Mapping sediment thickness of Islamabad city using empirical relationships: Implications for seismic hazard assessment

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Soft sediments make an important component of the subsurface lithology, especially in areas underlain by river/stream basins. Occupying a position directly above the bedrock up to the land surface, these soft sediments can range in thickness from few centimeters to hundreds of meters. They carry a special nuisance in seismic hazards, as they serve as a source of seismic amplification that may enhance the seismic shaking of many folds. Determination of the thickness of the soft sediments is therefore crucial in seismic hazard analysis. A number of studies in recent years have demonstrated that frequency and amplitude spectrum obtained from the noise measurements during the recording of natural seismicity can be used to obtain thickness of soft sediments covering the bedrock. Nakamura (1989) presented a technique to determine such spectrum using ratio of horizontal to vertical components of the Rayleigh waves. The present study is based on an extensive set of microtremor measurements carried out in the Islamabad city, Pakistan. Fundamental frequencies were obtained from weak motion sensors and Tromino Engy Plus instruments to show that the correlation is clearly valid for a wide range of sediment thickness. A simple formula was derived for the investigated area to determine directly the thickness of sediments from the main peaks in the H/V spectrum for seismometer and Tromino data separately. A comparison is made between sediment thicknesses derived from empirical relations developed in this study with those given in literature to demonstrate a positive correlation. The correlation of instrumental resonant frequencies with calculated resonant frequencies (theoretical) suggests that the relation derived from the noise measurements mostly depends on the velocity depth function of the shear wave. The fundamental frequency of the main peak of spectral ratio of H/V using the both instruments correlates well with the thickness of sediments at the site obtained from the borehole data. It is found out that there is a wide variation in soft-sediment thickness in the Islamabad area, but as a general rule, soft sediments are thicker adjacent to stream courses compared to the areas intervening the streams. The distribution of sediments in the studied area is illustrated by means of cross sections constructed from results of the microtremor analyses and available borehole data, which provides a visual distribution of the soft sediments underlying the Islamabad city.

1. Introduction

Factors like magnitude and distance from the epicenter are the principal issues determining the

intensity of the earthquake hazard. However, it has been repeatedly noticed that adjacent areas underlain by different soil types respond differently during the earthquakes (Vucetic 1992). Seismic waves

Keywords. H/V ratio; Nakamura method; $V_{s,30}$ site classification; resonance frequency; sediment thickness.

propagate faster in bedrock than in soft sediments (Field and SCEC 2000). Waves travelling in soft sediments have greater amplitude compared to those in the bedrock, resulting in greater shaking in areas underlain by soft sediments compared to those underlain by bedrock (Cakir and Walsh 2012). This phenomenon involving the influence of the underlying soil on the local amplification of earthquake shaking is called site effect that makes an important parameter in modern seismic hazard assessments (Theilen-Willige 2010).

Information regarding the quality and thickness of soils for most building sites are best obtained by direct observations of subsurface geology at outcrops or through boreholes. Outcrops are not always available, whereas boreholes are an expensive proposition. Geophysical techniques provide a cost-effective and non-destructible alternative

(Aki 1957; Milana *et al.* 1996; Bard 1998; Ohmachi and Umezono 1998).

There exists conditions of high impedance contrast between sediment and bedrock to interpret frequencies and shear wave resonance. An empirical correlation between sediment thickness and resonance frequencies can be determined when required conditions are met, provided independent information are available about the depth of sediment–bedrock interface.

For seismic hazard assessment, the site effect is typically represented by resonance frequency and the associated ground motion amplification. Several methods are introduced to find such parameters, i.e., Nakamura method (H/V spectral ratio of ambient noise), array data analysis, site to reference spectral ratio, and receiver function type analysis. Among these, the Nakamura method is accepted

Figure 1. Location map of the study area, the bold light grey line shows the boundary of the Islamabad region.

Figure 2. Geological map of the study area. Data points for ambient noise measurements survey were run at 81 sites in the study area (shown as grey dots).

worldwide as very popular method to estimate the natural frequencies of soil columns at single stations (Kudo 1995; Bard 1998). There are many successful application to estimate the H/V spectral ratio towards studying fundamental frequency from microtremors in urban environments (Guéguen *et al.* 2000; Duval *et al.* 2001; Lebrun *et al.* 2001; Panou *et al.* 2005; Lombardo and Rigano 2007; García-

Jerez *et al.* 2007; Mundepe *et al.* 2009 and many others).

The metropolitan area of the Islamabad city lies between longitude $72^{\circ}45' - 73^{\circ}30'N$ and latitude $33^{\circ}30' - 33^{\circ}50'E$ in northern Pakistan (figure 1). Geographically, it occupies parts of the Islamabad District of the capital territory; the Rawalpindi District of the Punjab province and the Abbottabad

Figure 3. H/V spectra from seismograph data processed in Geopsy software.

Figure 3. (Continued.)

District of the Khyber Pakhtunkhwa province in northern Pakistan. The studied area is primarily part of the Potwar Plateau and consists of hills, plains and gorges. The northern part of the studied area lies in the mountainous terrain of the Margala Hills. Southward of the Margala Hills, is a piedmont bench underlain primarily by folded sandstone and shale of the Miocene Rawalpindi Group (Williams *et al.* 1999). The study area accommodates buried sandstone ridges covered by interbedded sandy silt and limestone gravel. A discontinuous ~ 40 m thick layer of eolian loess and reworked silt covers much of the northern Potwar Plateau (figure 2).

This paper focuses on determining the site effects for the Islamabad metropolitan area. In this regard, we present data of weak motion and Tromino Engy and use H/V spectral ratio methods (originally designed for site evaluation) to determine the distribution and thickness of sediments in the Islamabad city. Simultaneously, derivation of empirical relationship between the main resonance frequencies, overburden thickness obtained by two H/V spectral ratios, and shear wave velocity in the Islamabad city, also remained as one of the prime objective.

Table 1. *SESAME criteria for reliable and clear H/V peak used in the current study.*

Criteria for a reliable H/V curve

- $f_0 > 10/L_w$
- $n_c(f_0) > 200$
- $\sigma_A(f) < 2$ for $0.5f_0 < f < 2f_0$ if $f_0 > 0.5$ Hz
- $\sigma_A(f) < 3$ for $0.5f_0 < f < 2f_0$ if $f_0 < 0.5$ Hz

Criteria for a clear H/V peak

- Exists f^- in $[f_0/4, f_0] \mid A_{H/V}(f^-) < A_0/2$
- Exists f^+ in $[f_0, 4f_0] \mid A_{H/V}(f^+) < A_0/2$
- $A_0 > 2$
- $f_{\text{peak}}[A_{H/V}(f) \pm \sigma_A(f)] = f_0 \pm 5\%$
- $\sigma_f > \sigma(f_0)$
- $\sigma_A(f_0) > \sigma(f_0)$

L_w =window length; n_w =number of windows used in the analysis; $n_c = L_w n_w f_0$ =number of significant cycles; f =Current frequency; f_0 = H/V peak frequency; σ_f =standard deviation of H/V peak frequency; $\varepsilon(f_0)$ =threshold value for the stability condition $\sigma_f > \varepsilon(f_0)$; A_0 = H/V peak amplitude at frequency; $f_0 A_{H/V}(f)$ =frequency between $f_0/4$ and f_0 for which $A_{H/V}(f^-) > A_0/2$; f^- = H/V curve amplitude at frequency f ; 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. $\theta(f_0)$ =threshold value for the stability condition $\sigma_A(f) > \theta(f_0)$.

2. Methodology

Ambient noise measurement survey was done at 81 locations (figure 2) in Islamabad city using two instruments of Guralp broadband seismograph (CMG-3TD) and Micromede Tromino (Tromino Engy Plus). The instruments are housed at the NCE in Geology, University of Peshawar, Pakistan. For data recording and processing, SCREAM and Grilla software were used. The data from seismograph was recorded at 50 sites at 200 Hz samples per second for 5–10 min in GCF format. We also carried out ambient noise measurements at 31 sites using Tromino Engy Plus at a sampling rate of 128 Hz for 30 min and recorded all three components (transverse, longitudinal, and vertical) in Grilla trace format. Each digital signal file was processed in Geopsy software (for GCF files) (figure 3) and

Grilla software (for Tromino trace files) (Appendix following SESAME (2004) criteria (table 1). According to this criteria, first curve reliability (i.e., sufficient number of windows and significant cycles for a given fundamental frequency (f_0), acceptably low scattering among all windows over a given frequency range around f_0) was verified (table 2 and Appendix). Then, reliability of H/V peaks (i.e., fulfillment of amplitude and stability criteria) was checked. Great attention was given to the identification of eventual peaks induced by low frequency disturbances (wind blowing, in case of near tall buildings, bad soil-sensor coupling, etc.) and to better resolve broad or multiple peaks (i.e., by varying the smoothing parameters). Detailed information about the thickness of subsurface sedimentary covers is also available from 21 well logs drilled by the Capital Development Authority

Table 2. Processing parameters used to process seismograph data (figure 3) for reliable and clear H/V peaks. Only the result of 10 different curves which are relevant to figure 3 are shown.

Location	SD error	Window length (L_w)	Smoothing type	Sample (sec)	Number of windows (n_w)
F-8/3	0.125	25	Konno and Ohmachi-40	0.5–15	15
AIOU	0.036	25	Konno and Ohmachi-40	0.5–15	16
ECP	0.469	25	Konno and Ohmachi-40	0.5–15	12
F-10/1	0.210	25	Konno and Ohmachi-40	0.5–15	13
F-11/1	0.212	25	Konno and Ohmachi-40	0.5–15	14
F-15/1	0.237	25	Konno and Ohmachi-40	0.5–15	13
G-6/2	0.167	25	Konno and Ohmachi-40	0.5–15	13
G-7/4	0.941	25	Konno and Ohmachi-40	0.5–15	13
Embassy	0.729	25	Konno and Ohmachi-40	0.5–15	11
Lodge G-7(Markaz)	0.729	25	Konno and Ohmachi-40	0.5–15	14

Figure 4. Geophysical well logs drilled in the study area; out of 21 only 10 drilled logs were selected near to noise measurement points.

(CDA), Pakistan in 2007 and published in the report of Sheikh *et al.* (2007). We use information of well logs close to our data points (figure 4) for calibrating the results with noise investigations.

The processed data was interpreted quantitatively to develop a relation between peak frequency and sediment thickness following the SESAME (2004) guidelines and two basic assumptions of Albarello *et al.* (2011), i.e., (1) Rayleigh waves in the fundamental mode dominate by ambient vibration wave field, and (2) these waves propagate within nearly homogeneous soft layer overlying rigid

bedrock. The assumptions of Nakamura (1989) about the origin of fundamental frequencies is related to shear wave resonance in a single layer of sediment, and with this assumption the layer thickness can be related to fundamental peak frequency of H/V spectral ratio by $f_r = nV_s/4H$ where n are uneven integers and V_s is the shear wave velocity of sediment. Budny (1984) give another assumption that shear wave velocity (V_s) as function of depth (z) can be described as $V_s(z) \approx V_0(1+z)^x$ (where V_0 = average shear wave velocity at 1 m below the surface, the constant ' x ' obtained empirically by fitting the power law regression ($V_s(z)$ as Y-axis and $V_0(1+z)$ as X-axis) as did the work by the pioneer researcher Budny (1984) from geotechnical borehole data. In the current study, we obtained the values of V_0 and x from 119 geotechnical boreholes using method of Budny (1984). Worldwide, predefined values of V_0 and x (table 3) by Budny (1984), Albarello *et al.* (2011) and Hinzen *et al.* (2004) were also utilized for correlation purpose with studied results. Experimental studies in

Table 3. Values of V_0 and x from different researches and current study.

Study	V_0	x	R^2
Current study	185.3	0.1	0.65
Albarello <i>et al.</i> (2011)	210	0.2	
Budny (1984)	162	0.278	
Hinzen <i>et al.</i> (2004)	215.5	0.2

Figure 5. Spatial distribution of fundamental frequencies in the area, the outcrop rock area consists of high mode frequencies while basin part and other area have low mode frequencies.

soil layers show that a significant negative correlation exists between the values of V_0 and x because the stronger the lithostatic load effect (i.e., as x is higher), the lower the expected value of V_s at surface (Ibs Von Seht and Wohlenberg 1999; Albarello *et al.* 2011).

From the work of Ibs Von Seht and Wohlenberg (1999), the velocity function can be integrated with fixed parameters of x and V_0 (calculated from borehole geotechnical data) to find a simple relationship

between frequency and overburden sediment thickness (Albarello *et al.* 2011) as:

$$m = \frac{(1-x) \sqrt{V_0(1-x)}}{4fr} + 1 - 1. \quad (1)$$

Table 4. The constant parameters a and b used to correlate the results with our study.

Study		a	b	R^2
Seismometers	} Current study	134.06	-1.23	0.96
Tromino Engy Plus		63.68	-1.09	0.99
Ibs Von Seht and Wohlenberg (1999)		96	-1.388	0.981
Parolai <i>et al.</i> (2002)		108	-1.551	
Hinzen <i>et al.</i> (2004)		137	-1.190	

Using this general relation, a power law function between the thickness and the frequency of the main peak in H/V spectra was established. We obtained two relationships by fitting linear regression, yielded equations (2) and (3) for seismograph data and Tromino Engy Plus data, respectively. We required average shear wave velocities for 30 m ($V_{s,30}$) depth to classify the site according to NEHRP codes. Tromino Engy Plus instrument gives calculated value of $V_{s,30}$ (using $V_{s,ave} = 4mf_{(H/V)Tromino}$) by fitting thickness of first layer as constraint from available geotechnical boreholes and outcrop data in software Grilla. The seismograph data from CMG-3TD was processed in software

Figure 6. Fundamental resonance frequencies from seismograph (triangles) and Tromino Engy Plus (solid circles) *versus* sediment thickness, the graph shows nearly same trend and fit to data points (equations 2 and 3). The dashed line is the theoretical dependence (equation 1) between thickness and resonant frequency.

Figure 7. H/V resonance frequencies *versus* the thicknesses at the sites, the plot shows that a good trend exists between our results and the results from empirical relations for sediment thickness and resonance frequency from different researchers.

Figure 8. Sediment thickness throughout the study area, the sediment thickness is more in the basin part (thin circular line) and remains shallow-to-intermediate in other parts (e.g., area with dotted lines).

Table 5. Coordinates of the sites at which the sediment thickness, site classification (SC) and fundamental frequencies ($f_{H/V}$) has been obtained. The table also include the compared values of sediment thickness adopted from empirical relations proposed by researchers ¹Budny (1984), ²Hinzen et al. (2004) and ³Albarelo et al. (2011) for other regions.

Site	SC	Long.	Lat.	$f_{H/V}$ (Hz)		H_{Drill} (m)	$H_{Calc.}$ (Current study) (m)	$H_{Calc.}$ (Budny 1984) (m)	$H_{Calc.}$ (Hinzen et al. 2004) (m)	$H_{Calc.}$ (Albarelo et al. 2011) (m)
				$f_{H/V}$ (Tromino) (Hz)	$f_{H/V}$ (Seismograph)					
26 no.	D	72.94	33.63	2.72			21	29	36	32
Abpara Market	D	73.09	33.71		4		14	18	22	20
AIOU H-8	D	73.05	33.69		1.4		44	71	82	72
Bari Imam	D	73.11	33.74	2.81			21	28	34	31
Chaman road	D	73.04	33.69		0.8	125	82	151	168	144
(G-8/1)										
Chattar park	C	73.24	33.78	13.44			4	4	5	5
City villa	C	73.2	33.74	14.69			3	4	5	4
Comsatt	D	73.16	33.64	3.28			17	23	28	26
D-12	C	72.94	33.7	19.22			3	3	3	3
Daman e Koh	C	73.06	33.74	33.41			1	1	2	2
DHA (G3)	D	73.16	33.52	1.19			53	88	101	88
DHA	D	73.09	33.55		2.4		24	35	42	37
DHA Phase iii	D	73.2	33.49	1.47			42	66	77	68
DhokMuradakhli	D	73.18	33.53	1.53			40	63	74	65
DhokSaedakbar	D	73.24	33.55	4.56			12	15	19	17
E-11 end	C	72.97	33.7		12.2		4	4	6	5
(north strip)										
E-11 service road	C	72.98	33.7		11		5	1	1	1
E-11	C	72.98	33.71	44.81			1	5	7	6
E-7 Aurangzeb Rd	C	73.04	33.73		12.5		4	4	6	5
ECP-G-5	D	73.1	33.72		4.3		13	16	20	19
Embassy Lodge	C	73.11	33.69		6.9		8	9	11	11
F-10 Markaz	D	73.01	33.7		4.3	2	64	16	20	19
F-11-1	D	73	33.68	1.8			34	51	60	53
F-7/1	D	73.06	33.71		1.5		41	65	76	66
F-7/2	D	73.05	33.72		0.5		138	286	305	257
F-8/2	D	73.03	33.72		0.6		113	223	242	205
F-8-3 (UCI)	D	73.03	33.71		1.7		36	55	64	57
F-9 Park	C	73.02	33.71		14		95	4	5	5
FaqirAipee road	C	73.02	33.64		8.3		6	7	9	9
(I-11/3)										
G-10-2	C	73.01	33.68		13	2	4	4	5	5
G-10-4	D	73.02	33.68		9.6	80	113	223	242	205

G-10	D	73.08	33.68	4.78				12	14	18	16
G-11/2	D	72.99	33.67		0.5			138	286	305	257
G-11/4	D	73	33.67		0.5			138	286	305	257
G-13	D	72.96	33.65	9.69				113	6	8	7
G-13-4	C	72.97	33.65		0.6			5	223	242	205
G-15-3	D	72.92	33.64		4.2			13	17	21	19
G-16	D	72.92	33.63		2.7			22	30	36	32
G-6-1	C	73.08	33.71		7.7			7	8	10	9
G-6-2 St.12	D	73.08	33.72		2.7			22	30	36	32
G-6-3 St.5	D	73.09	33.72		0.7			95	181	199	169
G-7/3	C	73.07	33.71		3.6			16	20	25	23
G-7/4	D	73.08	33.7		6.2			9	10	13	12
G-8/3 Ibn.e.Sina road	D	73.05	33.71		1.5			41	65	76	66
G-9/1 Kuram road	D	73.03	33.68		0.6			113	223	242	205
G-9	D	73.03	33.69	1.56				39	61	72	63
GeoScience Lab	D	73.16	33.67	2.06				29	42	51	45
Gulberg town	D	73.15	33.6	4.78				12	14	18	16
Gulreiz	D	73.11	33.56		1.3			48	78	90	79
Gulzar e Qaid	C	73.13	33.6	5.94				9	11	14	13
H-11 Graveyard	D	73.01	33.66		2.7			22	30	36	32
H-12 NUST	C	72.99	33.65		13			4	4	5	5
H-8-1 Shifa	D	73.06	33.67		2.7	128		22	30	36	32
H-9-4	D	73.05	33.67		0.7	126		13	181	199	169
I-10-3	D	73.04	33.66		2.8			21	28	35	31
I-10-A	D	73.03	33.64	5.44				10	12	15	14
Model College (I-8)	D	73.07	33.67		3.3			17	23	28	25
I-8 Markaz	D	73.08	33.67		4.5	136		12	15	19	18
I-9-3	D	73.05	33.66		0.6			113	223	242	205
I-9-4	D	73.06	33.66		3.5	69		16	21	26	24
Islamic International University	D	73.02	33.66		0.6			113	223	242	205
Jagiot	C	73.21	33.67		15			3	3	5	4
Khanna	D	73.13	33.63		1.8			34	51	60	53
Lake View Park	D	73.13	33.72		0.8			82	151	168	144
Malpur	D	73.15	33.73		0.5			138	286	305	257
Margala town	C	73.11	33.67		5			11	13	17	15
MeeraBhagwal	C	73.23	33.72	32.81				1	1	2	2
MeharAbadi	C	72.98	33.67		10.4			5	5	7	7
Mohrasoan	C	73.1	33.66	5.81				9	11	14	13
NIST H-8	D	73.06	33.68		0.6	123		113	223	242	205
Orchard Scheme	D	73.1	33.67		2.6			22	31	38	34

Table 5. (Continued.)

Site	SC	Long.	Lat.	$f_{H/V}$ (Hz)		H_{Drill} (m)	$H_{Calc.}$ (Current study) (m)	$H_{Calc.}$ (Budny 1984) (m)	$H_{Calc.}$ (Hinzen <i>et al.</i> 2004) (m)	$H_{Calc.}$ (Albarelo <i>et al.</i> 2011a) (m)
				$f_{H/V(Tromino)}$ (Hz)	$f_{H/V(Seismograph)}$ (Hz)					
Phatrial	C	73.27	33.69	29.69			2	2		2
QAU	C	73.14	33.75	14.47			4	4		4
QAU residential colony	C	73.13	33.75		14.2		4	4		5
Rawal town	D	73.12	33.69	4			14	18		20
Said Pur Village	D	73.07	33.74	4.78			12	14		16
Sangjani	D	72.84	33.67	3.22			18	24		26
Sarae Kharbuza	C	72.91	33.68	8.13			7	7		9
SCECHS (G-7)	C	72.89	33.61	10.44			5	5		7
Shadravelley	D	73.17	33.78	3.63			16	20		23
Sihalagaon	D	73.2	33.55	1.31			48	77		78

1. $H_{calc} = \{162 * (1 - x)\} / [4 * \{(f_0 + 1)^{(1-x)} - 1\}]$; 2. $H_{calc} = \{215.5 * (1 - x)\} / [4 * \{(f_0 + 1)^{(1-x)} - 1\}]$; 3. $H_{calc} = \{210 * (1 - x)\} / [4 * \{(f_0 + 1)^{(1-x)} - 1\}]$.

Geopsy and only peak frequency ($f_{(H/V)Seismograph}$) and corresponding amplification values were obtained, the average shear wave velocity was evaluated using thickness obtained from equation (1) and frequency by $V_{s,ave} = 4mf_{(H/V)Seismograph}$. These average velocities for shallow sediment layers (thickness >30 m) were interpolated to calculate $V_{s,30}$ using relation of Boore (2004). The results from seismograph and Tromino were combined to analyze the site according to NEHRP code. The parameters a and b were obtained empirically by fitting the power law function as did the work by the pioneer researchers Ibs Von Seht and Wohlenberg (1999), Delgado *et al.* (2000a and b), Parolai *et al.* (2002) and Albarello *et al.* (2011). These parameters can be used for sites where independent information about the sediment thickness is available.

$$m = 134.06 f_{(H/V)(Seismograph)}^{-1.23} \quad (2)$$

$$m = 63.676 f_{(H/V)(Tromino)}^{-1.09} \quad (3)$$

3. Results and discussion

The noise measurement survey was carried out using two types of instruments, i.e., seismograph and Tromino Engy Plus, housed at NCE in Geology, University of Peshawar. The spectral ratio from these instruments was evaluated for 81 sites in conformity with the guidelines of SESAME (2004). The data was analyzed for peak frequencies and the resultant frequencies were categorized in low and high modes of frequencies. The estimated frequencies obtained using seismograph were categorized as low mode (0.1–4 Hz) and using Tromino Engy Plus as low modes (0.1–10 Hz) and higher modes (11–60 Hz). The site was classified according to NEHRP codes into site C and D, based on the $V_{s,30}$ values. In general, a notable contrast exists in the mechanical properties of the soft soils and hard rock. Moreover, H/V spectral ratio method is based on the theme that a low rigid soil layer exists overlying a more rigid layer. Consequently, for hard-rock sites, the H/V spectral ratio emerges to be flat. Apart from this, stiff soils and soft rocks exhibit different properties and therefore the spectral ratios resulting from soft soils could easily be distinguished (a clear bell shape peak results) rather than stiff soils or soft rock (a flat curve results).

Figure 9. Cross section showing the subsurface structure of the areas investigated, constructed using results of microtremor analysis. For location of profile 1, see figure 8.

The reason to use two instruments lies in the correlation of the results of two different instruments that gives H/V as an output with theoretical curve of Ibs Von Seht and Wohlenberg (1999). The plot of frequencies obtained from both instruments shows a parallel trend with theoretical curve (figure 5). Therefore both the instruments can be utilized for H/V spectral ratio measurement following the SESAME (2004) guideline.

Resonance frequencies determined from spectral ratios were spatially interpolated that led us to the contour plot (figure 5). It is clear that the basin part shows peak frequencies of higher mode due to presence of soft soil and other sites show moderate frequencies due to the presence of stiff soil and soft rocks. It also appears that these sites are marked by presence of weathered soil cover, as evidenced in the geological map (figure 2). Worldwide, several researchers have observed this type variation of resonant frequencies in their region where they mostly attribute the lower resonant frequencies to the

existence of higher overburden thickness. In our observations we also come across sites having higher range of frequencies (15–60 Hz). This might be caused by the immediate subsurface harder soil strata. Additionally, thinning of sediment cover can also be a contributing factor for the observation of higher frequencies.

3.1 Relating resonant frequency with thickness

In figure 6, data of the drilling sites were used to plot the H/V main frequencies *versus* the thicknesses at the sites. The cross-plot reveals good correlation for the H/V frequencies over a wide range of thickness, namely, from tens of meters to more than 1000 m. The resulting straight lines are nearly parallel. The resultant parameters 'a' and 'b' from both instruments were correlated with parameters of Ibs Von Seht and Wohlenberg (1999); Albarello *et al.* (2011) and Hinzen *et al.* (2004) from other

regions for validation purpose (table 4). Finally, we compared the estimated depth with the geological model in the form of cross section (details are given in table 4).

The sediment thicknesses calculated in this study were compared with the results obtained based on relations proposed by Hinzen *et al.* (2004), Ibs Von Seht and Wohlenberg (1999) and Albarello *et al.* (2011) for other regions (figure 7). The plot shows that a good trend exists between our results and the results from empirical relations for sediment thickness and resonance frequency from different researchers. In the available well data information, the depth of the bedrock ranges from 2 to >141 m and due to limited well data points, only H/V spectral ratio points near to wells are correlated (table 5). Considering the geological background information, the sediment thickness is more in the basin part and remains shallow to intermediate in other parts; figure 8 illustrates this variation of thickness. Estimation of sediment thickness using relations of Hinzen *et al.* (2004), Ibs Von Seht and Wohlenberg (1999), and Albarello *et al.* (2011), and our results exhibit same trend (but different values) and found to be declining with rise in frequency. The results are quite expected as H/V spectral ratios give rise to peaks at higher frequencies for shallow bedrock sites (figure 7). The sediment thicknesses in our study are quite low values and correlated well with geophysical well logs and geological information (figure 9). The sediment thicknesses using relations proposed by Hinzen *et al.* (2004), Ibs Von Seht and Wohlenberg (1999), and Albarello *et al.* (2011) for other regions give high values in the frequency range of 0.1–1.0 Hz, which is not correlated to drilled well log and geological information in the study area.

4. Conclusion

The study area of Islamabad contains a significant portion of basin fill sediments. From available geotechnical information and well data, it was known that some of these soil deposits were naturally soft, but exact distribution and thickness was unknown in most of the study area. Therefore the Nakamura method of H/V spectral ratios of microtremors was used to compute the soil distribution and thickness of these soils. On the basis of this, we establish quantitative relationship between resonance frequency and thickness of overburden soil layer.

The soil was classified into site classes as site C and D according to NEHRP codes and the results obtained have demonstrated the presence of soft (site C) and stiff soil (site D) throughout the study area. The results of frequency, thickness and soil classification were mapped to analyze the spatial distribution of accumulated soil thickness and soil nature in the study area. These maps are of great interest (as an initial document) for the preliminary estimation of the foundation depth of public work. These maps are essential tool for the seismic hazard zonation as they implicate the movement of soil (static and dynamic) more susceptible to amplification during natural earthquake.

These results also explain the utilization of the H/V spectral ratio method for measuring of microtremors in the soils of investigation (mostly soft soil) and quickly determination of more reliable sediment thickness from resonance frequency at any site. The H/V spectral ratios were also computed for the sites close to drill wells and geotechnical boreholes where the thickness of the sedimentary cover was known. Consistent with previous studies (other regions), a validated relationship for sediment thickness and the frequency of the main peak in the H/V spectral ratios was established for the study area to better estimate the thicknesses of overburden sedimentary cover. The sediment thickness calculated using relations of Hinzen *et al.* (2004), Ibs Von Seht and Wohlenberg (1999), and Albarello *et al.* (2011) are much higher in the frequency range of 0.1–1.0 Hz as compared to our results (although the trend is same). The relations proposed by other researchers cannot be used directly in this area for the estimation of sediment thickness as they are not well correlated with well log and geological data in Islamabad region. The results of sediment thickness, frequency mode and soil classification can be utilized further for seismic hazard assessment and microzonation of the study area.

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Appendix

Criteria for a reliable H/V curve	
[All 3 should be fulfilled]	
$f_0 > 10 / L_w$	32.81 > 0.50
$n_c(f_0) > 200$	59062.5 > 200
$\sigma_A(f) < 2$ for $0.5f_0 < f < 2f_0$ if $f_0 > 0.5\text{Hz}$	Exceeded 0 out of 1524 times
$\sigma_A(f) < 3$ for $0.5f_0 < f < 2f_0$ if $f_0 < 0.5\text{Hz}$	
Criteria for a clear H/V peak	
[At least 5 out of 6 should be fulfilled]	
Exists f^* in $[f_0/4, f_0] \mid A_{H/V}(f^*) < A_0 / 2$	NO
Exists f^* in $[f_0, 4f_0] \mid A_{H/V}(f^*) < A_0 / 2$	NO
$f_{peak}[A_{H/V}(f) \pm \sigma_A(f)] = f_0 \pm 5\%$	OK
$\sigma_A < \varepsilon(f_0)$	OK
$\sigma_A(f_0) < 0(f_0)$	OK

Location: Geo-Science Lab		Instrument: TEP-0186/01-12	Geology: Clay/sandy gravel	Trace length: 20 minutes	Start recording: 15/11/14 12:20:43
City: Islamabad		Sampling rate: 128 Hz	Window size: 20 s	Smoothing type: Triangular window	End recording: 15/11/14 12:40:43
Analysis performed on the entire trace			Smoothing: 15%	GPS location: : 073°09.3801 E, 33°40.4189 N (523.8 m)

Criteria for a reliable H/V curve [All 3 should be fulfilled]		
$f_0 > 10 / L_w$	$2.06 > 0.50$	OK
$n_c(f_0) > 200$	$247/5.0 > 200$	OK
$\sigma_A(f) < 2$ for $0.5f_0 < f < 2f_0$ if $f_0 > 0.5\text{Hz}$	Exceeded 0 out of 100 times	OK
$\sigma_A(f) < 3$ for $0.5f_0 < f < 2f_0$ if $f_0 < 0.5\text{Hz}$		
Criteria for a clear H/V peak [At least 5 out of 6 should be fulfilled]		
Exists f^* in $[f_0/4, f_0] \mid A_{HV}(f^*) < A_0 / 2$	1.469 Hz	OK
Exists f^* in $[f_0, 4f_0] \mid A_{HV}(f^*) < A_0 / 2$	2.594 Hz	OK
$A_0 > 2$	$6.51 > 2$	OK
$f_{peak}[A_{HV}(f) \pm \sigma_A(f)] = f_0 \pm 5\%$	$10.018451 < 0.05$	OK
$\sigma_f < \varepsilon(f_0)$	$0.03806 < 0.10313$	OK
$\sigma_A(f_0) < \theta(f_0)$	$0.476 < 1.58$	OK

Location: 26 number	Instrument: TEP-0186/01-12	Geology: overburden clay/sandy gravel	Trace length: 30 minutes	Start recording: 10/11/14 18:40:02
City: Islamabad	Sampling rate: 128 Hz	Window size: 20 s	Smoothing type: Triangular window	End recording: 10/11/14 19:10:02
Analysis performed on the entire trace				GPS location: 072°56.1816 E, 33°37.7420 N (557.5 m)

Criteria for a reliable H/V curve		
[All 3 should be fulfilled]		
$f_0 > 10 / L_w$	$2.72 > 0.50$	OK
$n_e(f_0) > 200$	$4893.8 > 200$	OK
$\sigma_A(f) < 2$ for $0.5f_0 < f < 2f_0$ if $f_0 > 0.5\text{Hz}$	Exceeded 0 out of 132 times	OK
$\sigma_A(f) < 3$ for $0.5f_0 < f < 2f_0$ if $f_0 < 0.5\text{Hz}$		
Criteria for a clear HV peak		
[At least 5 out of 6 should be fulfilled]		
Exists f^* in $[f_0/4, f_0] \mid A_{HV}(f^*) < A_0/2$	1.75 Hz	OK
Exists f^* in $[f_0/4f_0] \mid A_{HV}(f^*) < A_0/2$	4.375 Hz	OK
$A_0 > 2$	$4.48 > 2$	OK
$f_{\text{peak}}(A_{HV}(f) \pm \sigma_A(f)) = f_0 \pm 5\%$	$[0.0257] < 0.05$	OK
$\sigma_1 < e(f_0)$	$0.06988 < 0.13594$	OK
$\sigma_A(f_0) < \theta(f_0)$	$0.2887 < 1.58$	OK

References

- Aki K 1957 Space and time spectra of stationary stochastic waves with special reference to microtremors; *Bull. Earthq. Res. Inst.* **35** 415–456.
- Albarelo D, Cakir R and Walsh T J 2011 Single station ambient vibration measurements in the Puget lowland and coastal area, Washington; DNR-DGER internal report.
- Bard P-Y 1998 Microtremor measurements: A tool for site effect estimation? In: *The Effects of Surface Geology on Seismic Motion* (eds Irikura K, Kudo K, Okada H and Sasatani T (Balkema, Rotterdam), pp. 1251–1279.
- Boore D M 2004 Estimating $V_{s(30)}$ (or NEHRP site classes) from shallow velocity models (depths <30 m); *Bull. Seismol. Soc. Am.* **94**(2) 591–597.
- Budny M 1984 Seismische Bestimmung der Bodendynamischen Kennwerte von oberflächennahen Schichten in Erdbebengebieten der niederheinischen Bucht und ihre ingenieurseismologische Anwendung; PhD Thesis, *Geol. Inst. University of Cologne Spec. Publ.* **57** 208p.
- Cakir R and Walsh T J 2012 Shallow seismic site characterizations at 25 Anss/Pnsn stations and compilation of site-specific data for the entire strong motion network in Washington and Oregon, Pacific Northwest. Final Technical Report, U.S. Geological Survey, USGS/NEHRP award no. G11AP20045.
- Delgado J, Lopez Casado C, Estévez A, Giner J, Cuenca A and Molina S 2000a Mapping soft soils in the Segura river valley (SE Spain): A case study of microtremors as an exploration tool; *J. Appl. Geophys.* **45**(1) 19–32.
- Delgado J, Lopez Casado C, Giner J, Estevez A, Cuenca A and Molina S 2000b Microtremors as a geophysical exploration tool: Applications and limitations; *Pure Appl. Geophys.* **157**(9) 1445–1462.
- Duval A M, Vidal S and Méneroud J P 2001 Caracas, Venezuela, site effect determination with microtremors; *Pure Appl. Geophys.* **158**(12) 2513–2523.
- Field N SCEC (southern California Earthquake Center) Phase III working group 2000 Accounting for the site effects in probabilistic seismic hazard analysis of southern California: Overview of the SCEC Phase III report; *Bull. Seismol. Soc. Am.* **90** S1–S31, doi: 10.1785/D120000512.
- García-Jerez A, Navarro M and Alcalá F J 2007 Shallow velocity structure using joint inversion of array and H/V spectral ratio of ambient noise: The case of Mula town (SE of Spain); *Soil Dyn. Earthq. Eng.* **27**(10) 907–919.
- Guéguen P, Chatelain J-L, Guillier B and Yepes H 2000 An indication of the soil topmost layer response in Quito (Ecuador) using noise H/V spectral ratio; *Soil Dyn. Earthq. Eng.* **19**(2) 127–133.
- Hinzen K G, Scherbaum F and Weber B 2004 On the resolution of H/V measurements to determine sediment thickness, a case study across a normal fault in the Lower Rhine Embayment, Germany; *J. Earthq. Eng.* **8**(6) 909–926.
- Ibs Von Seht M and Wohlenberg J 1999 Microtremor measurements used to map thickness of soft sediments; *Bull. Seismol. Soc. Am.* **89**(1) 250–259.
- Kudo K 1995 Practical estimates of site response; In: *Proc. 5th Int. Conf. on Seismic Zonation, Nice, France*, pp. 1878–1907.
- Lebrun B, Hatzfeld D and Bard P Y 2001 Site effect study in urban area: Experimental results in Grenoble (France); *Pure Appl. Geophys.* **158**(12) 2543–2557.
- Lombardo G and Rigano R 2007 Local seismic response in Catania (Italy): A test area in the northern part of the town; *Eng. Geol.* **94**(1–2) 38–49.
- Milana G, Barba S, Del Pezzo E and Zambonelli E 1996 Site response from ambient noise measurements: New perspectives from an array study in central Italy; *Bull. Seismol. Soc. Am.* **86** 320–328.
- Mundepi A K, Lindholm C and Wadia K 2009 Soft soil mapping using horizontal to vertical spectral ratio (HVSr) for seismic hazard assessment of Chandigarh city in Himalayan foothills, north India; *J. Geol. Soc. India* **74**(5) 551–558.
- Nakamura Y 1989 A method for dynamic characteristic estimation of subsurface using microtremors on the ground surface; *Q. Rep. Railw. Tech. Res. Inst. Tokyo* **30**(1) 25–33.
- Ohmachi T and Umezono T 1998 Rate of Rayleigh waves in microtremors; In: *Second Int. Symposium on the Effects of Surface Geology on Seismic Motion* **2** 587–592.
- Panou A A, Theodulidis N P, Hatzidimitriou P M, Savvaidis A S and Papazachos C B 2005 Reliability of ambient noise horizontal-to-vertical spectral ratio in urban environments: The case of the Ssaloniki city (northern Greece); *Pure Appl. Geophys.* **162**(5) 891–912.
- Parolai S, Bormann P and Milkereit C 2002 New relationships between V_s , thickness of sediments, and resonance frequency calculated by the H/V ratio of seismic noise for Cologne Area (Germany); *Bull. Seismol. Soc. Am.* **92**(6) 2521–2527.
- SESAME 2004 Guidelines for the implementation of the H/V spectral ratio technique on ambient vibrations: SESAME, European project, WP12, Deliverable D23.12 [http://sesame-fp5.obs.ujf-grenoble.fr/Papers/HV_User_Guidelines.pdf].
- Sheikh I M, Pasha M K, Willams V S, Raza S Q and Kanwar, S A K 2007 Environmental geology of the Islamabad–Rawalpindi area, northern Pakistan; Bulletin 2078-G. USGS, pp. 1–32.
- Theilen-Willige B 2010 Detection of local site conditions influencing earthquake shaking and secondary effects in southwest Haiti using remote sensing and GIS methods; *Natural Hazards Earth Syst. Sci.* **10** 1183–1196.
- Vucetic M 1992 Soil properties and seismic response; In: *Proc. 10th World Conference on Earthquake Engineering*, pp. 1199–1204.
- Williams V S, Pasha K M and Sheikh M I 1999 Geologic map of the Islamabad–Rawalpindi area, Punjab, Northern Pakistan; Open File Report 99-0047, U.S. Department of Interior: vol. 16.