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Ambient noise measurements in Rawalpindi–Islamabad, twin cities of Pakistan: a step towards site response analysis to mitigate impact of natural hazard

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Abstract Earthquakes are one among the highly dangerous geological hazards. The damage from earthquakes is greatly influenced by the local geological conditions. The history of Pakistan is full of severe earthquakes that caused the mass destruction at national scale. Major earthquake-affected areas in Pakistan are mainly concentrated in the north and western sections of the country. Site response analysis is an initial step towards seismic risk assessment. The present study aims at local site effects by acquiring data along 105 sites of Rawalpindi–Islamabad, the twin cities of federal capital of Pakistan, by applying H/V spectral ratio method. Out of the data acquired for 105 sites, data for 88 sites were considered reliable after observing reliability conditions determined by SESAME guidelines devised in 2004. Fundamental frequency f_0 of soft sediments, amplitude A_0 of corresponding H/V spectral ratios, thickness of soft sediments residing on the bedrock and soil vulnerability index K_g over 88 reliable data sites within the study area were estimated and analysed. The results show that the fundamental frequency of the sediments reflects variation and lies within a wide range between 0.6 and 14.4 Hz. Similarly, amplification factor A_0 up to 5.5 was observed at a site. Overburden thickness of soft sediments H also indicates high variation and has been calculated in the range of 1.7–316.5 m. As far as K_g is concerned, it is also highly variable and is lying in the range of 0.30–62.7. These results will help in designing a policy to mitigate the impact of seismic hazard in the study area.

Keywords Site response analysis · H/V spectral ratios · Fundamental frequency · Soil vulnerability index · Amplification factor

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1 Introduction

The history of human civilization discloses that man has been combating with natural disasters from his origin. Every year, thousands of people are killed by volcanic eruptions, earthquakes, landslides and floods. These natural disasters cause damage to human settlements and infrastructure (Ramkumar 2009). These inevitable events not only disturb the normal life pattern but also create heavy life losses, disaster to property and seriously halt the developmental processes of a country or a region. Although mankind has adopted conventional and technological techniques to combat the effects of natural disasters, risks posed by them are increasing as a result of habitation on hazardous zones or areas vulnerable to such disasters. So, man is struggling to overcome the effects of all disasters, till date. Earthquakes are one of such disasters that are associated with ongoing tectonic processes. It suddenly occurs for seconds and causes great loss to life and property. So, earthquake disaster prevention/reduction and mitigation strategy are of global concern, today.

Every site has its particular seismic response at which ground shaking can be amplified, and if it matches with the fundamental frequency of manmade structures, there is great probability of damage. Role of local site conditions in the amplification of ground motion has been evident from 1989 San Francisco earthquake, 1995 Mexican earthquake and 1995 Los Angeles earthquake in the recent past and is reported by various scientists (e.g. Ansal et al. 2004; Slob et al. 2002; Olieveira 2004; Street et al. 2001). The areas located on young unconsolidated sedimentary deposits experienced greater amplification of ground motion (Hunter et al. 2002). In 2001, the epicentre of Bhuj earthquake was about 400 km away from Ahmadabad (India), but the city was highly affected by earthquake because it was located over the younger alluvial deposits (Ranjan 2005).

Low-amplitude soft sediment vibrations produced by the natural disturbances such as wind, sea tides or cultural noise such as traffic and industrial noise are called ambient noise. It is evident from various researches that the horizontal motion exceeds the vertical motion in soft ground. Many scientists have utilized H/V spectral ratios and compared this technique with other conventional techniques and proved the reliability and credibility of this technique such as Chavez-Garcia et al. (1990, 1996), Bard (1999) and Bour et al. (1998). Site characterization and microzonation of area of interest can be accomplished by utilizing H/V method (Qadri et al. 2015). There is agreement among research community about the reliability of H/V spectral ratios in terms of fundamental frequency of soft sediments. By using fundamental frequency of H/V spectral ratios, soil thickness can be estimated in a reliable way (Morales et al. 1991; Yamanaka et al. 1994; Parolai et al. 2002; Panou et al. 2005; Qadri et al. 2015). The cities of Rawalpindi and Islamabad are located in north of Pakistan. Both cities (Rawalpindi and Islamabad) are jointly named as "twin cities" as they are geographically merged due to the expansion of the urban area on both sides. Islamabad is the federal capital of Pakistan. The twin cities have a population of 3 million and consist of an area of 427 km^2 (Demographia 2013). The study area is subjected to seismic hazard due to its close connection with the several active faults (Lisa et al. 2004, 2007). Main Boundary Thrust (MBT), the Margalla, Panjal, Hazara, Jhelum, Mansehra and Murree fault systems are some of the noteworthy fault systems in the proximity of the study area (Lisa et al. 2004, 2007). Three structural zones (Margalla Hills, the piedmont fold belt and Soan syncline) trending generally east to northeast are present in our study area, which can be seen in Fig. 1. These structures represent the domination of compressional forces (Williams et al. 1999). Murree formation which is shown by Nrm in
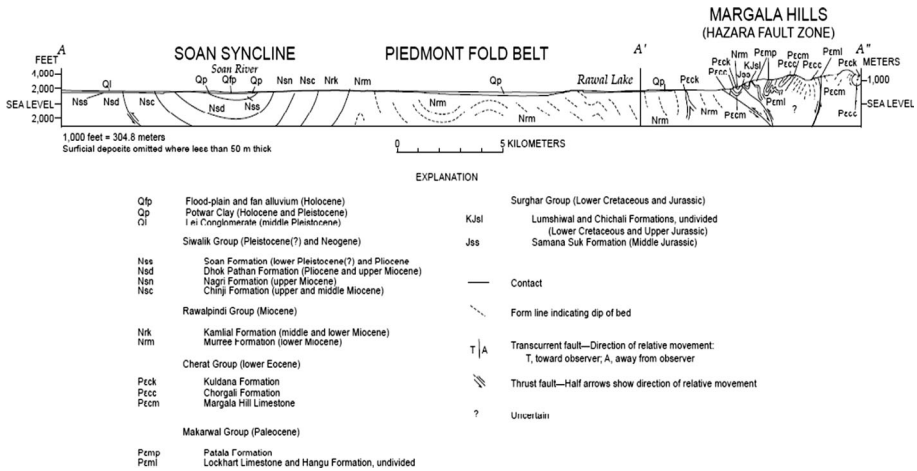
Fig. 1 Geological cross section A–A″ in the Islamabad–Rawalpindi study area, after Williams et al. (1999)

Fig. 1 is composed dominantly of sandstone and acts as bedrock in the study area. The loose sediments residing over bedrock comprises Potwar clay, terrace alluvium, undifferentiated alluvium, stream channel and windblown silt, stream channel alluvium of Holocene age (Williams et al. 1999). The stratigraphic detail of the study area can be seen in Fig. 2. The geology of the study area reveals that the lives of the inhabitants of twin cities are subjected to seismic hazard at any time.

The impact of local site conditions was exposed by the devastating Kashmir earthquake on 8 October 2005 ($M = 7.6$). Although its epicentre was nearly 200 km in NE of the study area, it not only jolted the whole Kashmir region but also trembled whole region of Islamabad. This natural disaster resulted in 86,000 fatalities and 1,00,000 injuries as well as heavy structural damage across the region. Mountainous areas near the epicentre suffered the most by the devastating impacts of the earthquake, while the study area was also subjected to considerable damage due to the sediment-induced amplification (NEIC 2005). In context of the importance of the study area, the aim of this work is to evaluate the local site effects and their role in amplifying hazard by estimating overburden depth (H), soil vulnerability index (K_g), fundamental frequency of soft soil (f_0) and corresponding H/V amplitude level (A_0) by utilizing H/V spectral ratio. It will help to understand the mechanism of sediment-induced amplifications triggering the disaster and to identify the most hazardous zone within the study area. The findings of the study will be beneficial for the town planners as well as for the policy makers to design the mitigation strategies to combat the effects of frequent earthquakes.

2 Data acquisition and processing

In present days, there are several techniques to evaluate and estimate local site effects and their role in amplifying disaster. Nakamura modified this technique in 1989 which makes use of spectral analysis of ambient noise to characterize the site response in urban environment. Initially, this technique was used in Japan (Nakamura 1989). CMG-40T is a rough-and-tough broad-based seismometer that is ideal to be installed in vaults with
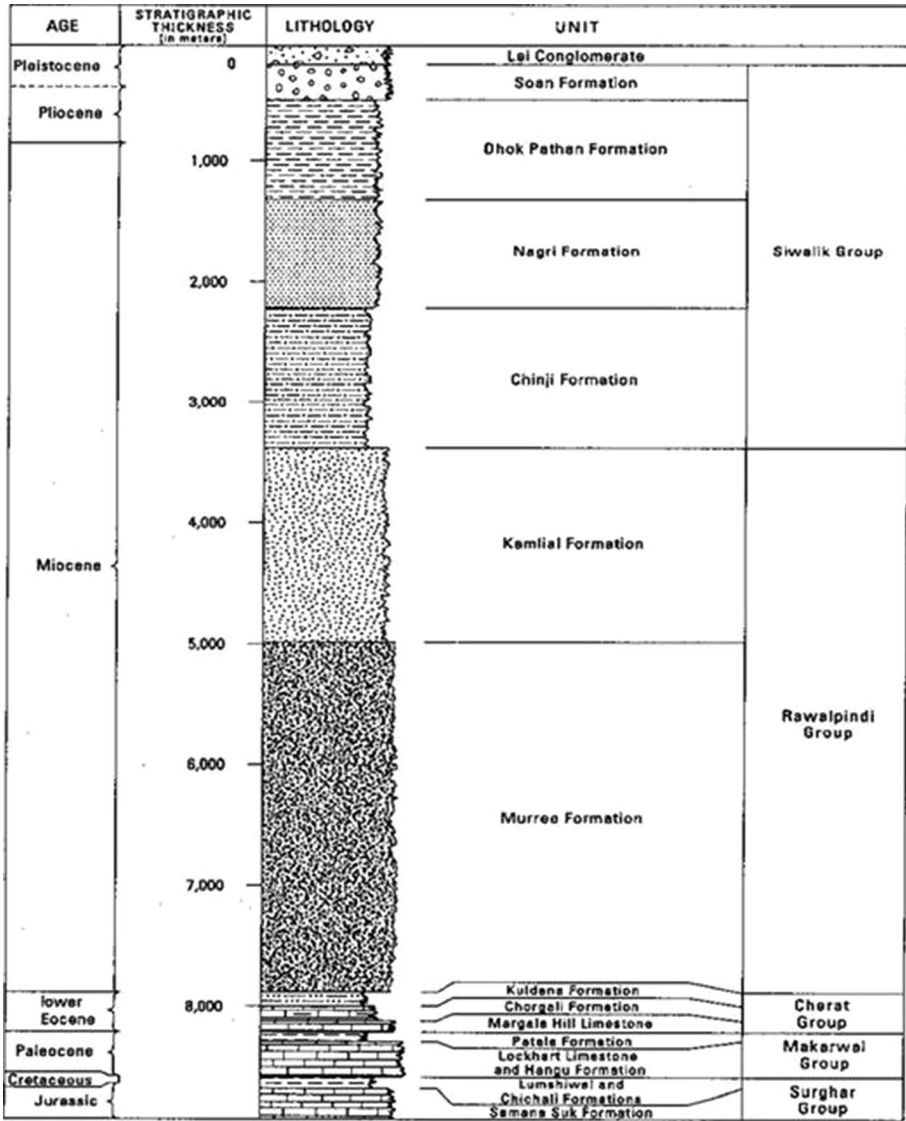
**Fig. 2** Stratigraphic section of consolidated rocks in Islamabad–Rawalpindi area, after Williams et al. (1999)

normal disturbances or ambient noise. It is enclosed in water-resistant stainless steel body. CMG-40T is a potable instrument that is easier to use in the field for data collection (just plug in and start using). There is no mass clamping associated with the seismometer that makes it easier and reliable to record the ambient noise (Fig. 3).

For this study, this instrument was used to acquire the ambient noise data from 105 sites of the twin cities located at different places (Fig. 1). In order to develop good soil/sensor coupling, seismometer was directly installed on the ground by using spikes on the base of seismometer. Sampling rate of 100 Hz was used during acquisition by keeping in view the
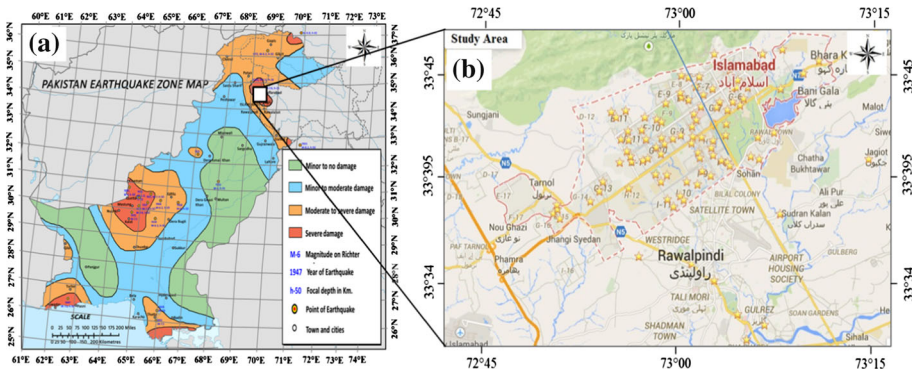
Fig. 3 **a** Seismic zonation map designed by Pakistan Metrological Department and **b** satellite image of study area, showing sites where data have been acquired

research carried out by various researchers (e.g. Paudyal et al. 2012; Warnana et al. 2011; Horike et al. 2001). Moreover, ambient noise recording was conducted for 10–30 min by keeping in view the work of different researchers (e.g. Bala et al. 2007a, b; Mundepi and Mahajan 2010; Chatelain and Guillier 2013). Ambient noise was acquired during night time to avoid manmade strong motion signals. SESAME guidelines (2004) along with Geopsy software (can be seen at www.geopsy.org) were also considered during data acquisition and processing. Acquired data were displayed on the receiver (laptop) by using SCREAM software, which helps in viewing, editing and replaying the waveform data in Guralp compressed file (GCF) format. Time windows contaminated by transients were removed by application of short-term average and long-term average abbreviated as STA and LTA, respectively. The basic objective of applying STA and LTA is to confirm the stationary of ambient vibrations and to overcome the signals associated with specific cultural noise, e.g. close traffic and footsteps (Bonnefoy-Claudet et al. 2009). Therefore, by applying a classical comparison between short-term average and long-term average, those problematic transients were detected (Bonnefoy-Claudet et al. 2009). Each ambient noise recording was fragmented into 25-s window. STA deals with the average level of signal amplitude over short period of time, and LTA deals with the average level of signal amplitude over long time period. STA and LTA were allocated a value of 2 and 30 s, respectively, with a low and high threshold of 0.2 and 2.5, respectively. While processing ambient noise data, Cosine taper was applied at both ends of the selected signal window to overcome the sudden and unexpected discontinuities which can affect the Fourier spectrum (Chatelain and Guillier 2013). Fourier amplitude spectra were smoothed by applying Konno–Ohmachi algorithm along with the Cosine taper (width = 0.25 %) and smoothing constant with a value of 40.00 (Konno and Ohmachi 1998). Automatic gain control (AGC) was applied to improve weak signals, while DC suppress played an important role to eliminate the instrumental effects in the waveform data. Next step was to compute H/V in each window by integrating the horizontal (north–south, east–west) components with a quadratic mean. Finally H/V was averaged over all selected windows. H/V curves in Fig. 4 indicate the average H/V curve (black line), the H/V amplitude, A_0 standard deviation curves (dashed lines) and the peak frequency standard deviation domains (the two vertical grey areas). The peak frequency is the value at the limit between the two grey areas. Soil vulnerability index (K_g), which is the ratio between A_0^2/f_0 was also calculated which helped
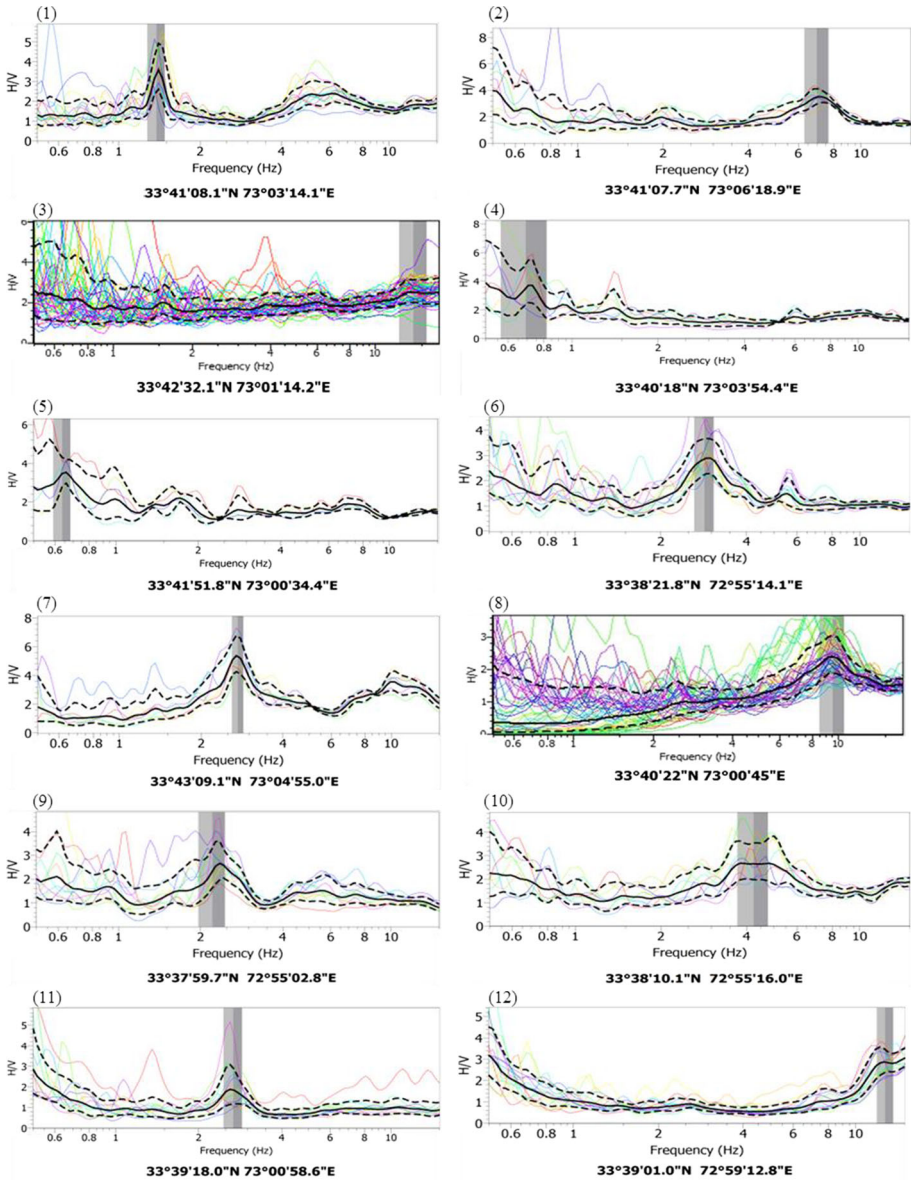
Fig. 4 Amplitude of *H/V* spectral ratios as a function of fundamental frequencies representing the site response at few selected sites in the study area. The *coloured lines* are *H/V* spectral ratio for different windows: *black solid line* is the average value, while *black discontinuous lines* represent standard deviation from the average value. The *bar* represents the fundamental frequency with two *grey shades* showing standard deviation

in indication of the areas where seismic hazard and susceptibility to disaster is high. By using inverse distance weighting (IDW) method, technique of interpolation was then applied on the data sets to notice the spatial extent of different local site effect parameters by
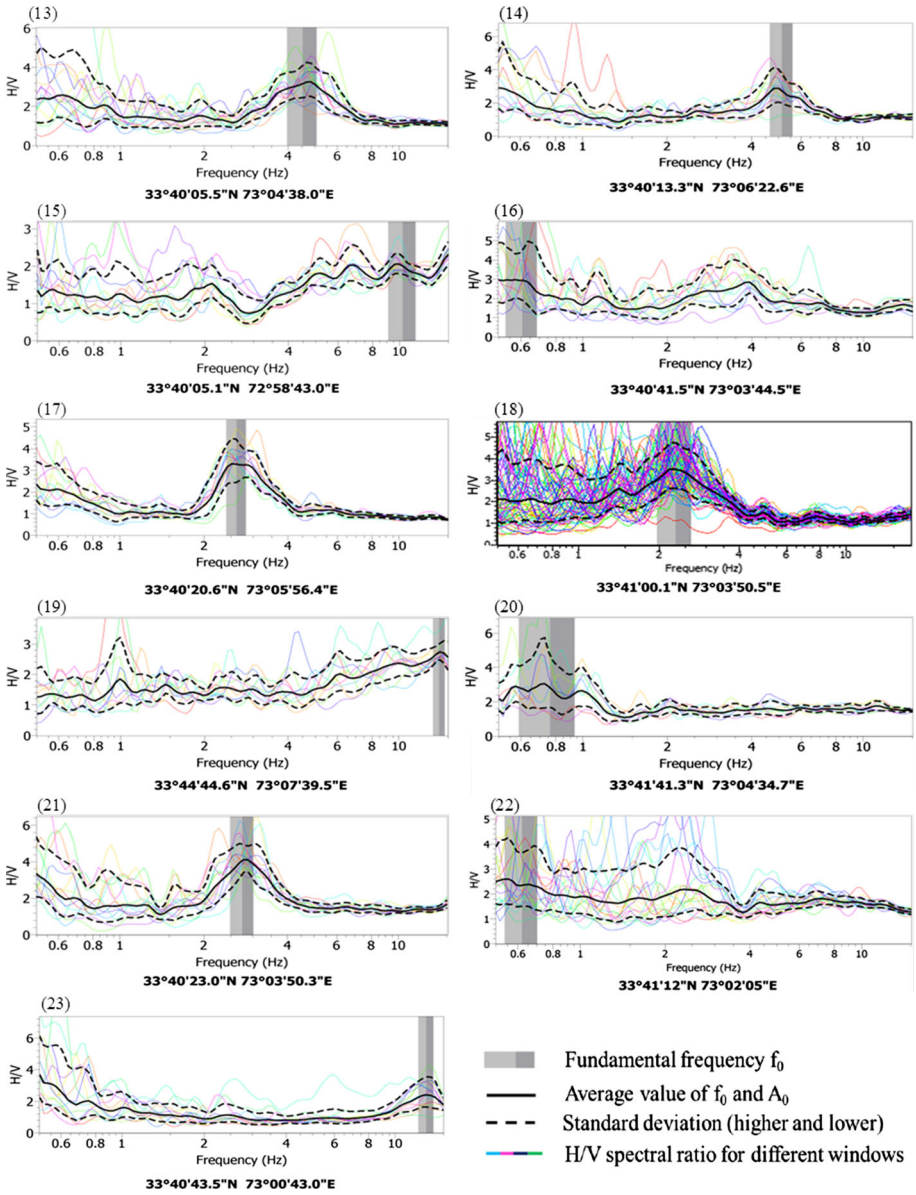
(13) 33°40'05.5"N 73°04'38.0"E

(14) 33°40'13.3"N 73°06'22.6"E

(15) 33°40'05.1"N 72°58'43.0"E

(16) 33°40'41.5"N 73°03'44.5"E

(17) 33°40'20.6"N 73°05'56.4"E

(18) 33°41'00.1"N 73°03'50.5"E

(19) 33°44'44.6"N 73°07'39.5"E

(20) 33°41'41.3"N 73°04'34.7"E

(21) 33°40'23.0"N 73°03'50.3"E

(22) 33°41'12"N 73°02'05"E

(23) 33°40'43.5"N 73°00'43.0"E

Fundamental frequency f_0
Average value of f_0 and A_0
Standard deviation (higher and lower)
H/V spectral ratio for different windows

Fig. 4 continued

using ArcGIS software. Some important data reliability conditions as mentioned by SESAME (2004), e.g. $f_0 > 10/L_w$, n_c (f_0) > 200 (where $n_c = n_w \times L_w$) and $A_0 \geq 2$, were also considered during data acquisition and processing. On the basis of these reliability conditions, data for 88 sites appeared as reliable.

3 Results and discussion

Figure 4 represents the H/V amplitude along y-axis and natural frequencies of the sediments along x-axis for all the sites. A grey bar is presented in each figure which represents average value of f_0 to its corresponding ambient noise H/V spectral ratio amplitudes A_0. Wiggles of multicolours are also present in each figure, indicating the presence of different frequency ranges. Middle continuous line is bounded by two discontinuous lines on either side. The upper discontinuous line represents "new high noise model" and lower discontinuous line represents "new low noise model". Some H/V curves reflect single peak with amplitude values decreasing on either side of curve: some reflect two or more peaks, while rest of the curves represent a broad pattern. According to studies conducted by Yong et al. (2008), study area depicts V_s in a range of 200–600 m/s, with lowest velocities in the southern most parts of the study area and highest velocities in the northern most parts of the study area. Interpolation has also been carried out to study the spatial extent of fundamental frequency of soft sediments, amplification factor and thickness of overburden and soil vulnerability index. These interpolated maps (Fig. 8) have been designed by using ArcGIS and applying Inverse Distance Weighted (IDW) method. In Fig. 8 interpolated maps have been classified as four colour schemes in part (a) and (b), while three colour schemes are allocated to part (c) and (d). It is important to mention that light grey colour depicts least value class, while dark grey colour reflect highest value class in terms of f_0, A_0, H and K_g. These interpolated maps show that f_0 was quite low in the central part of the area of interest and ranges between 0.6 and 15.00 Hz, approximately, while the amplification factor up to 5.5 was estimated within the study area. Moreover, overburden thickness of soft sediments residing on the bedrock was estimated up to 316.5 m by using Parolai's equation $108f_0^{-1.551}$. According to the results it is quite evident that depth to bedrock is extremely variable throughout the study area, which can be seen in Fig. 1. Irregular trend is observed in terms of fundamental frequency of soft sediments and their corresponding overburden thickness. Sites located in the central and southern most part of study area are reflecting greater overburden thickness of soft sediments (a roughly increasing trend from NE to SW in terms of overburden thickness) and are therefore more susceptible to the impact of hazard. The results obtained through H/V data, borehole data and structural map of the study area show very good correlation as shown in Fig. 8. Nakamura (1997) introduced vulnerability index parameter which comprises of A_0 and f_0 for the identification of areas which are susceptible to damage imposed by seismic hazard by using HVSR technique. Thus, K_g reflects local site effect and can be considered as a useful indicator for selection of sites vulnerable to damage Warnana et al. (2011). Moreover, high values of soil vulnerability index can significantly enhance the shaking hazard. As far as K_g is concerned, it was also highly variable, was lying in a range of 0.30–62.7 and was very high in the central part of the study area. Borehole data were also utilized to check the reliability of results related to overburden thickness. CDA1A, CDA5, CDA6, CDA8, CDA16, CD17, CDA18 and CDA21 borehole data in Fig. 5 are located at some of the sites of data acquisition with their corresponding H/V curves in Fig. 4(8), (22) and showed a very good correlation with the overburden thickness estimated by H/V spectral ratio technique. Borehole log CDA1A shows that bedrock was not observed up to a depth of more than 409 feet (>125 m), while the depth of bedrock estimated by H/V spectral ratio technique for the same site shown in Fig. 4(22) was 230 m by using Parolai's equation $108f_0^{-1.551}$. Similarly, CDA5 shows a bedrock depth of 10 feet (3.05 m), while depth estimated by H/V spectral ratio technique for the same site shown in Fig. 4(8)
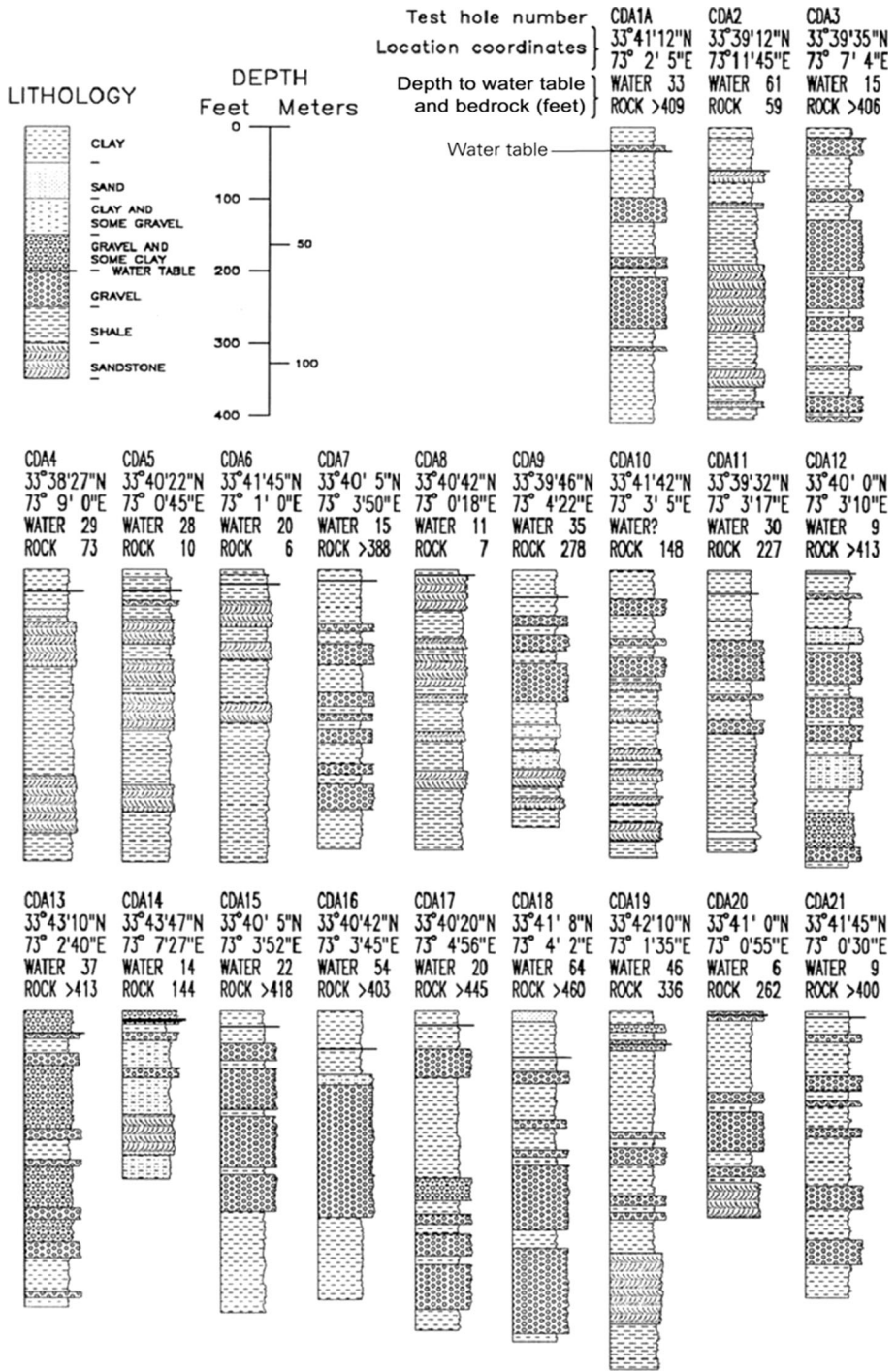
Fig. 5 Borehole logs of the Capital Development Authority (CDA) within the study area after Ashraf and Hanif (1980) and Williams et al. (1999)

describes the bedrock depth as 3.1 m. *H/V* curve for the site near CDA6 shown in Fig. 4(3) reflects an overburden depth of 1.73 m, while borehole data in Fig. 5 state it as 6 feet (1.8 m). Figure 4(23) is *H/V* curve obtained by acquiring ambient noise data near to CDA8 borehole site shown in Fig. 5. Bedrock depth information obtained from *H/V* curve for this site shows it to be 1.91 m, while borehole data show it as 7 feet (2.1 m). CDA16 in Fig. 5 is quite near to the site of *H/V* curve shown in Fig. 4(16). Borehole data show that bedrock was not found up to 403 feet (123 m), while *H/V* spectral ratio technique states overburden thickness up to 185 m. *H/V* curve shown in Fig. 4(20) comprises of ambient noise data acquired in the vicinity of CDA17. The soft sediment thickness estimated by *H/V* spectral technique is approximately 161 m (528 feet), while the borehole data show that bedrock was not found up to the depth of 445 feet or the bedrock was in depth of more than 445 feet (>135 m). Figure 4(1) reflects ambient noise data acquired in the vicinity of CDA18 borehole site. The information obtained from CDA18 borehole data shows a very close estimation of depth calculated by *H/V* spectral ratio technique. Both data sets represent greater overburden thickness residing over bedrock. CDA18 borehole data state that bedrock depth was more than 460 feet (140 m), while *H/V* spectral ratio technique estimates it to be 82 m. Similarly, CDA21 borehole data show a very good correlation in terms of bedrock depth with overburden thickness or bedrock depth calculated by *H/V* spectral ratio technique. *H/V* curve obtained by the ambient noise data in the vicinity of CDA21 is shown as Fig. 4(5). CDA21 describes that bedrock was not observed up to 400 feet or that it is at a depth >400 feet (122 m), while the information inferred from Fig. 4(5) describes that bedrock is at a depth of 190 m approximately. In general, the data used in Figs. 4 and 5 show a very good correlation and establish the reliability of ambient noise data acquired in the study.

Figure 6 elaborates the graph in which bedrock depth (*H*) is plotted against fundamental frequency, f_0 recorded from 88 sites (only reliable data) of the studied area. It can be seen that the fundamental frequency is decreasing with the increasing trend of loose sediment deposits. The findings shown in Fig. 6 are in strong agreement with the studies of other researchers, e.g. Parolai et al. (2002) and Panou et al. (2005).
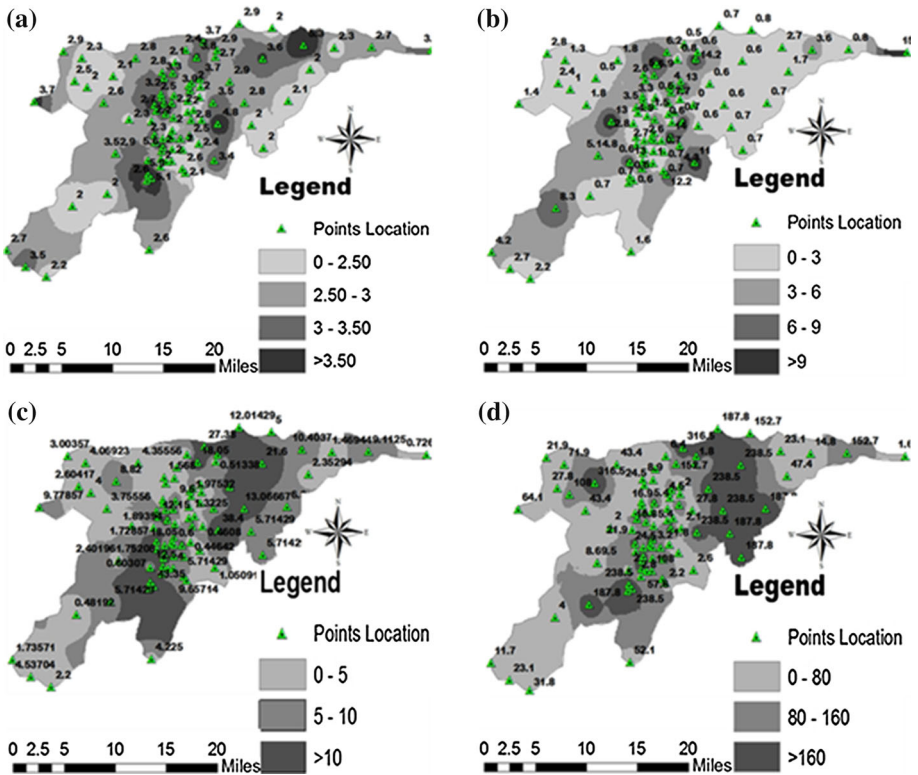
Figure 7 shows absence of any correlation between amplification factor and fundamental frequency of loose sediments. Both the parameters, i.e. A_0 and f_0, are independent
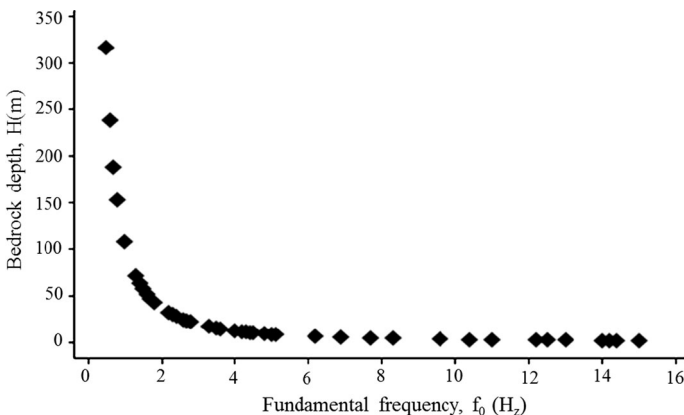
Fig. 6 Graph showing bedrock depth (*H*) versus fundamental frequency (f_0)
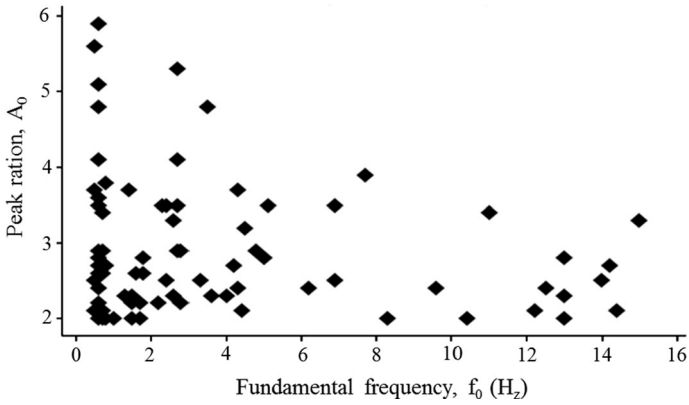
Fig. 7 Peak ratio (A_0) versus predominant frequency graph of HVSR peak

Fig. 8 Interpolated map representing amplification factor A_0 (**a**) and fundamental frequency f_0 in Hz (**b**), soil vulnerability index K_g (**c**) and the soft sediment thickness distribution H in meter (**d**)

of each other. This finding is also in agreement with the findings of Parolai et al. (2002), Panou et al. (2005) and Warnana et al. (2011). These researchers did not find any relation between f_0 and A_0 in their work (Fig. 8).

4 Conclusion

In this study, *H/V* spectral ratio technique was applied for local site effects estimation and correlation with seismic risk assessment in Rawalpindi–Islamabad by recording ambient noise through CMG-40T seismometer. This area is fully seismic prone which already suffered through this kind of natural hazard in the past. Unfortunately, there is no specific study about this area in which this threatening issue has been highlighted by using this *H/V* spectral ratio technique. In this context, this study is highly significant to determine the seismic risk assessment. For this purpose, the ambient noise data from 105 sites of the twin cities located at different places were acquired and analysed. By using these data, fundamental frequency, amplification factor and thickness of soft sediments were estimated along with the estimation of soil vulnerability index. The acquired ambient noise data and their corresponding *H/V* curves (Fig. 4) showed a very good correlation with borehole data (Fig. 5). Results indicate that the study area is vulnerable to damage and under serious threat by an earthquake.

The findings of the study are highly useful for the policy makers and disaster management authorities to make the mitigation strategies to combat the effect of the natural hazard.

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