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ORIGINAL PAPER

Evaluation of site response characteristics of King Abdulaziz City for Science and Technology, Saudi Arabia using microtremors and geotechnical data

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Abstract Microtremor measurements become one of the widely accepted tools to evaluate the site response characteristics since the last two decades. These measurements have been conducted at four sites inside King Abdulaziz City for Science and Technology (KACST), Riyadh city, Saudi Arabia to estimate the resonance frequency and the associated amplitude of sediments. Microtremor measurements have been recorded for 24 h with a sampling frequency of 100 Hz in the range from 0.2 to 25 Hz band-pass filter. Origin of the identified peaks has been tested. The estimated peaks are correlated with borehole geotechnical data: (1) the first peak with an average frequency of 8.25 Hz that reflects the impedance contrast between the uppermost surface soil and the underlying completely weathered limestone and (2) the second peak of 1.43 Hz which corresponds to the impedance contrast between the completely weathered limestone and the underlying limestone rocks. In addition, the relation between sediment thickness and resonance frequency has been assessed. Based on the results of this study, it can be stated that microtremor measurements are capable to estimate thickness of sedimentary overburden. These results will support for seismic safety in case of civil engineering constructs in KACST area.

Keywords Resonance frequency · Amplification · Microtremors · Borehole data · Riyadh city

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Introduction

The local geologic effects on the ground motion have been assessed a long time ago where the soft and loose soils amplify the ground shaking more intensely than that of the hard rock at the same distance from the same earthquake magnitude. Bonnefoy-Claudet et al. (2006a, b) stated that horizontal-to-vertical spectral ratio (HVSR) is mainly controlled by the ellipticity of Rayleigh waves. Local amplification of the ground is governed by the soft surface layer, which leads to the seismic energy trapping, due to the impedance contrast between the soft surface soils and the underlying bedrock (Rao et al. 2011).

Nakamura (1989) updated the HVSR technique of Nogoshi and Igarashi (1970) to estimate the site response characteristics. This technique has been widely tested experimentally and theoretically at several locations by several researchers all over the world (Ohmachi et al. 1991; Lermo and Chavez-Garcia 1993, 1994; Lachet and Bard 1994; Field and Jacob 1993; Malagnini et al. 1996; Seekins et al. 1996; Teves-Costa Matias and Bard 1996; Theodulidis et al. 1996; Konno and Ohmachi 1998; Mucciarelli 1998). Results of Nakamura's technique support such use of microtremor measurements for estimating the site response of surface deposits. Recently, Fnais et al. (2010), Al-Yousef et al. (2014), and Al-Malki et al. (2014) estimated site response for Yanbu and Dammam

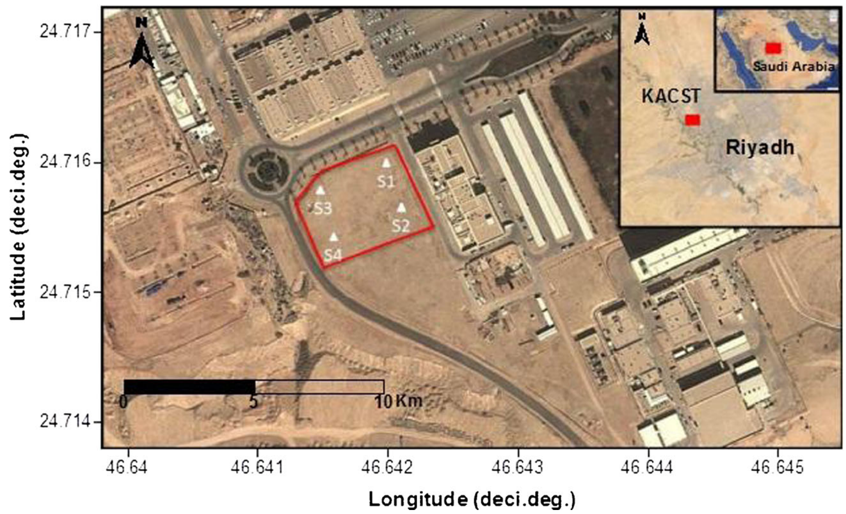


Fig. 1 A photo taken from "Google" showing the studied site including the measurement points

cities in Saudi Arabia, respectively, using the HVSR technique.

The site of interest is located inside King Abdulaziz City for Science and Technology (KACST) to the north of Riyadh city (Fig. 1). Due to the increase of urban expansion of KACST, the evaluation of site response characteristics is an issue of utmost importance where a new site has been recently selected to be the location for a high-rise building within KACST. Accordingly, and due to the importance of this building, site response characteristics at this location have to be assessed.

Geological setting of KACST site

The surface geological setting of Riyadh region (Fig. 2) consists of fluvial or aeolian clay, silt, sand, and gravel deposits (Vaslet et al. 1991). These sediments include fluvial and

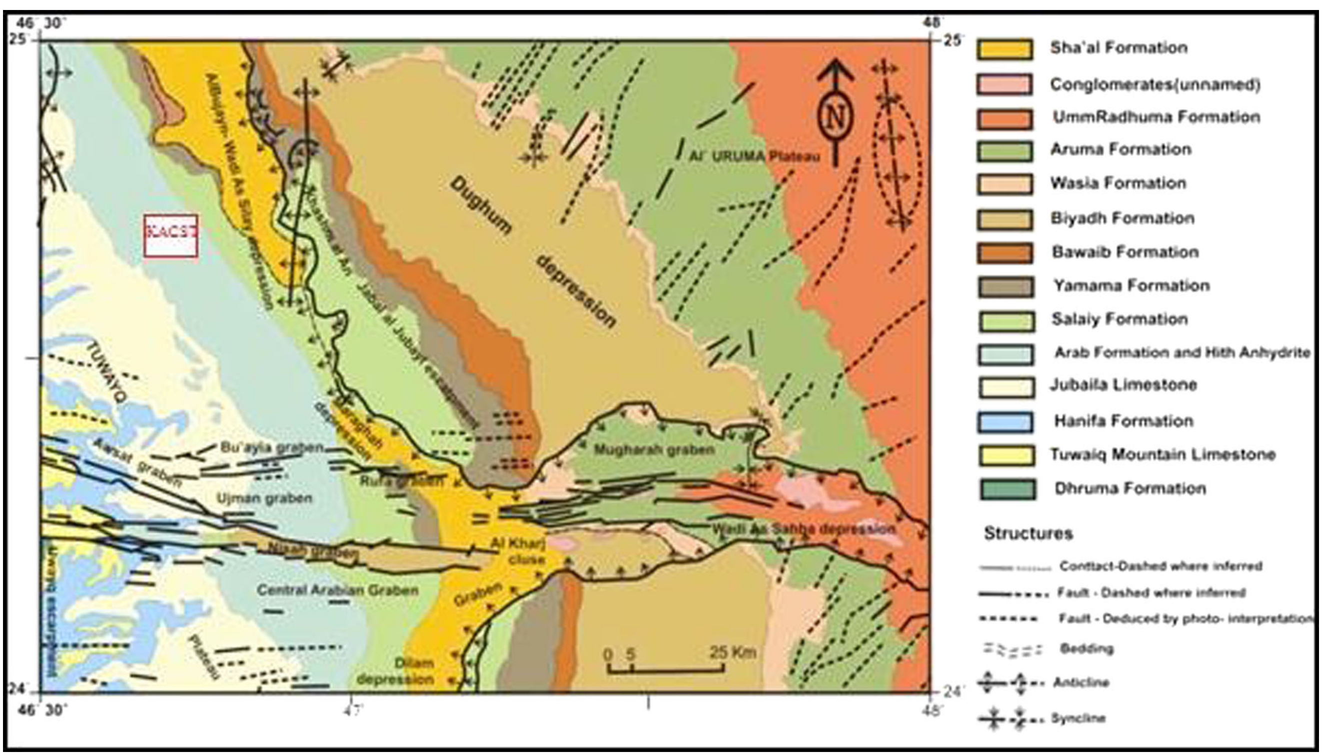


Fig 2 Geology of Riyadh City

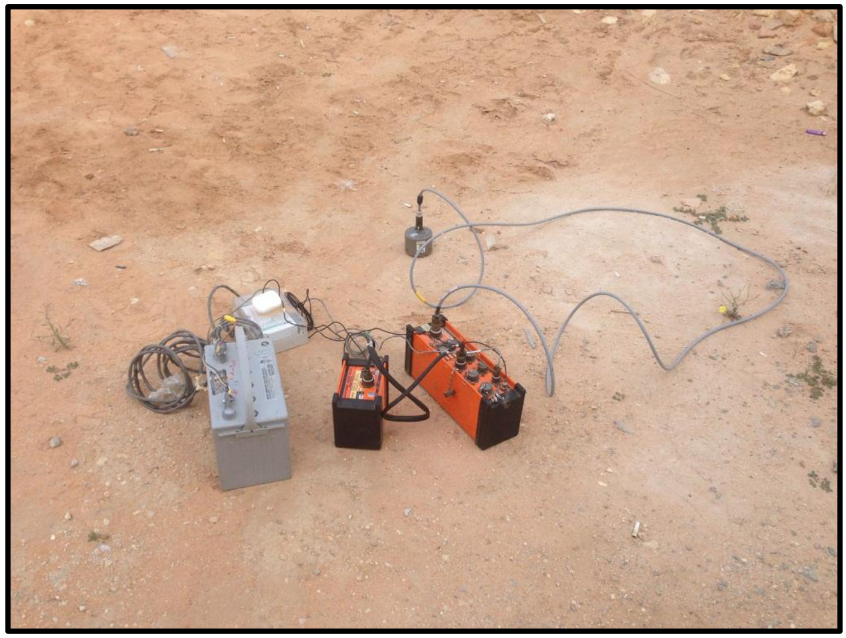


Fig. 3 Field measurements

lacustrine deposits overlain by variable amounts of wind-blown sand. While subsurface geology is composed of great thickness of shallow marine limestone with shale and clay intercalations. Local geologic section of KACST site is composed of three layers (Soil and Foundation Company 2007): (1) Silty clayey sand with gravel of brown, dense to very dense, dry to damp silty sand and gravel with an average thickness of 5.5 m. (2) Completely weathered limestone of very dense, dry to damp, creamy completely weathered limestone with varying thickness from 0.6 to 6.5 m. (3) Limestone of creamy moderately weathered and highly fractured limestone rock.

Data acquisition

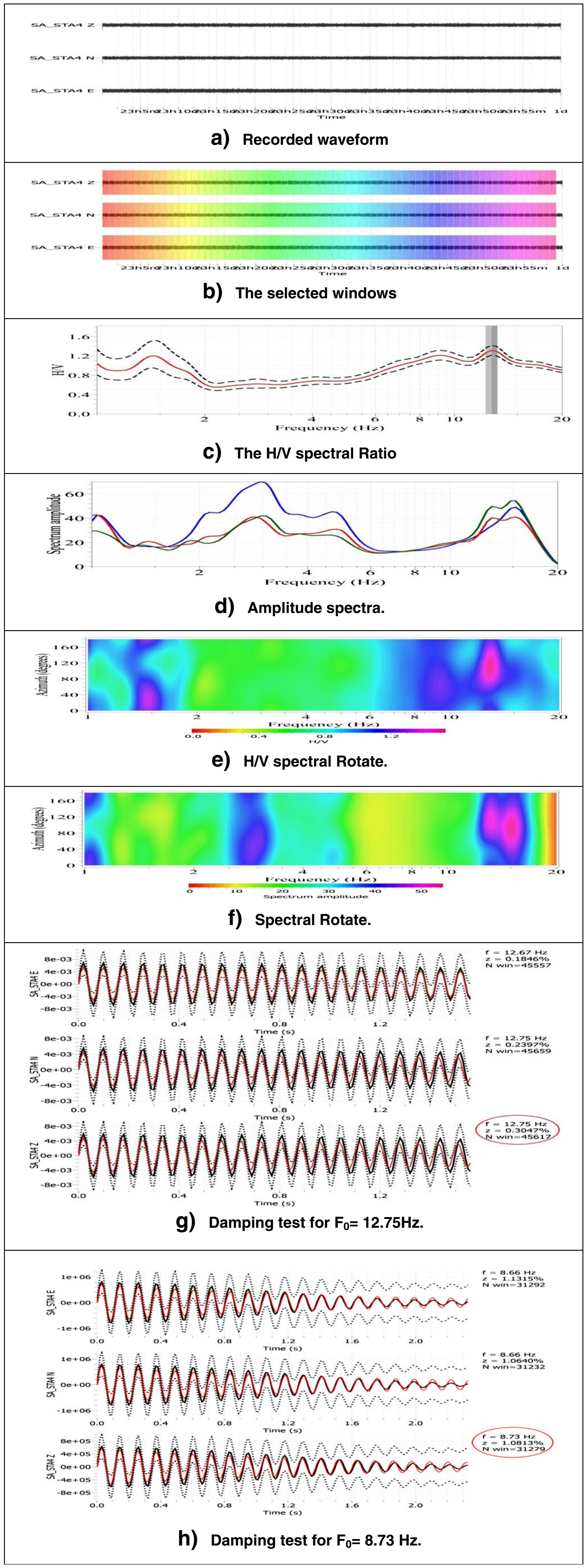
Based on the geological setting of KACST site where it is composed of limestone hard rocks, so the expected frequency peaks will be greater than 1 Hz. Furthermore, Sobaih et al. (2008) and Foti et al. (2011) used the accelerometers to estimate the dynamic characteristics of the surface soil on the ground motion from ambient noise measurements. Local site response at four sites at the selected location within KACST has been acquired using a Q330 instrument, which is a multi-channel, PC-based, digital seismic data system designed for site response for field investigations (Fig. 3). These measurements were recorded continuously for 24 h through a frequency range of 0.2–25 Hz band-pass filter with a sampling rate of 100 Hz.

Data processing and results

The collected data have been processed through the Geopsy software and according to SESAME (2004) and Al-Yousef et al. (2014) recommendations where microtremor data file was divided into several time windows of 50 s for spectral calculations. This time window is proven to be sufficiently long to provide stable results. The selected time windows were Fourier transformed using cosine tapering before transformation. The spectra were then smoothed with Konno and Ohmachi algorithm (Konno and Ohmachi 1998). After data smoothing, and in order to obtain spectral ratios, the spectra of EW and NS channel at a site were divided by the spectra of the

Table 1 Results of microtremor measurements

Site no.	Resonance frequency (f_r)	Natural period (T_0)	Amplification factor (A_0)
1	8.72	0.114	1.48
2	8.53	0.117	1.39
3	7.75	0.129	1.43
4	8.72	0.114	1.56


SA_STA4 Z
SA_STA4 N
SA_STA4 E
Time
a) Recorded waveform
b) The selected windows
H/V
Frequency (Hz)
c) The H/V spectral Ratio
Spectrum amplitude
d) Amplitude spectra.
Azimuth (degrees)
H/V
e) H/V spectral Rotate.
Spectrum amplitude
f) Spectral Rotate.
f = 12.67 Hz
z = 0.1846%
N win=45557
f = 12.75 Hz
z = 0.2397%
N win=45659
f = 12.75 Hz
z = 0.3047%
N win=45617
Time (s)
g) Damping test for F0= 12.75Hz.
f = 8.66 Hz
z = 1.1315%
N win=31292
f = 8.66 Hz
z = 1.0640%
N win=31232
f = 8.73 Hz
z = 1.0813%
N win=31279
h) Damping test for F0= 8.73 Hz.

◀ **Fig 4** Processing of microtremor measurements at site No. 4. **a** Recorded waveform. **b** The selected windows. **c** The H/V spectral ratio. **d** Amplitude spectra. **e** H/V spectral rotate. **f** Spectral rotate. **g** Damping test for f_0=12.75 Hz. **h** Damping test for f_0=8.73 Hz

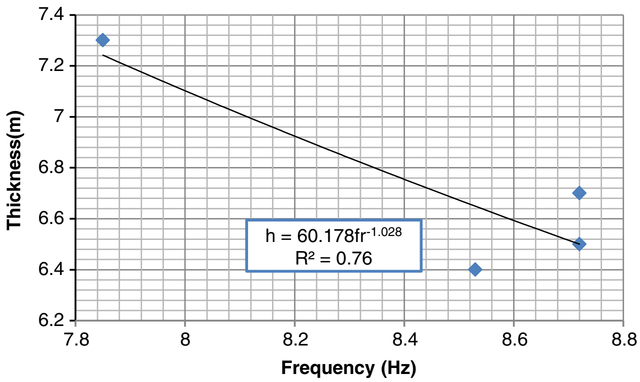


Fig. 5 Relationship between fundamental resonance frequencies calculated from H/V spectral ratio and sediment thickness from borehole data. The *solid line* is the fit to the data points

vertical channel (Nakamura estimate). The geometrical average of the two component ratios will be the site amplification function. Fundamental frequencies (f_r) and the corresponding amplifications (A_0) at the measuring sites are summarized in Table 1. Figure 4 illustrates the processing procedure for site no. 4 as a representative example for the proposed location.

Site no. 1 shows a fundamental frequency peak at 13.01 Hz and the corresponding amplification factor at 1.57. According to the abovementioned criteria, the HVSR curve is reliable. This peak has been tested to verify its origin whether it is natural or industrial by applying the damping test and amplitude spectra. It is indicated that this peak is of industrial origin, and consequently, this peak should not be considered in the interpretation. Another peak of natural origin was found at 8.72 Hz with amplitude of 1.34, which represents the effect of impedance contrast between the weathered limestone and the overlying sediments. There is a second peak that has been picked at 1.41 Hz with an amplitude of 1.25. This peak is of natural origin and illustrates the effect of impedance contrast between the weathered limestone and the underlying limestone rocks.

Site no. 2 illustrates a clear peak at 12.92 Hz associated with an amplitude of 1.52. The H/V spectral ratio curve is reliable. Damping value and amplitude spectra tests were used to check the origin of this peak where it was found to be of industrial origin and should not be considered in the interpretation. First peak of natural origin was identified at 8.53 Hz with an amplitude of 1.43, due to the effect of impedance contrast between the weathered limestone and the overlying sediments. While the second clear and natural peak was picked at 1.46 Hz with an amplitude of 1.3. This peak clarifies the effect of impedance contrast between the weathered limestone and the underlying limestone rocks.

Site no. 3 shows a clear peak at 12.79 Hz with an amplitude of 1.52. The HVSR spectral ratio curve is reliable. The origin of this peak is industrial and not be considered in the interpretation. It is noticed that the presence of clear peak at 7.85 Hz with an amplitude of 1.43 of natural origin reflects the effect of impedance contrast between the weathered limestone and the overlying sediments. Another peak of natural origin is recoded at a frequency of 1.41 Hz with an amplitude of 1.13, which indicates the effect of impedance contrast between the weathered limestone and the underlying limestone rocks.

Site no. 4 presents peak at 12.75 Hz and an amplification factor of 1.56 (Fig. 4). The H/V spectral ratio curve is reliable. Origin of this peak was tested and it is of industrial origin (Fig. 4g), so this peak should not be considered in the interpretation. There is another peak of natural origin at a frequency of 8.72 Hz with an amplitude of 1.4 (Fig. 4h) due to the effect of impedance contrast between the weathered limestone and the overlying sediments. In addition, third peak has been recorded at a frequency of 1.43 Hz with an amplitude of 1.36. This peak was found to be of natural origin that reflects the effect of impedance contrast between the weathered limestone and the underlying limestone rocks.

Sediment thickness and resonance frequency relationship

Several studies indicated that microtremor measurements can be used to estimate the sediment thickness (Ibs-von Seht and

Table 2 Soil profiles in boreholes

BH1		BH2		BH3		BH4	
Depth	Soil type	Depth	Soil type	Depth	Soil type	Depth	Soil type
0.0–6.8	Silty clayey sand with gravel	0.0–6.4	Silty clayey sand with gravel	0.0–7.3	Silty clayey sand with gravel	0.0–6.5	Silty clayey sand with gravel
6.8–8.0	Completely weathered limestone	6.4–8.0	Completely weathered limestone	7.3–8.0	Completely weathered limestone	6.5–8.0	Completely weathered limestone

Table 3 Geotechnical parameters of boreholes

Depth (m)	BH1			BH2			BH3			BH4		
	SPT N value	N_{60}	V_s (m/s)	SPT N value	N_{60}	V_s (m/s)	SPT N value	N_{60}	V_s (m/s)	SPT N value	N_{60}	V_s (m/s)
0.0	41	25	187	40	24	184	37	22	177	45	27	193
1.5	55	33	209	59	35	214	60	36	217	58	34	212
3.0	70	42	231	75	45	238	68	40	227	72	43	233
4.5	81	49	246	87	52	252	75	46	240	70	42	231
6.0	100	60	267	85	51	250	88	52	252	81	48	244
8.0	100	60	267	100	60	267	100	60	267	100	60	267

Wohlenberg 1999; Delgado et al. 2000; Parolai et al. 2002; Motamed et al. 2007; Abdel-Rahman et al. 2012). Of particular, Ibs-von Seht and Wohlenberg (1999) stated that the resonance frequency (f_r) of a soil layer is closely related to its thickness (h) as follows:

$$h = a f_r^{\,b} \tag{1}$$

According to the estimated f_r from microtremor measurements from the present study and sediment thickness from borehole data (Fig. 5), a new equation was obtained from the site:

$$h = 60.178\, f_r^{\,-1.028} \tag{2}$$

Borehole geotechnical data

Four geotechnical boreholes were logged at the proposed location with a maximum depth of 8.0 m (Table 2). The standard penetration test (SPT) has been performed every 1.5-m depth at each and every borehole according to the ASTM D1586 (Table 3). The measured SPT values in the field have been corrected for the following: (1) overburden pressure (C_N), (2) hammer energy (C_E), (3) borehole diameter (C_B), (4) presence or absence of liner (C_S), (5) rod length (C_R), (6) fines content (C_{fines}) (Seed et al. 1983; Skempton 1986; Sitharam et al. 2005) using the following equation:

$$\boldsymbol{N}_{60} = \boldsymbol{N} \times (\boldsymbol{C}_{\mathrm{N}} \times \boldsymbol{C}_{\mathrm{E}} \times \boldsymbol{C}_{\mathrm{B}} \times \boldsymbol{C}_{\mathrm{S}} \times \boldsymbol{C}_{\mathrm{R}} \times \boldsymbol{C}_{\mathrm{fines}}) \tag{3}$$

The calculated N_{60} values (Table 3 and Fig. 6) can be used to estimate the average shear wave velocity V_s for each layer using Anbazhagan and Sitharam (2006) equation for silty sand soil:

$$\boldsymbol{V}_s = 50(\boldsymbol{N}_{60})^{0.41} \tag{4}$$

Then, the derived V_s values were averaged for the sediment thickness at each borehole. The fundamental frequency at every borehole was estimated (Table 4) using the well-known relation:

$$\boldsymbol{f}_r = \frac{\boldsymbol{V}_s}{4\boldsymbol{h}} \tag{5}$$

Discussions and conclusions

Microtremor measurements have been recorded at four sites inside KACST for 24 h and in the frequency range of 0.2 to 25 Hz band-pass filter with a 100-Hz sampling rate. The origin of the identified peaks of resonance frequency has been tested to check whether it is natural or industrial. The industrial peaks are not to be taken in the interpretation.

Two peaks of natural origin are identified: (1) the first peak varies from 7.85 to 8.72 Hz. This peak clarifies the impedance contrast between the uppermost soil surface and the underlying completely weathered limestone. The large peak values are generally associated with sharp velocity contrasts and are likely to amplify the ground motion. (2) the second peak ranges between 1.41 and 1.46 Hz that correspond the impedance contrast between the completely weathered limestone and the underlying limestone rocks.

The characteristic site period (or site resonance frequency) which depends on the thickness (h) and shear wave velocity (V_s) of the soil represents a very useful indication of the period of vibration at which the most significant amplification can be expected.

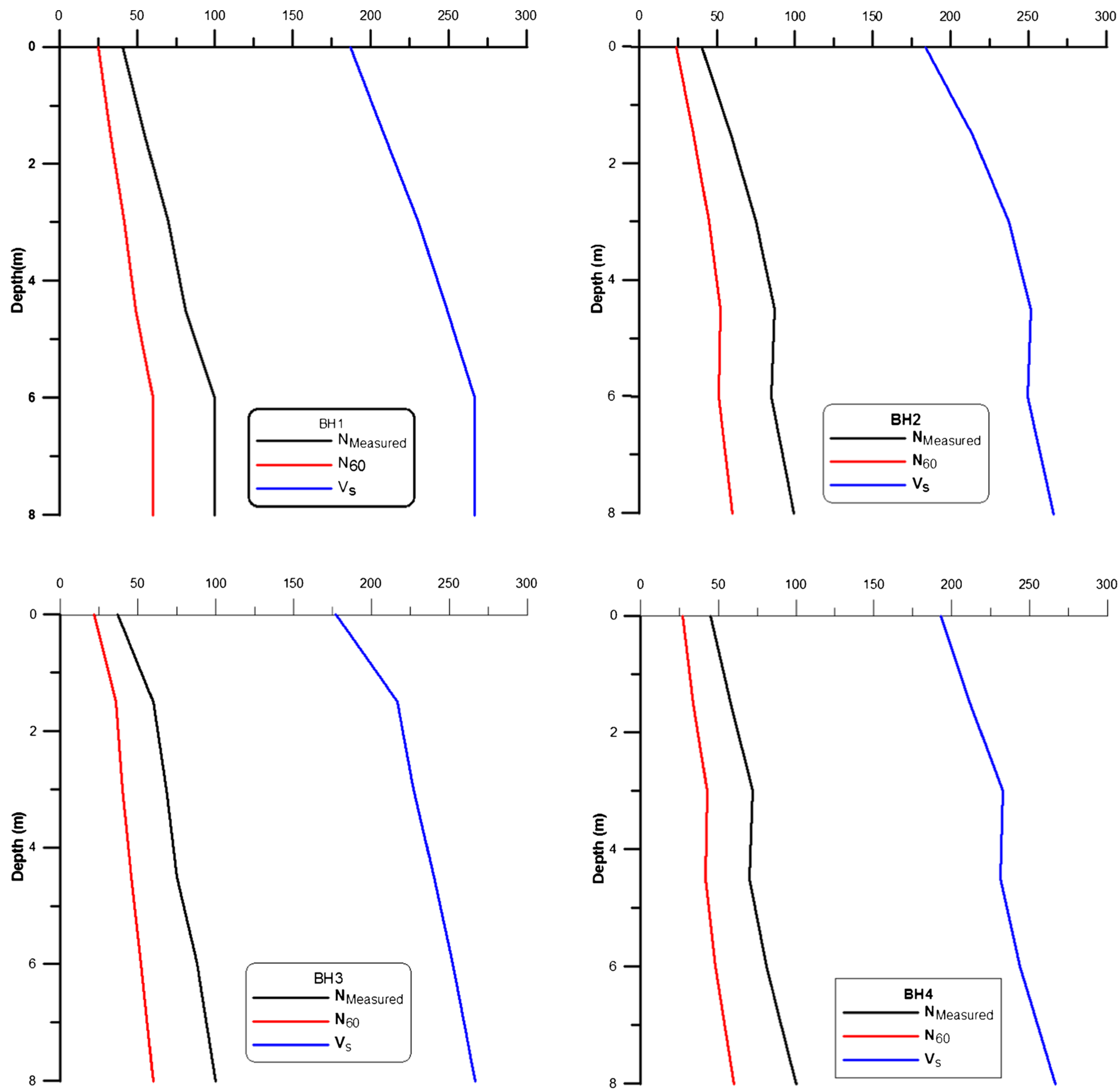


Fig. 6 Corrected *N* values and calculation of V_s at four boreholes

Results of microtremors compared with that of the geotechnical borehole data proved to be in agreement in terms of f_r. Furthermore, microtremor measurements have been used to estimate the sediment thickness. It is concluded that the use of both methods lead to reliable results, and consequently, the estimated f_r values through this study should be taken into account through designing and implementing phases of new constructions inside KACST.

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Table 4 Estimated values of f_0 from boreholes

BH1			BH2			BH3			BH4		
Average V_s (m/s)	f_0 (Hz)	T_0 (s)	Average V_s (m/s)	f_0 (Hz)	T_0 (s)	Average V_s (m/s)	f_0 (Hz)	T_0 (s)	Average V_s (m/s)	f_0 (Hz)	T_0 (s)
218	8.54	0.117	228	8.38	0.119	223	7.63	0.131	223	8.58	0.116

References

Abdel-Rahman K, Abdel-Aal AK, El-Hady SM, Mohamed AA, Abdel-Moniem E (2012) Fundamental site frequency estimation at new Domiat city, Egypt. Arab J Geosci 5:653–661

Al-Malki M, Fnais M, Al-Amri A, Abdelrahman K (2014) Estimation of fundamental frequency in Dammam City, Eastern Saudi Arabia. Arab J Geosci. doi:10.1007/s12517-014-1337-5

Alyousef K, Al-Amri A, Fnais M, Abdelrahman K, Loni (2014) Site effect evaluation for Yanbu city urban expansion zones, western Saudi Arabia, using microtremor analysis. Arab J Geosci. doi:10.1007/s12517-014-1310-5

Anbazhagan P, Sitharam TG (2006) Evaluation of dynamic properties and ground profiles using MASW: correlation between V_s and N_{60}. Proceedings of 13th Symposium on Earthquake Engineering, Indian Institute of Technology, Roorkee, December 18–20, Paper No. 008

Bonnefoy-Claudet S, Cornou C, Bard P, Cotton F, Moczo P, Kristek J, Faeh D (2006a) H/V ratio: a tool for site effect evaluation. Results from 1-D noise simulations. Geophys J Int 167:827–837

Bonnefoy-Claudet S, Cotton F, Bard P (2006b) The nature of noise wavefield and its applications for site effects studies. A literature review. Earth Sci Rev 79(3–4):205–227

Delgado J, Lopez Casado C, Estevez AC, Giner J, Cuenca A, Molina S (2000) Mapping soft soils in the Segura river valley (SE Spain): a case study of microtremors as an exploration tool. J Appl Geophys 45:19–32

Field E, Jacob KH (1993) The theoretical response of sedimentary layers to ambient seismic noise. Geophys Res Lett 20(24):2925–2928

Fnais MS, Abdel-Rahman K, Al-Amri AM (2010) Microtremor measurements in Yanbu City of western Saudi Arabia: a tool of seismic microzonation. J King Saud Univ- Sci (ElSEVIER). doi:10.1016/j.jksus.2010.02.006

Foti S, Parolai S, Bergamo G, Di Giulio G, Maraschini M, Milana G, Picozzi M, Puglia R (2011) Surface wave surveys for seismic site characterization of accelerometric stations in ITACA. Bull Earthq Engin 9(6):1797–1820. doi:10.1007/s10518-011-9306-y

Soil and Foundation Company (2007) Geotechnical investigation report for the proposed KACST project, 60 p

Ibs-von Seht M, Wohlenberg J (1999) Microtremor measurements used to map thickness of soft sediments. Bull Seismo Soc Am 89:250–259

Konno K, Ohmachi T (1998) Ground-motion characteristics estimated from spectral ratio between horizontal and vertical components of microtremors. Bull Seism Soc Am 88:228–241

Lachet C, Bard PY (1994) Numerical and theoretical investigations on the possibilities and limitations of the Nakamura's technique. J Phys Earth 42:377–397

Lermo J, Chavez-Garcia FJ (1993) Site effect evaluation using spectral ratios with only one station. Bull Seism Soc Am 83:1574–1594

Lermo J, Chavez-Garcia FJ (1994) Are microtremors useful in site response evaluation? Bull Seism Soc Am 84:1350–1364

Malagnini L, Tricarico P, Rovelli A, Herrmann RB, Opice S, Biella G, de Franco R (1996) Explosion, earthquake and ambient noise recording in a Pliocene sediment-filled valley: inferences on seismic response properties by reference- and non-reference-site techniques. Bull Seism Soc Am 86:670–682

Motamed R, Ghalandarzadeh A, Tawhata I, Tabtabaei SH (2007) Seismic microzonation and damage assessment of Bam City, southeastern Iran. J Earthq Eng 11:110–132

Mucciarelli M (1998) Reliability and applicability of Nakamura's technique using microtremors: an experimental approach. J Earthq Eng 4:625–638

Nakamura Y (1989) A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface. Quat Rep Rail Tech Res Inst RTRI 30(1):25–33

Nogoshi M, Igarashi T (1970) On the propagation characteristics of microtremors. J Seismol Soc Japan 23:264–280 (in Japanese with English abstract)

Ohmachi T, Nakamura Y, Toshinawa T (1991) Ground motion characteristics of the San Francisco bay area detected by microtremor measurements. Second International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, St. Louis, Missouri, 1643–1648

Parolai S, Bormann P, Milkereit C (2002) New relationships between Vs, thickness of sediments, and resonance frequency calculated by the H/V ratio of seismic noise for the Cologne area (Germany). Bull Seismo Soc Am 92:2521–2526

SESAME Project (2004) Site effects using ambient excitations. http://sesame-fp5.obs.ujf-grenoble.fr

Rao P, Kumar R, Seshunarayana M, Shukla T, Suresh AK, Pandey G, Raju Y, Pimprikar R, Chandra Das S, Gahalaut K, Mishra P, Gupta H (2011) Site amplification studies towards seismic microzonation in Jabalpur urban area, central India. Phys Chem Earth 36:1247–1258

Seed HB, Idriss IM, Arango I (1983) Evaluation of liquefaction potential using field performance data. J Geotech Eng 109(3):458–482

Seekins L, Wennerberg L, Margheriti L, Hsi-Ping L (1996) Site amplification at five locations in San Francisco, California: a comparison of S waves, codas and microtremors. Bull Seism Soc Am 86:627–635

Sitharam TG, Anbazhagan P, Mahesh GU, Bharathi KB, Nischala Reddy P (2005) Symposium on seismic hazard analysis and microzonation, Sept. 23–24, Roorkee, India

Skempton AW (1986) Standard penetration test procedures. Geotechnique 36(3):425–447

Sobaih M, kamal Abdel-Rahman, Mady M (2008) Estimation of dynamic characteristics of existing common reinforced concrete buildings in Egypt using ambient vibrations. Proceedings of the 14th World Conference on Earthquake Engineering, 12–17 Oct., pp 1–8

Teves-Costa Matias PL, Bard PY (1996) Seismic behavior estimation of thin alluvium layers using microtremor recordings. Soil Dyn Earthq Eng 15:201–209

Theodulidis N, Bard PY, Archuleta R, Bouchon M (1996) Horizontal-to-vertical spectral ratio and geological conditions: the case of Garner valley down-hole in Southern California. Bull Seism Soc Am 68: 767–779

Vaslet D, Muallem M, Brosse J, Fournieuet J, Breton J, Le Nindre Y (1991) Geologic map of the Ar Riyad Quadrangle, Sheet 24 I. Kingdom of Saudi Arabia, Saudi Arabian Deputy Ministry for Mineral Resources (DGMR) Geoscience Map GM-121 C, scale 1: 250000.