






Site Effects Study in the Peshawar District using Seismic Noise

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Abstract

Surficial geology plays an important role during earthquakes in terms of its impact on the resulting ground shaking, referred to as site effects. Site effects influence the level of earthquake hazard and risk in a region. Peshawar, the provincial capital of Khyber Pakhtunkhwa, is one of the most seismically active cities in Pakistan. However, it lacks any such seismic characterization. In this work, a seismic ambient noise study was performed in Peshawar using observations from a total of 92 stations. The seismic noise data is recorded using a broadband seismometer for a period of about 30 minutes at every station point. The fundamental resonance frequency and a first-order amplification based on the seismic noise recording are estimated using the method of Nakamura. First-order estimates of the amplification range from 1.0 to 7.0, whereas the resonance frequency ranges between 0.2 to 2.5 Hz. The results suggest a complex geological structure with low seismic impedance and deep soil deposits in Peshawar. The depth of soil deposits is estimated to be more than 300 m, leading to a potential amplification of low-frequency seismic waves. These findings are crucial for tall structures with fundamental vibration periods greater than 0.40 sec.

Keywords: Seismic Noise Peshawar; Site Effects; H/V Ratios.

1. Introduction

Peshawar is the provincial capital of the Khyber Pakhtunkhwa province of Pakistan. It is one of the oldest and most densely populated cities in Pakistan, with a total population of more than 4.2 million according to the 2017 census [1]. Peshawar is located very close to some of the world's most seismically active regions. The Hindu Kush region in Afghanistan lies only about 200 km north-west of Peshawar, while the Main Boundary Thrust (MBT) faults pass about 30 km to the south of the city. According to the building code of Pakistan, Seismic Provision 2007, Peshawar is in zone 2B, which corresponds to a peak ground acceleration (PGA) range of 0.16 g to 0.24 g with a 10% probability of exceedance over 50 years for rock site conditions [2]. Various studies have estimated different levels of seismic hazard for Peshawar, as summarized in Table 1 of Mahmood et al. (2020) [3]. These estimates range from 0.06 g to a maximum estimate of 0.4 g for return periods of 475 years for rock site conditions. This huge range of variability exists because of different assumptions and the methodologies adopted in the assessment of the seismic hazard. A recent earthquake of Mw 7.5 in 2015, whose epicenter was in Hindukush, about 280 km from Peshawar, saw a peak ground horizontal acceleration of 0.053 g recorded in Peshawar [4]. The hypocentre of this earthquake was located at a depth of 210 km,

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and despite the large depth and epicenter distance, this earthquake caused some heavy damage to residential and public buildings in the city [5]. For example, due to this earthquake, the masonry retaining wall of the historic Qila Bala Hisar fortress collapsed.

Apart from the size and the epicenter distance of an earthquake, the response of buildings and the consequent damage in a region depends on the condition of local surficial materials, such as soft or hard strata, and the presence of certain geological structures, e.g., geological basins. The contribution of surficial materials and geological structures to the ground motion is generally referred to as site effects. The 2005 Kashmir earthquake, which was one of the largest earthquakes recorded in the region, caused more than 80,000 casualties and made over a million people homeless. Apart from the buildings' high vulnerability in the region, one major reason for such large-scale damage was the site effects due to valley structures in the mountains and the presence of unstable slopes [6]. Therefore, the quantification of site effects is necessary for accurate estimates of appropriate seismic hazard and, consequently, the response of structures at a place of interest.

Seismic noise recordings, which correspond to the ambient vibration of the earth surface, are quite often used as a tool for subsoil exploration. It is especially used for the estimation of site effects, determining the depth of soil deposits, and estimating the resonance frequency of surficial materials. Nardone et al. (2020) used broadband seismic noise array to estimate shear wave velocity structure and attenuation structure of Ischia Island, Italy [7]. Parolai et al. (2019) used seismic noise to identify and locate the depth to the major impedance contrast in Almaty, Kazakhstan [8]. Pilz et al. (2014) employed seismic noise to study the stability of landslides in Central Asia and were able to identify the presence of a low-velocity body of weakly consolidated claystone and limestone materials which constitutes as landslide body [9]. Ullah et al. (2013) used seismic noise recordings to improve the spatial resolution of previously estimated site effects in the city of Bishkek, Kyrgyzstan, using earthquake data recorded over a time span of 3 months [10]. In Pakistan, Qadri et al. (2015) exploited seismic noise to estimate the resonance frequency soil deposits of the Fateh Jang area [11].

With the current trend of urbanization and increased prices of properties, the construction of high-rise residential and commercial buildings is a major activity in Peshawar. The seismic hazard studies carried out for Peshawar so far consider only the site effects in terms of V_{s30} values, i.e., the average shear wave velocity to a depth of 30 m, which is also mostly estimated from techniques that use regional slopes as a proxy. However, V_{s30} neither captures the full behaviour of soil at depths greater than 30 m, nor does it provide the multi-dimensional site effects which could arise from complex geological structures such as basins [12, 13]. Therefore, the purpose of this paper is to estimate the frequency-dependent first-order site effects and resonance frequencies of Peshawar. This is carried out by applying the Nakamura [14] technique, using seismic noise data collected from 92 locations. Considering the lack of earthquake data and the high density of population and building in Peshawar, the Nakamura method is appropriate for densely populated areas having a high level of seismic noise and, therefore, is a time and cost-effective method for seismic site assessments.

2. Geological and Tectonic Setting of Peshawar

From a geological point of view, Peshawar is located in a geological basin also known as the Peshawar Vale. This basin also includes other nearby cities such as Charsadda, Nowshera, and Mardan (Figure 1). The Peshawar basin is filled with Quaternary alluvium lake deposits consisting of sand, gravel, silt, and clay. According to Burbank and Tahirkhili (1985) [15], in the Peshawar Vale, intermontane-basin sediments begin to accumulate at least 2.8 million years (Myr) ago. This resulted in the settlement of more than 300 m of sediments over the folded and faulted Murree Formation of Miocene age. Also, from the uplift of the Attock Range, beginning about 2.5 Myr ago, the alluvial fans slowly crept into the Peshawar basin [16]. According to Nizami (1973), at that time, whenever the outflow of the Indus River was blocked, the Peshawar area was transformed into a lake, which occurred several times [17]. Therefore, the lake deposits show alternating silty and sandy strata. However, at some places in the Peshawar Vale, loess is also found between different lacustrine layers, indicating a dry period between two consecutive lake periods. Average shear wave velocities to a depth of 30 m (V_{s30}) estimated from the regional slope [18] also show the presence of the Peshawar basin (Figure 1). The average V_{s30} in this area is about 300 m/s, and according to the National Earthquake Hazards Reduction Program (NEHRP) classification, this corresponds to soil class D.

Peshawar is located within the close vicinity of several active faults. The tectonic activity is governed by the active collision of the Arabian, Indian, and Eurasian plates, where the convergence rate is about 37 to 42 mm per year [19]. This collision has led to the formation of the nearby Hindukush and Himalayan seismic zones. The seismicity in Peshawar is mostly contributed to by the Hindukush ranges in Afghanistan, the Kohat ranges to the south of the city, and the Hazara Kashmir syntax in the north [20]. Figure 2 shows the distribution of active seismic faults around Peshawar, taken from the database of the Global Earthquake Model [21]. These faults are mainly distributed in the north and south of Peshawar. Apart from several smaller faults, the Main Boundary Thrust (MBT) fault, which is part of the Hazara Kashmir syntax, is located just a few km to the south of the city.

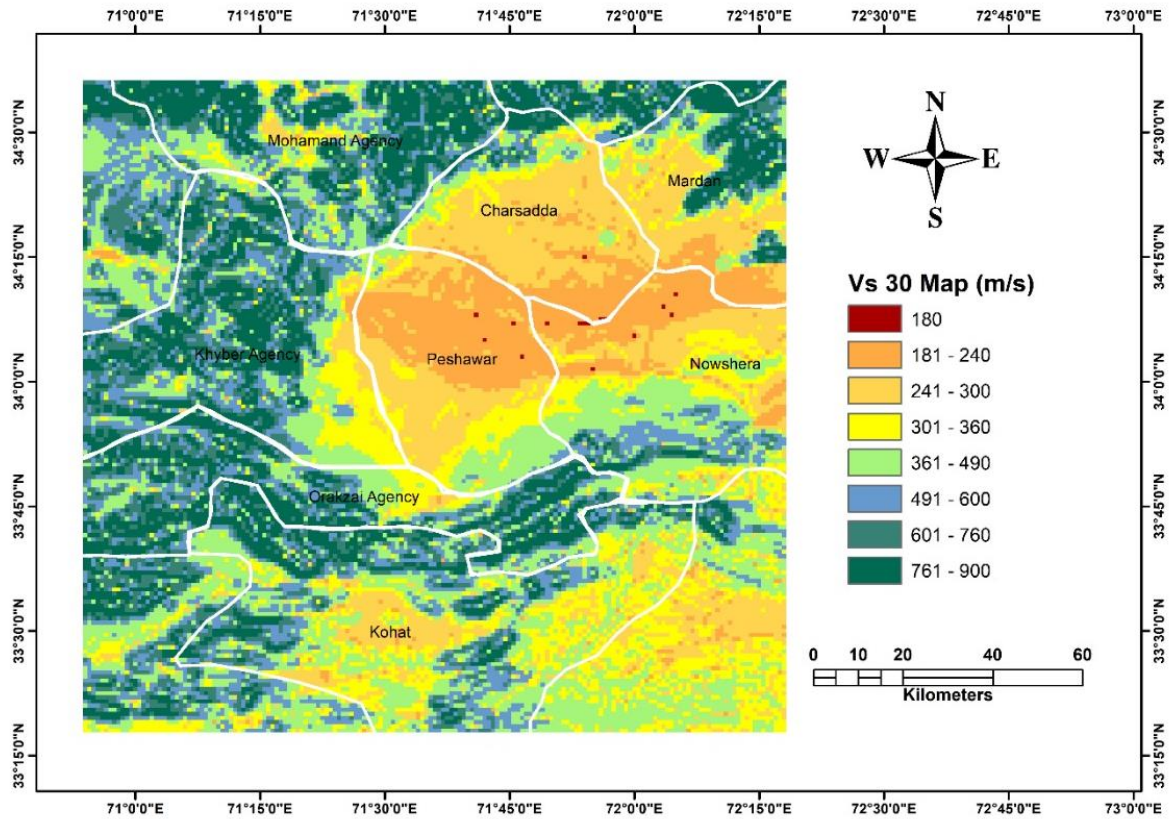


Figure 1. VS30 map of Peshawar Valley (extracted using methodology of Wald and Allen, 2007 [18])

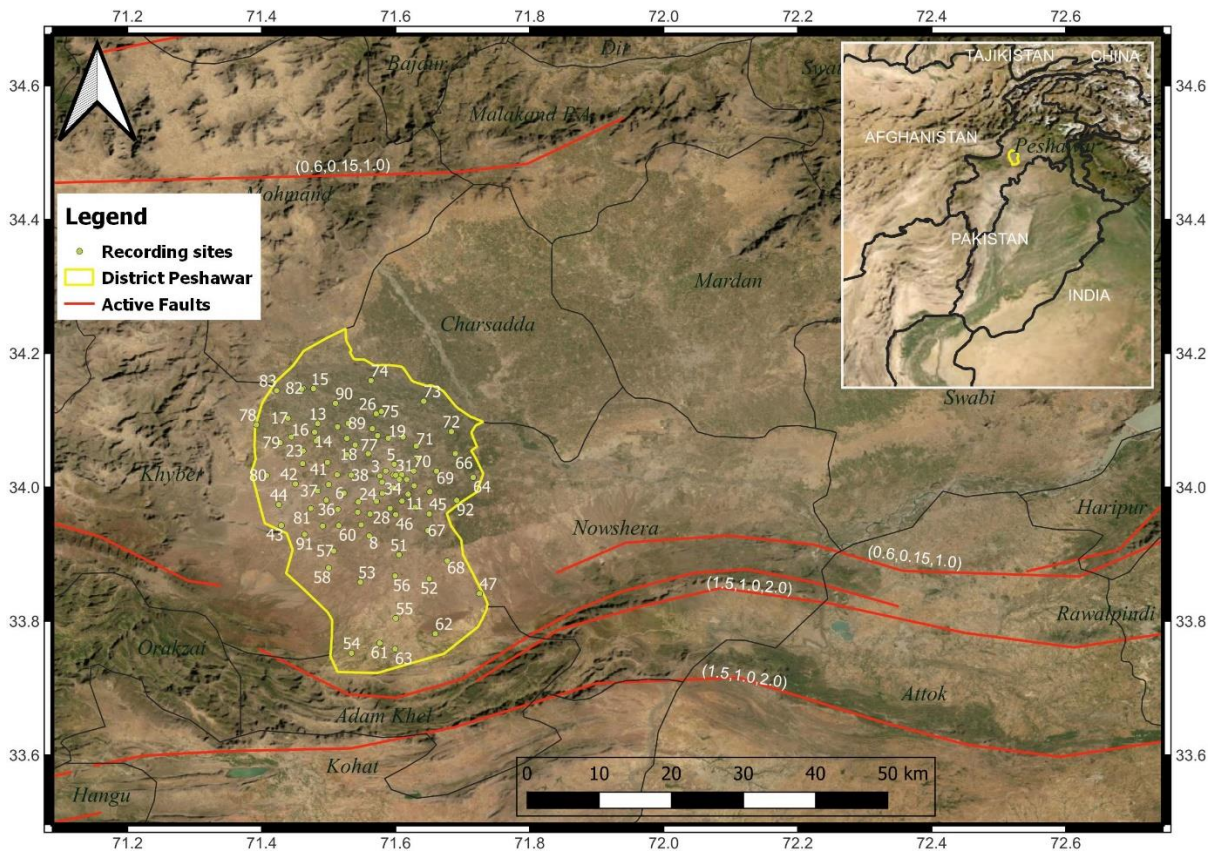


Figure 2. Map of the study area. The city of Peshawar is highlighted by the yellow border, with the numbers inside representing the recording stations. The red lines represent active seismic faults around Peshawar. The numbers associated with each fault represents the most probable, minimum, and maximum slip rates in cm/year. The inset figure presents the regional overview of the study area, with the yellow polygon indicating Peshawar.

3. Research Methodology

Different techniques have been described in the literature to estimate the depth of soil deposits over bedrock and the corresponding site effects using seismic data. However, due to a lack of earthquake data and considering densely built areas like Peshawar, the Nakamura [14] method is often preferred. This technique was first introduced by Nogoshi and Igarashi (1973) [22], and later made popular by Nakamura (1989) [14]. It depends on the use of seismic noise or ambient vibrations caused by natural and anthropogenic sources. The seismic noise (three components, two horizontal components - north-south and east-west and the vertical component - up-down) is recorded in the time domain at a certain location and then converted to the frequency domain using a Fourier transformation. Finally, the ratio of the Fourier spectra of the horizontal component is taken with respect to the vertical component (H/V). This ratio provides two important pieces of information: 1) the fundamental frequency of subsoil corresponding to the peak of Fourier spectral ratio curve (H/V), and 2) the amplitude of the peak of the Fourier spectral ratio curve, which provides an estimate of site response by acknowledging the seismic impedance between different layers of subsoil. According to Nakamura [14], H/V gives the site response which corresponds to the propagation of S-waves, if the surface waves are neglected. However, within the seismological community, surface waves are the main reason of seismic noise and associated site response, e.g., [23]. Although, the results of the numerical simulations of Parolai and Richwalski (2004) show that at frequencies higher than the fundamental one this methodology underestimates amplification [24], nevertheless, the amplification estimated from the Nakamura method can be considered as representing a first order site effect.

4. Data Collection and Processing

In this study, seismic noise data was recorded at 92 different sites throughout Peshawar, corresponding to the 92 union councils of the city (Figure 2). At each station, the data is recorded by 3-component broadband seismometers for a continuous period of about 30 minutes. The data is collected with a DR-4000, 24 bit digital acquisition system (DAS) at a sampling rate of 100 SPS.

The data was processed following the guidelines of SESAME [25] using MATLAB software. According to the guidelines, the recorded data is divided into multiple windows. To have stable and reliable results, the individual window length must be long enough, hence, the individual window length was selected to accommodate at least 10 cycles of the lowest frequency of interest [26, 27]. Table 1 shows the recommendations of SESAME regarding the total duration of data and window length. Anticipating the large depth of sediments in the Peshawar valley, the 30 minutes record of seismic noise at each station was divided into windows with lengths of 50 seconds. The individual windows in the time domain were then tapered with a cosine window, 5% at both ends. The seismic noise in the time domain was then converted to the frequency domain using Fast Fourier transformation to obtain the Fourier amplitude spectrum. Moreover, to remove the artifacts the Fourier amplitude spectra are smoothed using Konno & Ohmachi (1998) smoothing windows [28].

Table 1. Recommended duration of window lengths and total recording duration

Minimum expected f_0 (Hz)	Minimum Window Length, l_w (s)	Minimum number of significant cycles (n_c)	Minimum number of Windows	Minimum useful signal duration (s)	Recommended minimum record duration (min)
0.2	50	200	10	1000	30'
0.5	20	200	10	400	20'
1.0		200	10	200	10'
2.0	10	200	10	100	5'
5.0		200	10	40	3'
10.0		200	10	20	2'

5. Results and Discussion

Figure 3 presents the average of the individual Fourier amplitude spectra (FAS) of the 3 components of seismic noise for selected union councils. Considering the windows length and sampling rate of the dataset, the analysis was considered up to a minimum frequency of 0.2 Hz and a maximum of 50 Hz. The overall amplitudes of the Fourier spectra show higher values for the horizontal components as compared to the vertical components. The horizontal components generally show flat spectra, however, at frequencies higher than 1 Hz, at most stations the vertical component shows two prominent peaks at around 3 and 20 Hz. Although the absolute amplitude of these two peaks varies from station to station, their existence is observed at almost all recording locations. The recording of seismic noise was carried out at different times of day and on different weekdays, but they showed similar behaviour, which rules out the contribution of any single anthropogenic source. Figures 3 and 4 shows the FAS of recordings at different places, far away from each other, but showing similar trends of the two peaks identified in the vertical components.

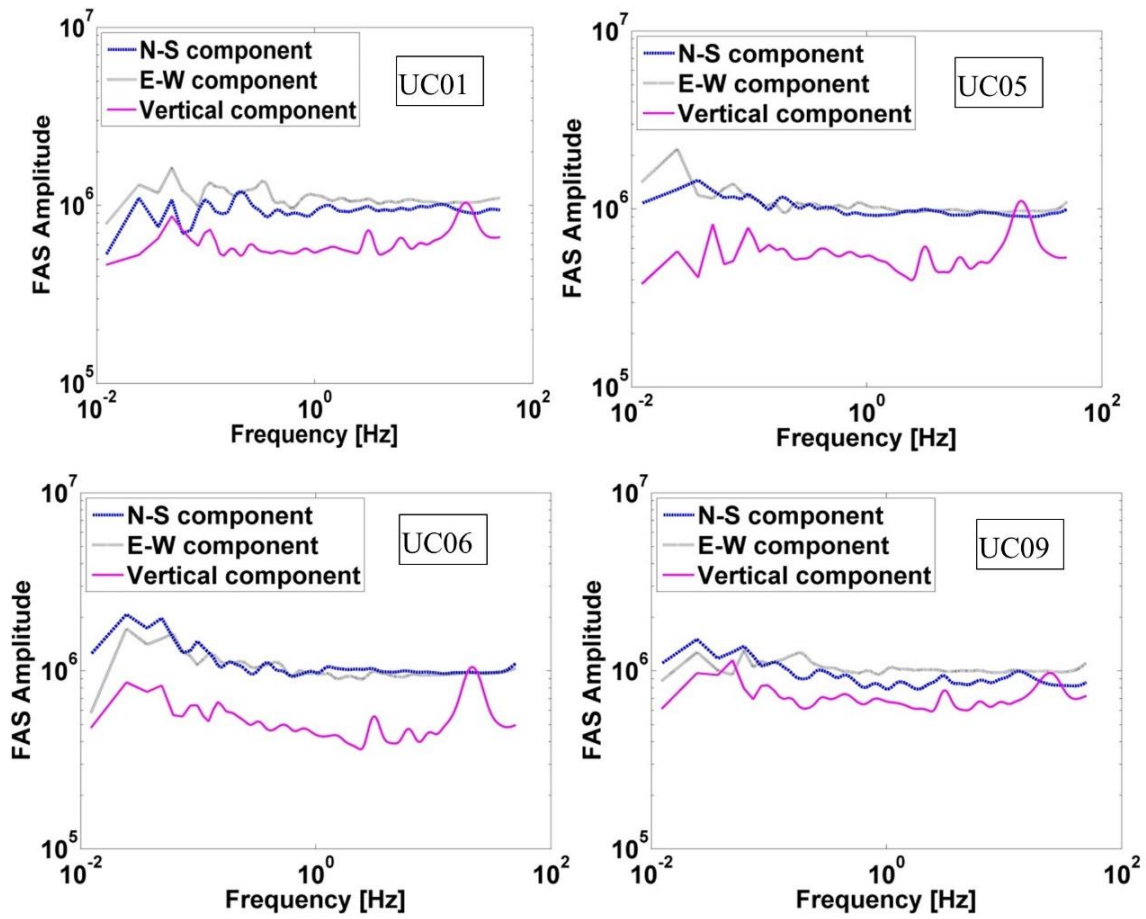


Figure 3. Fourier Amplitude Spectra of seismic noise at different union councils (UC) in Peshawar

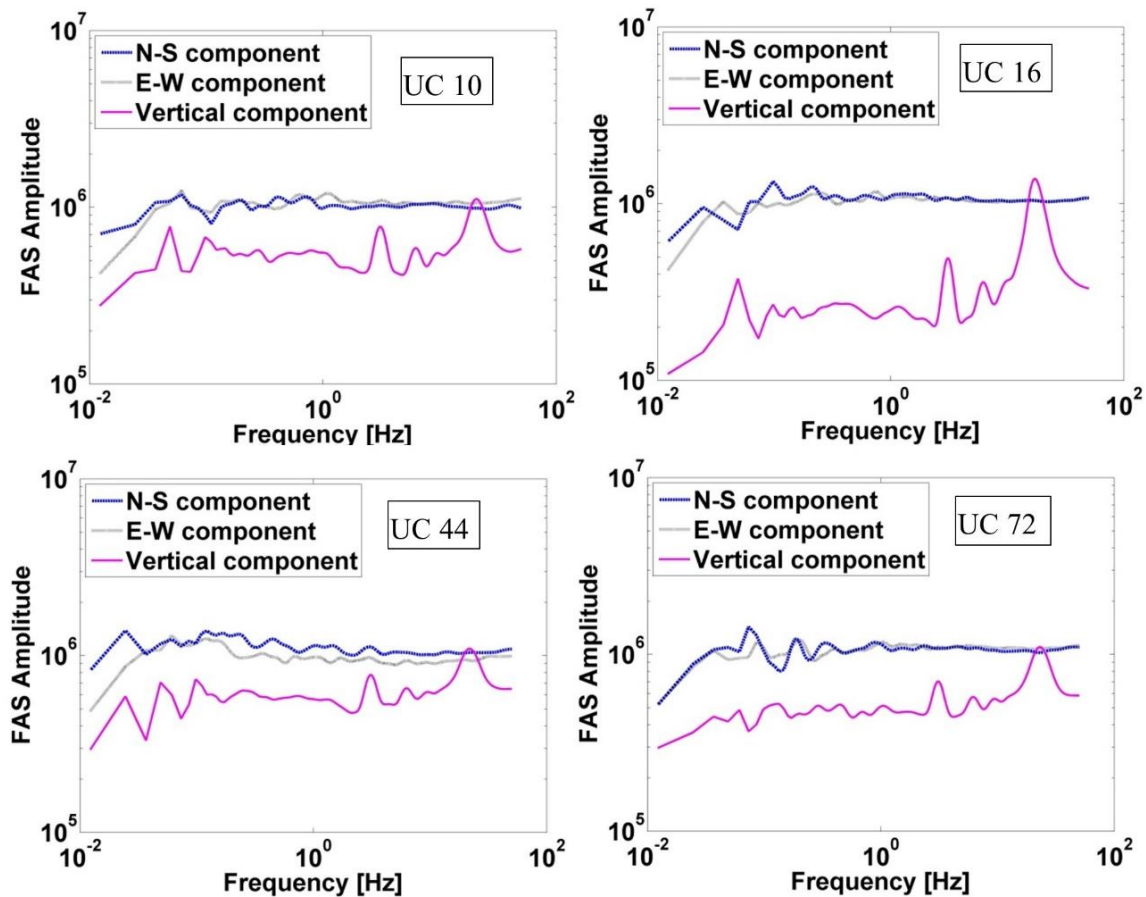
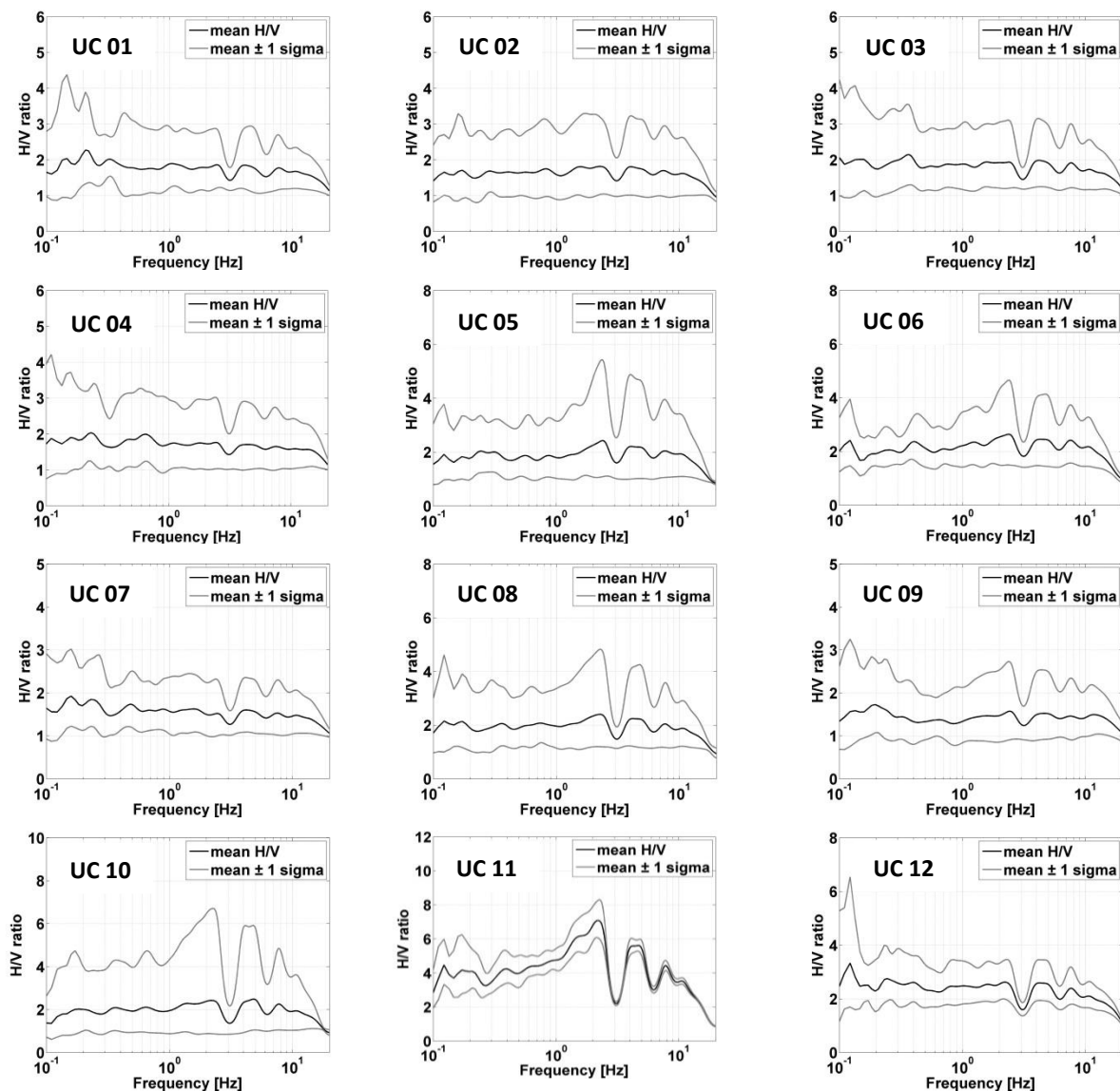


Figure 4. Fourier Amplitude Spectra of seismic noise at different union councils (UC) in Peshawar

Figure 5 shows the results of the H/V analysis, considering the average of the two horizontal components, for stations 1 to 18. The H/V results for the remaining stations are presented in the Appendix I. The dark black lines represent the mean of the H/V ratios, and the grey lines show the variation in terms of the mean plus-minus one standard deviation. Apart from small detail variations, the plots show very similar behaviour. The analysis generally shows the overall flat behaviour of H/V curves. Based on the amplifications, the stations can be divided in to two categories. Stations 11, 16, 18, 21, 25, 26, 31, 32, 58, 60, 81, and 86 show an overall amplification greater than 2 up to a maximum of about 7 (Figure 5). These stations are located mostly in the central part of the district where the average Vs30 ranges between 180 to 300 m/s (Figure 1). Among these stations, stations 16, 18, 21, 26, 25, 32, and 60 do not show a clear peak in the H/V according to the SESAME criteria (SESAME WP02 team [27]). However, stations 11, 31, 58, 81, and 86 show a clear peak at around 2.5 Hz, followed by a prominent drop at 3 Hz. The other stations have an average amplification of around 2 (Figure 5 and figures in the Appendix I) where the average Vs30 is between 301 to 490 m/s. These stations do not have any clear peak according to the SESAME criteria, but rather show a flat response. Some stations also show a less prominent low frequency peak, mostly around 0.2, 0.3 and 0.4 Hz, such as for stations 1, 3, 7, 15, 58, 72 etc. These stations are scattered in the central part as well in the outskirts of the city. Since the H/V ratios from seismic noise provides an estimate of one-dimensional site effects, there are two important pieces of information contained in it: one is the amplitude of the ratio, and the other is frequency of the peak (SESAME WP02 team [27]). The reliability and amplitude of peaks in H/V ratios is mostly a function of the seismic impedance contrast between the different soil layers. However, frequency of the peak is function of the velocity model of the sediments as well as the thickness of the sediment layer over the bedrock [26]. Therefore, the stations showing H/V ratio amplitudes more than 2 indicate soft soil deposits. However, the absence of a prominent peak in most of the stations also indicate the unavailability of sharp contrast in seismic impedance in surficial layers. This behaviour may also reflect the deep thickness of the sediments as suggested by the literature dealing with the region’s geology [15].



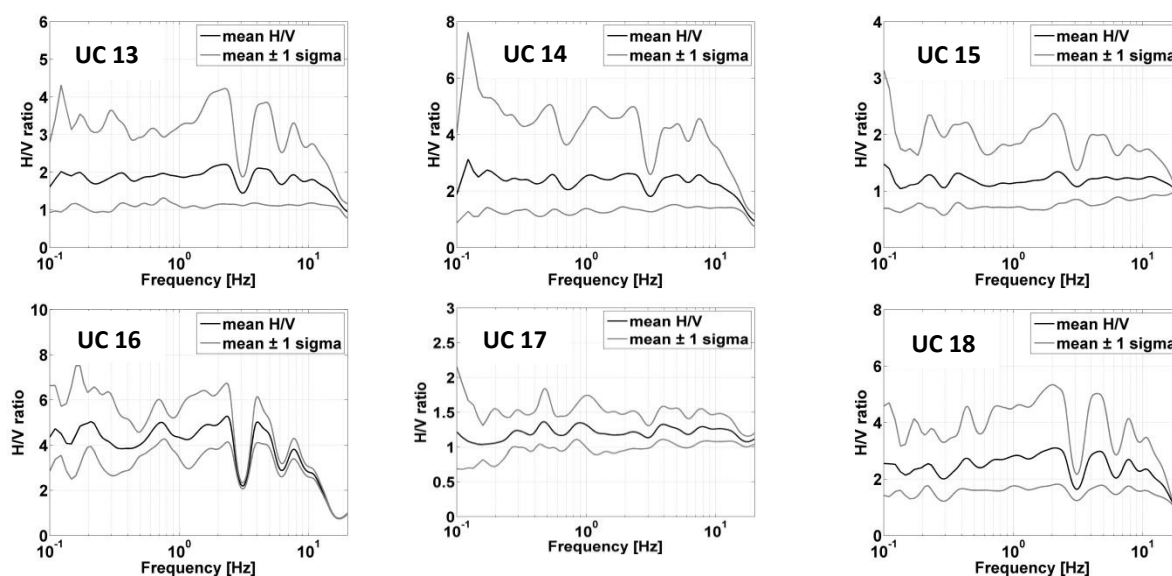


Figure 5. H/V spectral ratios of seismic noise at different UC locations in Peshawar

6. Conclusion

An attempt has been made to estimate the first-order site effects in the district of Peshawar using seismic noise and the H/V method of Nakamura. The H/V amplification ranges from 1.5 to about 7 throughout the district. Amplification larger than 2 is observed in the central part of the city, where the V_{s30} ranges between 180 to 300 m/s. However, in the outskirts of the city, where the average V_{s30} is more than 300 m/s and up to 490 m/s, an amplification of around 2 is observed. A clear peak was not observed in most of the station's H/V plots. This confirms the absence of strong bedrock in the near surficial geology. Out of the total 92 stations, only five stations show a rather reliable peak of H/V at around 2.5 Hz. Using an average V_{s30} of 300 m/s, this corresponds to about a 30 m depth of soil deposits. However, most of the stations also show a small amplitude of low frequency peaks ranging between 0.2 to 0.4 Hz. Using the same average V_{s30} of 300 m/s, this corresponds to depths of about 375 m and 187 m of soil deposits, respectively. This information is very important, which reveals the potential for amplification of low-frequency seismic waves, generally generated by large-magnitude earthquakes as well as deep earthquakes. Considering the natural frequency of structures, high rise buildings would potentially be more affected by this amplification. Further research is encouraged to estimate the depth of bedrock in the valley with the help of other techniques, which will refine the estimate of seismic hazard for the city.

7. Declarations

7.1. Author Contributions

Conceptualization, S.U.; methodology, S.U., and S.W.Y.; software, S.W.Y.; validation, M.A.; formal analysis, S.U.; investigation, S.U.; resources, M.A.; data curation, S.W.Y.; writing—original draft preparation, S.U., and S.W.Y.; writing—review and editing, M.F., Q.S., M.F., and M.W.; visualization, M.A.; supervision, S.U. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

The data presented in this study are available in the article.

7.3. Funding

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7.4. Acknowledgements

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7.5. Conflicts of Interest

The authors declare no conflict of interest.

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Appendix I: H/V Spectral Ratios of Different Union Councils (UC) in Peshawar

