RESEARCH PAPER

Ambient noise H/V spectral ratio in site effects estimation in Fateh jang area, Pakistan

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Abstract Local geology or local site effect is a crucial component while conducting seismic risk assessment studies. Investigations made by utilization of ambient noise are an effective tool for local site estimation. The present study is conducted to perform site response analysis at 13 different sites within urban settlements of Fateh jang area (Pakistan). The aim of this study was achieved by utilizing Nakamura method or H/V spectral ratio method. Some important local site parameters, e.g., the fundamental frequencies f_0 of soft sediments, amplitudes A_0 of corresponding H/V spectral ratios, and alluvium thicknesses over 13 sites within the study area, were measured and analyzed. The results show that the study area reflects low fundamental frequency f_0. The fundamental frequencies of the sediments are highly variable and lie in a range of 0.6–13.0 Hz. Similarly, amplification factors at these sites are in the range of 2.0–4.0.

Keywords Local site effect · Ambient noise · H/V spectral ratios · Fundamental frequency · Amplification factor · Alluvium thickness

1 Introduction

It is quite obvious from the history of human civilization that man has been struggling to defeat the natural disasters since its origin. Earthquakes are one of those deadliest events that change the entire landscape, and they are associated with tectonic processes. Heavy life losses, disaster to property, disturbance to the normal life pattern, and termination of the developmental processes of a country or region are some of disastrous impacts of these inevitable events (Ram Kumar 2009). There is a need to study and understand the contributing factors in this aspect for safety purpose and remedial measures. So earthquake disaster prevention/reduction and mitigation strategy is of global concern today.

Local site conditions can significantly enhance the risk factor in areas adjacent and remote from the epicenter. Every site exhibits its particular seismic response at which ground motion can be amplified. If it coincides or corresponds with the fundamental frequencies of manmade infrastructures, then there is great possibility of disaster. In the recent past, San Francisco earthquake 1989, Mexican earthquake 1995, Los Angeles earthquake 1995 are a few classical examples of amplification of ground motion triggered as a consequence of local site conditions (Ansal et al. 2004; Slob et al. 2002; Street et al. 2001). In 2001, the epicenter of Bhuj earthquake was about 400 km away from Ahmedabad (India), but it was highly affected by earthquake because the city was located over the younger alluvial deposits (Ranjan 2005).

The areas located on young unconsolidated sedimentary deposits experienced greater amplification of ground motion due to impedance contrast (Hunter et al. 2002). Sediment thickness and physical properties of the material vary from place to place, which can result in trapping and amplification of seismic waves during a seismic event resulting in different resonant frequencies at very small distances (Paudyal et al. 2012). This resonance frequency is very important because it represents the frequency at which

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soft sediments amplify the ground motion caused by a seismic event. This particular phenomenon is called the site effect (Paudyal et al. 2012). Due to anisotropic and heterogeneous characteristics of the site soil layer, local site conditions are considered more adaptable and compliant compared to the path effect (Ren et al. 2013). Natural disturbances such as wind, sea tides, or cultural noise such as industrial and traffic noise produce low-amplitude vibrations. These low-amplitude vibrations are termed the ambient noise. Various researchers have shown that horizontal motion exceeds the vertical motion in soft ground (Nakamura 1989). Many scientists such as Chávez-García et al. (1990, 1996), Bard (1999), Bour et al. (1998) have utilized H/V and proven the reliability and credibility of this technique. H/V method is a very reliable method for estimating alluvium thickness by means of fundamental frequencies of the soft sediments (Morales et al. 1991; Yamanaka et al. 1994; Parolai et al. 2002; Panou et al. 2005). Contrary to the fundamental frequency f_0, amplification factor A_0 reveals disagreement between opinions and findings of different scientists. Numerous scientists have reached satisfactory correlation, while others failed to do so (Horike et al. 2001).

Fateh jang is a small town situated within the longitudinal range of 72°38′26″E–72°50′37″E and latitudinal range of 33°32′7″N–33°40′7″N at a distance of nearly 50 km from Islamabad (Federal Capital of Pakistan). New developmental projects are expected to accelerate as a result of ongoing construction of New Islamabad

International Airport in the study area, which will be operational by April 2015. This airport is conjectured to be a contemporary marker structure symbolic representation of the twenty-first century, as it will be its political and trade entrance via the capital of Pakistan, Islamabad. The Civil Aviation Authority (CAA) has declared that it is to be named Gandhara International Airport, and it will be operational from April 2015. Therefore, Fateh jang area has been selected for the case study keeping in view the future perspective and its prime significance. As far as the recent deposits are concerned, thick alluvium, along with conglomerates, covers most of the study area (Qaisar et al. 2008).

Fateh jang lies in the south of Main Boundary Thrust (MBT) which indicates complex folding and faulting (Jaswal 1990). Rocks of Eocene to Paleocene ages have been thrust over molasses sediments. Study area reflects region of deformation during Neogene age situated in the footwall of MBT (Faisal 2005). These blind thrusts and imbrications of MBT disappear in overlying Murree formation (Faisal 2005). Stratigraphic succession of the study area is shown in Fig. 2. Fateh jang is seismically active area owing to its location in Himalayan foreland. As far as seismic zonation map (developed by Pakistan Meteorological department) is concerned, Fateh jang lies on the border of zone 2-B and zone 3 (Fig. 1). Therefore, the study area exhibits moderate level seismicity, and suffered from significant damage during M_w 5.3 earthquake in 1993 (Qaisar et al. 2008).
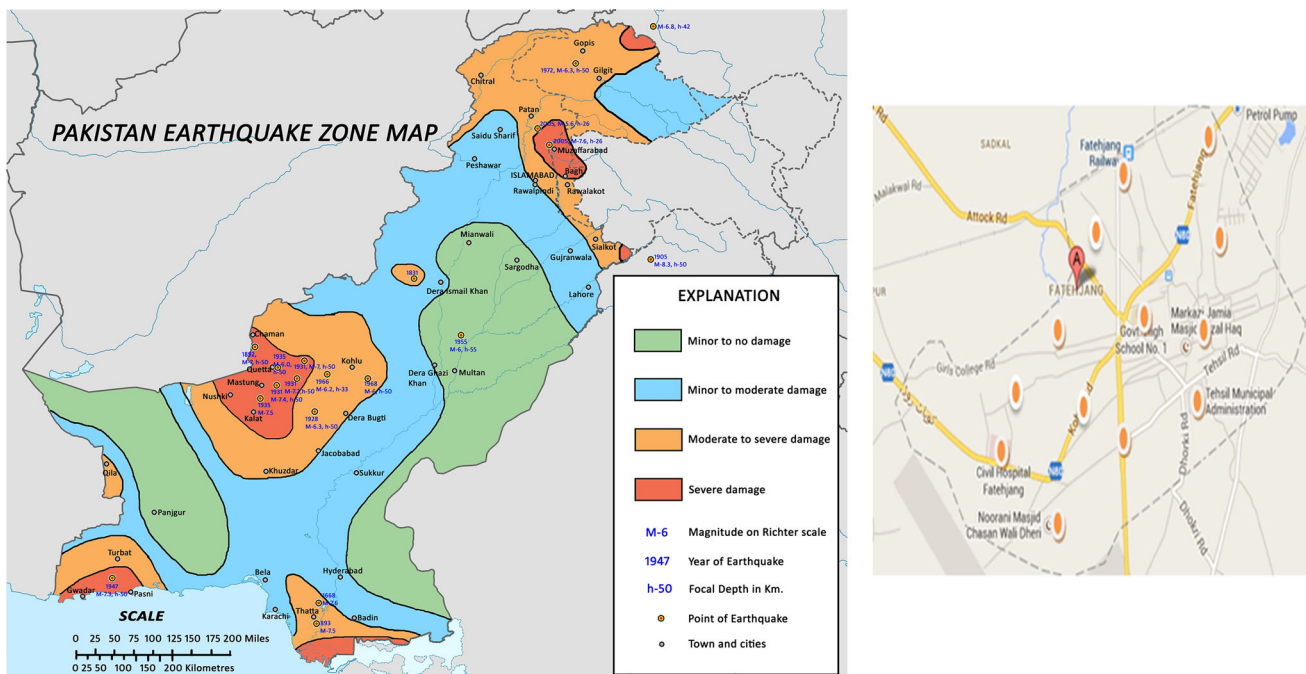

Fig. 1 Seismic zonation map designed by Pakistan Metrological Department and the satellite image representing sites of data acquisition within study area
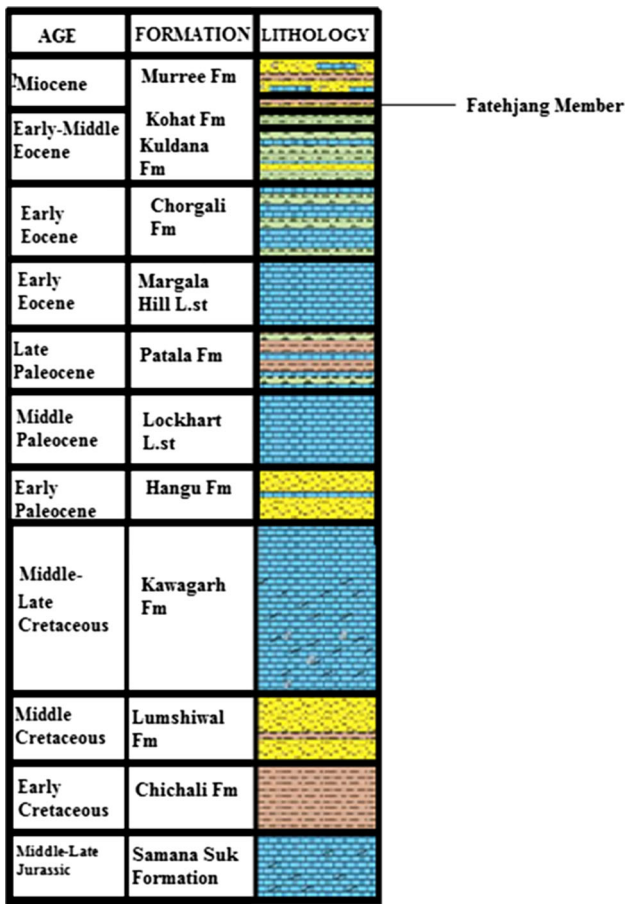
AGE	FORMATION	LITHOLOGY
Miocene	Murree Fm	
Early-Middle Eocene	Kohat Fm Kuldana Fm	
Early Eocene	Chorgali Fm	
Early Eocene	Margala Hill L.st	
Late Paleocene	Patala Fm	
Middle Paleocene	Lockhart L.st	
Early Paleocene	Hangu Fm	
Middle-Late Cretaceous	Kawagarh Fm	
Middle Cretaceous	Lumshiwal Fm	
Early Cretaceous	Chichali Fm	
Middle-Late Jurassic	Samana Suk Formation	

— Fatehjang Member

Fig. 2 Stratigraphic succession of Fateh jang area after Latif (1968) and Shah (1977)

Numerous fresh water streams in the Murree Formation drain into the northern area of Fateh jang. The overall drainage pattern of the study area (Fig. 3) is medium-to-fine dendritic which represents the homogeneous soft material. A medium-to-fine dendritic drainage without any angularity is freely developed in soft materials, and there is no control of soft material over development of drainage pattern (Way 1973).

As the substrate of the study area and its surrounding is soft and easily erodible, the meanders with variable sinuosity develop due to low stream gradient. Meandering streams are the characteristic geomorphic feature of fine-grained soft sediments (Plummer et al. 2005). The sinuous curves develop as a result of increase in stream's velocity on the outside of the curve, and this high velocity erodes the material on respective river bank, whereas the stream's velocity is low on the inside, and results in the deposition of sediments. Usually, sand bars are deposited in the form of arcuate ridges of sand. The position of the meanders is not fixed (Plummer et al. 2005). As far as the study area is concerned, the meandering streams are not

mature enough for the development of oxbow lakes. Almost the same patterns of drainage system and meandering streams have been observed from Fateh jang areas, which clearly indicate the presence of soft sediments in the study area. In the context of the importance of the study area, the aims of this work are evaluating the local site effects, and estimating the fundamental frequencies of soft soil f_0 and corresponding H/V amplitude levels A_0 utilizing the H/V spectral ratio. It will help us 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 with local or distant epicentral locations.

1.1 H/V method

The H/V method has received worldwide concentration from all over the world due to its simple methodology along with its ability to produce quick information about dynamic characteristics of ground and structures (Nakamura 1989). Another advantage of this technique is the simplicity in data collection and its implementation in areas of moderate-to-low seismicity. H/V method is also called as Nakamura method which was at first introduced by (Nogoshi and Igarashi 1971) and modified by Nakamura. This technique is based on recording of microtremors or ambient noise which is short-period vibration, which resulting from coastal effects, atmospheric loading, wind interaction with structure and vegetation, and cultural sources like traffic, trains, construction, and factories. To record microtremors, most researchers use only one or a few seismometers that can measure very weak ground motions. This method proves to be time effective and demands fewer instruments compared to requirements in classical geophysical techniques (Nakamura 1989). Moreover, it is a passive technique which can be readily used in urban areas. Moreover, Nakamura technique does not require any seismic event to occur. Due to wide ranges of noise sources, microtremors occur in a wide frequency range of 0.02–50 Hz, and this makes it possible to explore the depths of more than 100 m depending upon the sensitivity of sensor (Horike 1985). Reliability of this technique is significantly enhanced if we have knowledge of the sediment thickness or S-velocity structure of subsurface (Bard 1999). The microtremors are recorded with three components that include two orthogonal horizontal components and one vertical component. A microtremor time series recording represents the convolution of (i) source effects, (ii) propagation effects of source to receiver, (iii) the effect of the recording instrument, and (iv) the response
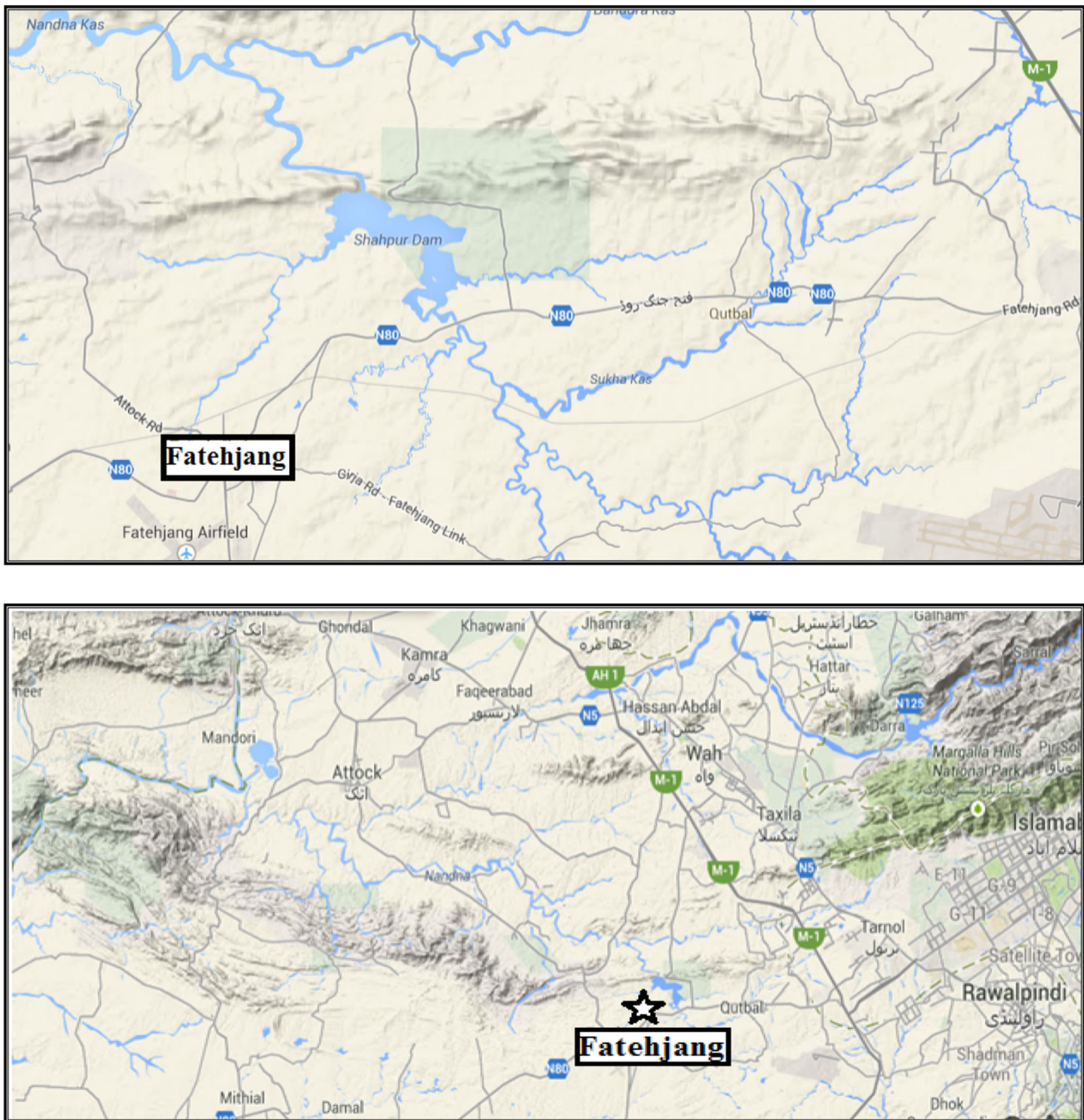
Fig. 3 Satellite image of the dendritic drainage pattern within the study area

of the site. These four factors are multiplied in the frequency domain, and given certain assumptions; the division of horizontal Fourier amplitude spectrum by the vertical spectrum can remove the first three effects, thereby isolating the site response (Molnar et al. 2007). In spite of its limitations, H/V method is a preliminary step toward site characteristics' estimation and microzonation of areas of interest (Qaisar et al. 2008).

1.2 Datasets and methodology

H/V method which was modified by Nakamura (1989) is one of the most utilized techniques for the analysis of site-response analysis these days. This technique makes use of spectral analysis of ambient noise to illustrate the site response in urban environment. The H/V spectral ratio is based on impedance contrast, which means the presence of

Table 1 Reliability of frequency peaks/curves on the basis of parameters defined by guidelines modified by SESAME (2004) against each station

Sr. no	Latitude (°N) and Longitude (°E)	f_0 (Hz)	$A_0 \geq 2$	$f_0 > 10/L_w$	N_w	$n_c = n_w \times L_w$	n_c $(f_0) > 200$	Comment
1	33.562972, 72.650368	0.6	2.5	0.4	19	475	285	Reliable
2	33.560653, 72.628470	4.6	3.2	0.4	17	425	1,955	Reliable
3	33.565894, 72.638792	0.8	2.1	0.4	13	325	260	Reliable
4	33.5765131, 72.647352	3.0	2.0	0.4	13	325	975	Reliable
5	33.567648, 72.644325	0.7	4.0	0.4	16	400	280	Reliable
6	33.5685572, 72.640754	4.2	2.2	0.4	15	375	1,575	Reliable
7	33.565447, 72.647801	12.0	2.3	0.4	18	450	5,400	Reliable
8	33.5621563, 72.6318812	2.3	2.3	0.4	16	400	920	Reliable
9	33.560923, 72.637180	3.1	2.9	0.4	13	325	1,007.5	Reliable
10	33.571751, 72.651999	13.0	2.3	0.4	12	300	3,900	Reliable
11	33.5772997, 72.6551628	3.4	3.3	0.4	16	400	1,360	Reliable
12	33.557069, 72.635061	5.1	2.8	0.4	13	325	1,657.5	Reliable
13	33.560362, 72.642386	6.6	2.6	0.4	17	425	2,805	Reliable

Table 2 Tabular display of 13 sites of data acquisition along with corresponding fundamental frequencies f_0, amplification factors A_0, and alluvium thicknesses H

Serial no	Latitudes and Longitudes	Fundamental frequency f_0 (Hz)	H/V amplitude (A_0)	Approx. thickness of alluvium $H(m)$ = $108\, f_0^{-1.551}$ (Parolai formula)
1	33.562972, 72.650368	0.6	2.5	238.5
2	33.560653, 72.628470	4.6	3.2	10.1
3	33.565894, 72.638792	0.8	2.1	152.7
4	33.5765131,72.647352	3.0	2.0	19.6
5	33.567648, 72.644325	0.7	4.0	187.8
6	33.5685572, 72.640754	4.2	2.2	11.7
7	33.565447, 72.647801	12.0	2.3	2.3
8	33.5621563,72.6318812	2.3	2.3	29.7
9	33.560923, 72.637180	3.1	2.9	18.7
10	33.571751, 72.651999	13.0	2.3	2.02
11	33.5772997, 72.6551628	3.4	3.3	16.2
12	33.557069, 72.635061	5.1	2.8	8.63
13	33.560362, 72.642386	6.6	2.6	5.8

overlying of soft sediments on a harder bed rock. The present study was conducted by acquiring ambient noise data at 13 different data points (Fig. 1) by means of CMG-40T broad-based seismometer. Acquired data were displayed on the receiver (laptop) by means of the software termed "SCREAM" which played an efficient role in acquiring, viewing, recording, transmitting, and replaying the GCF data received through any Guralp seismometer. Recorded ambient noise was inspected to check erroneous measurement by displaying and viewing GCF files of ambient noise data on SCREAM software. Guidelines from SESAME (2004) were considered during data acquisition

and processing steps to check the reliability of ambient noise data. Some of the conditions for data reliability such as $f_0 > 10/I_w$, n_c $(f_0) > 200$ (where $n_c = n_w \times I_w$) and $A_0 \geq 2$ were checked keeping in view the guidelines from SESAME (2004). These data reliability parameters are shown in Table 1. On the basis of information presented in Table 1, acquired data appear reliable. Although sampling rate of 50 Hz is sufficient for geotechnical purpose, sampling rate of 100 Hz was yet used to record the maximum number of types of ambient noise during data acquisition (SESAME 2004). In order to develop good soil/sensor coupling, seismometer was directly installed on the ground
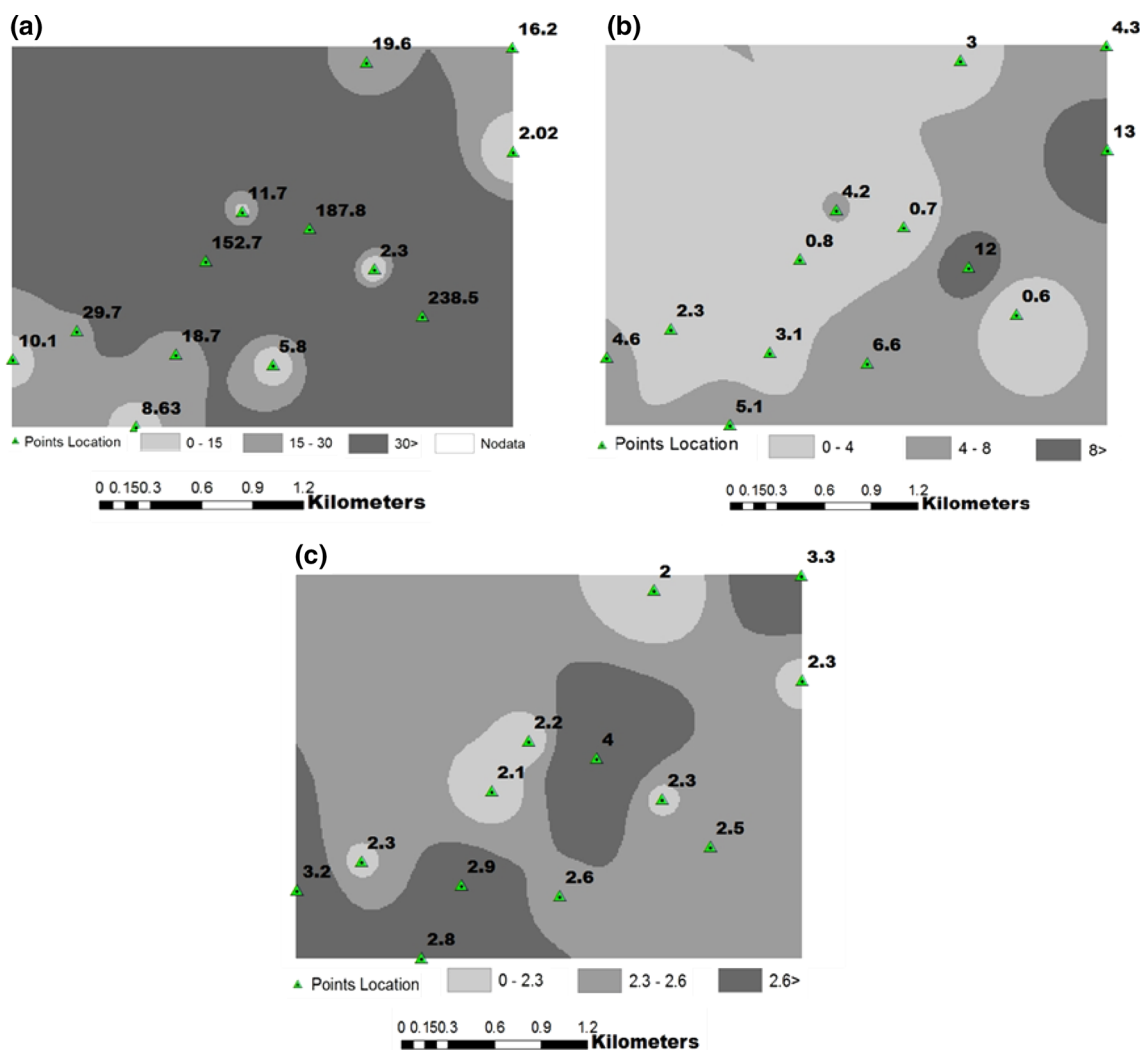
Fig. 4 Interpolated map representing **a** alluvium thickness distribution H in meter; **b** fundamental frequency f_0 in Hz; **c** amplification factor A_0

using spikes on the base of seismometer. With a sampling rate of 100 Hz, a continuous recording of ambient noise for 10–20 min was conducted keeping the studies of different scientists in view (Ohta et al. 1978). Software "Geopsy" played a vital role during ambient noise data processing. Each recording was then split into a 25-s window through short-term average (STA)/long-term average (LTA) anti-trigger. A value of 2 s was selected for STA, while a value of 30 s for LTA with low and high thresholds of 0.2 and 2.5, respectively. While processing ambient noise data, Cosine taper is 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). Weak signals were improved by means of automatic gain

control (AGC), and instrumental effects were removed using DC suppression. These processing steps were carried under the guidelines provided in the manual of Geopsy software (can be seen at www.geopsy.org). Next step is to compute H/V in each window by integrating the horizontal (north–south, east–west) components with a quadratic mean. Finally, H/V is averaged over all selected windows. H/V curves in Fig. 5 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 gray areas). The peak frequency is the value at the limit between the two gray areas. IDW method (Inverse Distance Weighted method) of interpolation was also applied on datasets by means of the software Arc GIS. Interpolation was applied to identify the spatial extent of fundamental frequency f_0 and the alluvium thickness H datasets within the study area as shown in Table 2.
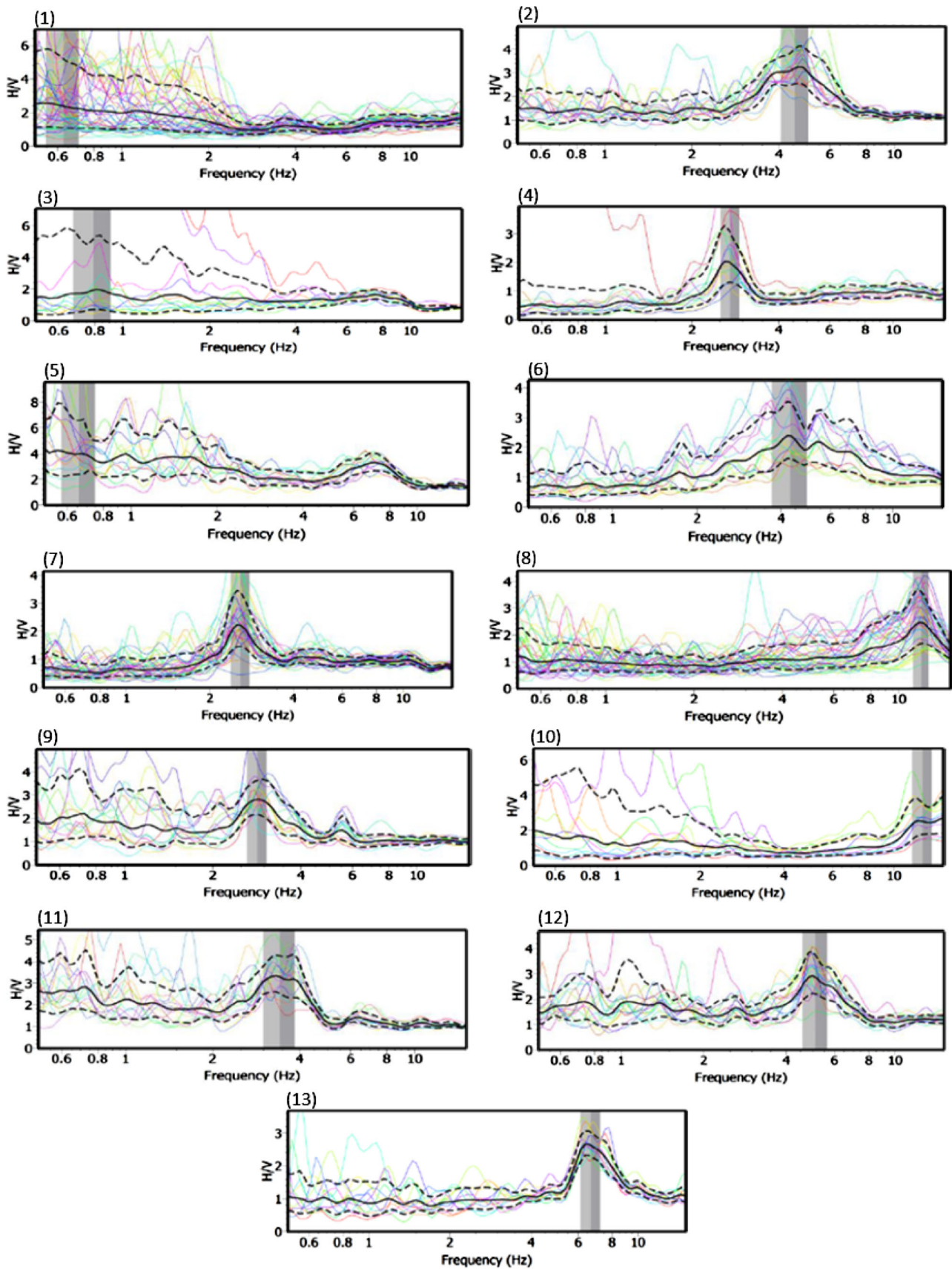
Fig. 5 Amplitudes of H/V spectral ratios as a function of fundamental frequencies

2 Results

Local site conditions contribute significantly to ground motion characteristics and seismic behavior of infrastructures (Ruizhi et al. 2011). Natural frequencies of the sediments (x-axis) and amplification factors A_0 or H/V amplitudes (y-axis) are plotted for all the 13 sites as shown in Fig. 2. The gray area represents the averaged peak frequency and its standard deviation. The frequency value is at the limit between the dark gray and light gray areas. The variegated colored lines are the H/V curves coming from each time window. The black plain line is the H/V average curve coming from individual time window H/V curves, and the discontinuous lines are the standard deviations. H/V curves reflect different patterns such as single peak curve, multiple peak curves, and broad curves. Fundamental frequencies f_0 of soft sediments lying over the bedrock were recorded at 13 different sites within the study area. IDW method is also applied to conduct interpolation of the fundamental frequencies f_0, which identifies the zones of the highest, the intermediate, and the lowest frequencies (Fig. 4). The study area has been divided into three different ranges in terms of fundamental frequency f_0, i.e., the zone 1 with f_0 ranging from 0 to 4.0 Hz (lowest f_0), the zone 2 with f_0 ranging between 4 and 8.0 Hz (intermediate f_0), and the zone 3 with f_0 greater than 8.0 Hz (highest f_0). The zone comprising the highest frequency value is shown by dark gray shade, while light gray shade represents the lowest-frequency zone. Zone of intermediate frequency is allotted a color in between dark and light gray in the interpolated map (Fig. 4). The maximum value for fundamental frequency f_0 was 13.0 in the study area, while the lowest value of fundamental frequency was 0.6 Hz. According to the results, it is quite evident that depth to bedrock is extremely variable throughout the study area ranging between 2.02 and 238.5 meters. Thickness of alluvium was derived from mathematical formula $H = 108\ f_0^{-1.551}$ (Parolai et al. 2002). These results were also interpolated to check the spatial extent of alluvium thickness (H) in the study area by using Arc GIS (Fig. 4). Alluvium thicknesses were also divided into three classes in the study area and were allotted different color schemes. It can be seen that the fundamental frequencies of soft sediments are very low in the central parts compared with the southern and the northernmost parts of the study area. That is why the sites in the central part of the study area exhibit more thickness of soft alluvium on the bed rock compared to the sites away from the central parts of the study area. The findings shown in Figs. 4, 5 are in strong agreement with the studies of other researchers who have utilized H/V spectral ratio analysis to identify the thickness of soft alluvium overlying the bed rock, e.g., Parolai et al. (2002).

Many researchers have shown that the largest amplification of ground motion will be observed at the lowest fundamental frequency (e.g., Bala et al. 2007a, b). As far as (A_0) amplification factor is concerned, a disagreement is observed while establishing its correlation with fundamental frequency f_0. This result was again in agreement with the studies of many researchers and scientists (e.g., Field and Jacob 1995; Lachet et al. 1996).

3 Discussion and conclusions

Local site effects such as fundamental frequency f_0, amplification factor A_0, and thickness of soft sediments over bedrock H were estimated at 13 sites of Fateh jang area using the H/V spectral method. CMG-40T seismometer was used to record ambient noise. The measurement of these local site effects was highly significant to assess the seismic risk in the study area. The study area reflects a high variability in terms of fundamental frequency f_0 and alluvium thickness H. Overall results reflect low values of fundamental frequency (f_0) and corresponding greater values of alluvium thickness (H), thus indicating a greater seismic risk triggered by soil amplification in the study area. The findings of the study showed complete agreement with the research studies conducted by Field and Jacob (1995), Lachet et al. (1996), Parolai et al. (2002), and Panou et al. (2005), (Bala et al. 2007a, b).

The first indispensable step toward seismic hazard's mitigation is the seismic risk assessment. The findings of the study are highly useful for the policy makers and disaster management authorities to devise the mitigation strategies in order to combat the effects of this natural hazard.

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