from microtremor spectra.

Figure 4 presents the result of microtremor measurements for YM-112. As shown, the dominant peak is near 1.03 Hz, while the observed amplification factor is about 2.1. The solid line represents the average value. Dominant frequencies and amplifications from all measurement sites across Yanbu City are summarized in Table 3 for the second period of microtremor measurements.

Figures 5 and 6 have been created based on the results of measured data and the distribution of the fundamental frequency and predominant period across Yanbu City. The site response functions of the soil sites exhibit peaks at dominant frequencies between 0.13 and 7.9 Hz. The lower resonance frequencies (ranging from 0.13 to 1.0 Hz) are optioned at sites in the coastal zone. On the other hand, the higher resonance frequencies (ranging from 4.0 to 7.9 Hz) are illustrated at some sites in the central zone, while the intermediate values of frequencies (1.0–4.0 Hz) are distributed in the eastern zone of Yanbu City towards the mountainous area.

The map of maximum amplification (Fig. 7) reflects the variation in the impedance values between the bedrock and the overlying sediments. The higher amplifications (greater than 3) are attained at the coastal zone with relatively thick sediments, while the lower amplifications cover the rest of Yanbu city with thin section of sediments.

Based on the analyzed data, the study area can be divided into three zones as follows: (1) The resonance frequency

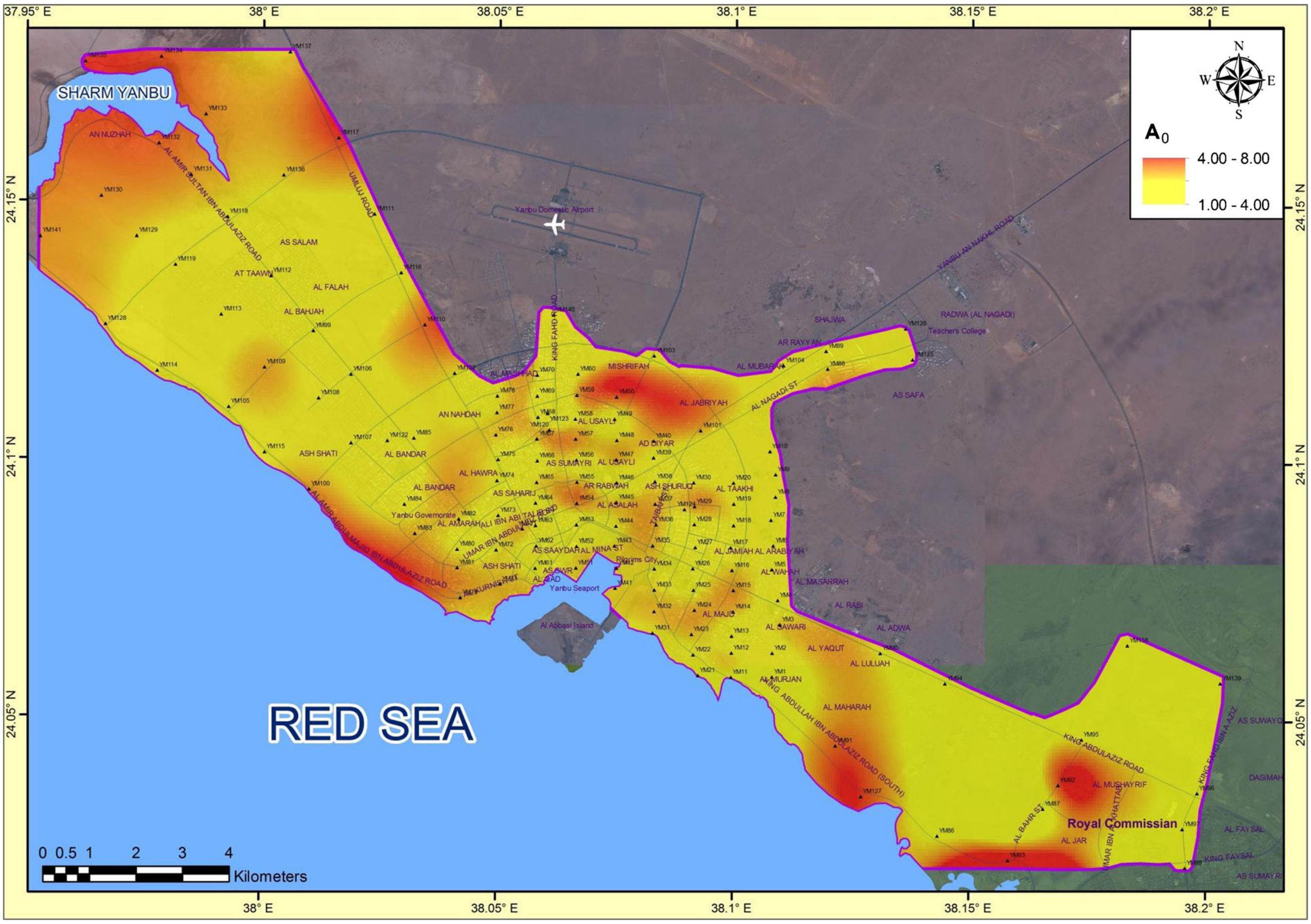


Fig. 7 Distribution of the *H*/*V* amplitude (A_0) throughout Yanbu City

ranges from 0.13 to 1.0 Hz; (2) the resonance frequency lies between 1.0 and 4.0 Hz; and (3) the resonance frequency ranges from 4.0 to 7.6 Hz.

Discussions and conclusions

Microtremor resonance frequency and spectral amplitude ratios have been calculated and applied as tools to perform earthquake hazard microzoning in densely populated areas of Yanbu City. Microtremor measurements were conducted at 56 points in the present study and integrated with those of Fnais et al. (2010a, b) to produce an overall map of Yanbu City and its urban expansion zones in terms of the fundamental resonance frequency (f_0) and the associated amplification factor. The results of the present study are in agreement with those of Fnais et al. (2010a, b). Accordingly, the obtained horizontal-to-vertical spectral ratio (HVSR) from the Nakamura technique is valuable to determine the local site response effects for the urban areas.

Furthermore, the fundamental resonance frequencies determined in the present study are correlated well with the thickness of the sediments in Yanbu City. The sediments are thick in the coastal zone (where site response spectra exhibit peaks at 0.13–1.0 Hz), while they are thin in the eastern zone of the city (predominant frequency of site response at 1.0–4.0 Hz). 'Moreover, the higher values from 4.0 to 7.6 Hz are recorded at some selected sites in the central zone of the city. This behavior indicates that there are horizontal variations in the thickness and type of sediments.

The Yanbu urban area illustrates the fundamental resonance frequencies in the range from 0.13 to 7.6 Hz considering the relationship between the height of a building and its fundamental period of vibration which can be expressed as T=(number of stories)/10. According to Parolai et al. (2006), it can be expected that in this urban area, the natural frequency of the soil matches the frequency of buildings with ≥1 story. On the other hand, Al-Haddad et al. (2001) indicated that site response frequencies less than 10 Hz are of engineering interest for one-story reinforced concrete structures. Yanbu City attains fundamental frequencies in the range between 0.13 and 4.0 Hz. This means that in the Yanbu urban area, the natural frequency of the soil matches the frequency of buildings with ≥3 stories. Most of the urban area characterized by low-rise buildings and the frequency of the soil cover can be close to their fundamental frequency of vibration. When the fundamental frequency of vibration of a building is higher than the fundamental frequency of soil f_0, it may, however, be close to the frequency of higher modes. Higher modes are expected at frequencies $f_n=(2n+1)f_0$ where $n=1, 2, 3\ldots$, and f_0 is the fundamental frequency. The H/V spectral ratio provides the lower frequency threshold from which ground motion amplification due to soft soil can be expected. Therefore, it cannot be excluded that in the Yanbu urban area, such soil amplification of ground motions may also occur at higher mode frequencies close to the fundamental frequency of vibration of low-rise buildings, even if it is smaller than that at the fundamental frequency of the sedimentary cover.

Site amplification for Yanbu City indicates that soils can amplify ground motion by as much as 3.0 times its bedrock level. This is applied for different soil classes, where all sites have resonance frequencies of engineering interest. The relation between resonance frequency and amplification represents the alarming condition that soil having resonance frequencies of interest can amplify earthquake ground motion as much as 3.0 times. It is indicated that the amplification is generally decreasing with increasing frequency. The obtained values of amplification are in agreement with the surface geology of the study area. Higher H/V values occupy the coastal zone of Yanbu City due to the presence of coastal deposits and sabkhah sediments. The lower values are encountered in the eastern zone of the city. This variation in the H/V values also reflects variation in sediment thickness.

The eastern zone of Yanbu City has a frequency range from 1.0 to 4.0, which means that these values correlated well with buildings that have three to ten stories. Accordingly, these buildings suffer the greatest damage from earthquake ground motion at a frequency close or equal to its natural frequency, and this is what already happened in Yanbu City where buildings with three and four stories were damaged in the eastern zone of Yanbu due to the Al-Ays earthquake swarm of May 2009

In the coastal zone, the frequency values (0.13–1.0 Hz) correlate with the high-rise buildings that suffer damage from earthquake ground motion of distant earthquakes. The higher values of frequency (4.0–7.6 Hz) that were distributed sparsely in the central zone of Yanbu City are correlated with buildings with one and two stories. This means that these buildings could suffer greater damage from local or nearby earthquakes.

Fnais et al. (2010a, b) simulated the ground motions of the Al-Ays earthquake (19 May 2009), in terms of PGA, PGV, and PGD at different sites in Yanbu City. They notice that the fundamental period of ground motions ranges from 0.1 to 0.3 s. This corresponds to buildings with one to three floors. Consequently, some of the buildings with one to three floors in Yanbu showed slight damage due to the Al-Ays earthquake. The fundamental frequencies for Yanbu City are a prerequisite to get knowledge about future earthquake scenarios in the area. These results can greatly support the government in setting priorities in managing land use, enforcing building codes, conducting programs for reducing the vulnerability of existing structures, and planning for emergency response and long-term recovery.

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