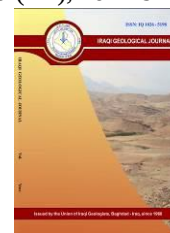




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Seismic Microzonation of the Peshawar Metropolitan Area, Pakistan, Based on One-Dimensional Nonlinear Site Response Analysis

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Abstract

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Seismic resilient design of infrastructure is crucial in active regions. The infrastructure development of Pakistan is based on the Building Code of Pakistan (BCP-2007), which is based on the Uniform Building Code (UBC-1997). The UBC is further based on deep soil conditions in the western United States, which have low impedance contrast and high seismic conditions. Applying foreign seismic criteria can give in the determination of results that deviate from the target area's actual geotechnical and geological ground conditions, as these conditions vary from place to place. This study adapts a simple yet more precise technique of nonlinear site-specific seismic response analysis for designing seismic resilient structures rather than relying on the results which are based on the Peak Ground Acceleration only. Site-specific seismic amplification factors were calculated using Geographic Information System and a geotechnical engineering dataset of 42 standard penetration test in the metropolitan area of Peshawar City, Pakistan. Shear wave velocities (V_s) were calculated using 50 SPTN- V_s correlations, and the results were validated using the available in situ measurements of shear wave velocity data. Furthermore, the average shear wave velocity (V_{sz}) and shear wave velocity up to 30m (V_{s30}) were calculated, and sub-site classification of the study area was developed for microzonation. The General Quadratic/Hyperbolic (GQ/H) model was used, and a non-linear one-dimensional analysis of sixteen shallow sub-site profiles under twenty (20) ground motions had been carried out using DEEPSOIL software. The resulting site-specific amplification factors were compared with the suggested values from the BCP. It was found that BCP overestimates short-period amplification factors (F_a) for 12 profiles and long-period amplification factors (F_v) for all 16 proposed profiles. This study proposes site-specific GIS-based maps for the bedrock depth, National Earthquake Hazards Reduction Program site classes, short-period amplification factors (F_a) and long-period amplification factors (F_v), which will eventually enhance economic and safety aspects of the future infrastructure designs at the understudy region.

Keywords: Seismic amplification factors; Shear wave velocity; Geographic information system; Building code of Pakistan

1. Introduction

The study of earthquake motions, related seismic hazards and risk play a key role in the sustainable development of societies in earthquake-prone areas (Siddique and Schwarz, 2015). The abrupt

population growth demands of modern high-rise buildings, high-level communication systems, and industrial dependence have increased the impact of natural disasters. However, these risks for living creatures and social well-being can be mitigated through modern studies and knowledge enhancements, especially the risk of earthquakes (Ge et al., 2010; Siddique and Schwarz, 2015). Pakistan is situated in one of the most seismically active regions in the world (Bhatti et al., 2011). In the last 10 decades, the country went through many devastating earthquakes including, the Mach earthquake of magnitude 7.3 M_L in August 1931, the Quetta earthquake of magnitude 7.4 M_L , in 1935, the Makran coast earthquake in 1945 with a magnitude greater than 8.0 M_L , the Pattan earthquake of magnitude 6.0 M_L in 1974, and the very destructive Muzaffarabad earthquake of magnitude 7.6 M_L in October 2005, which alone caused 87000 deaths, 2.8 Million displacements and an economic loss of 20 Billion USD; equivalent to 6 percent Gross Domestic Product (GDP) of the whole country (Ahmad et al., 2011; PMD and NORSAR, 2007).

The infrastructure development of Pakistan relies on Pakistan's building code (BCP-2007) (PEC, 2007). Such codes are based on the Uniform Building Code (UBC-1997), which are further based on the deep soil conditions and seismic data that correspond to the deep soil criteria applied to the United States (USA) and nearby countries, specifically, from the western region of the USA (Sadiq et al., 2021). On the other hand, Pakistan mostly has shallow bedrock conditions (Kim et al., 2019). Taking results based on the different types of geological and geotechnical data would be a disaster for infrastructure design and development in Pakistan. When passing through the different layers between bedrock and surface, seismic waves may significantly be amplified, which depends on the soil type underneath and bedrock depth (Ozmen, 2023). Recent research study results in Korea have shown differences in the seismic response characteristics due to differences in regional geological and geotechnical ground conditions (Kim et al., 2018; Kim et al., 2019). Specifically, the Uniform Building Code (UBC 1997) (International Conference of Building Officials, 1997) and the International Building Code (IBC 2000) (International Code Council Inc., 2000) have been derived from empirical seismic studies and damage data from the western region of the United States (Kim et al., 2019).

However, the research conducted by the Pakistan Meteorological Department (PMD), NORSAR Norway, and National Engineering Services Pakistan (NESPAK) provided new seismic provisions for the Building Code of Pakistan in 2007 (PEC, 2007). One of the outcomes of the research was the production of seismic zonation hazard maps for different cities in Pakistan which are based on the Peak Ground Acceleration (PGA) of the bedrock. Accordingly, Pakistan is divided into five seismic zones as depicted in Fig. 1, based on PGA (PMD and NORSAR, 2007).

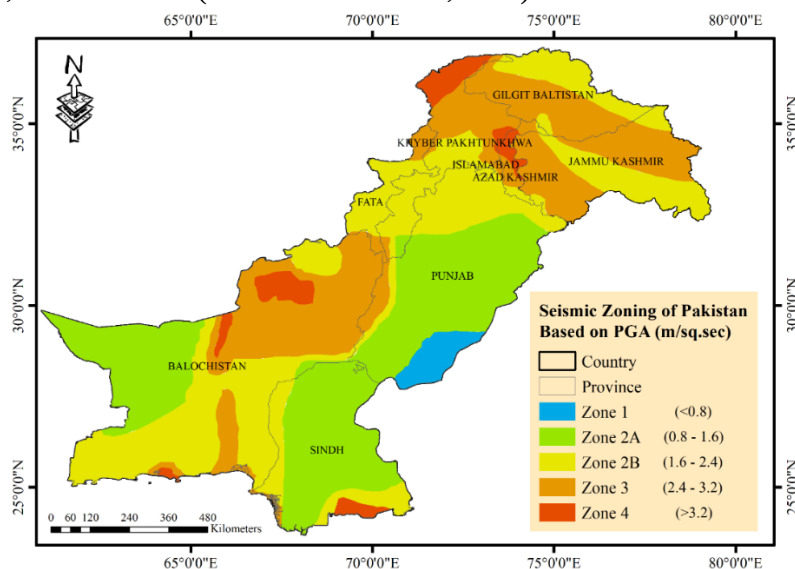


Fig. 1. Seismic Zonation map of Pakistan (PMD and NORSAR, 2007)

Numerous studies have highlighted the importance of determining site-specific amplification factors for different regions worldwide. For example, (Apriadi et al., 2023; Di Filippo et al., 2023) emphasized the need to account for local geotechnical conditions, while (Kim and Yoon, 2006) also proposed a site-specific classification system for shallow bedrock conditions in Korea and suggested revised amplification factors. (Anbazhagan et al., 2013), proposed that site amplification factors that were used in India, Australia and China were representing stiffer site characteristics because of the shallow bedrock in the region. (Pehlivan et al., 2017) proposed site-specific amplification factors for Korea and concluded that it underestimates the design criteria at short period amplification factors and overestimates at long period amplification factors values. (Kim et al., 2019) discussed the importance of site-specific amplification factors and their potential use in building design code operation for shallow bedrock areas. (Shahkar et al., 2021) calculated the site-specific amplification factors for the Islamabad region and plotted these values in GIS. The authors also worked on the amplification factors of shallow sites in the region, in which the soil types were re-classified for seismic hazard analysis. It was further concluded that BCP-2007 underestimates the design criteria at short period amplification factors and overestimates at long period amplification factor values. (Sadiq et al., 2021) performed 1-D non-linear site response analysis and calculated the amplification factors for Islamabad, Pakistan. The data was collected from 445 boreholes dug at 130 sites. However, the amplification factors were calculated and the response spectra was then compared with BCP-2007. Six soil profiles were created based on the stratigraphy which then concluded that the short-magnitude amplification was higher than the long magnitude due to shallow bedrock and high impedance contrast.

Even after the inclusion of seismic provisions in the building code of Pakistan in 2007, which was done after the devastating earthquake of 8th October 2005, only the seismic hazard macro zonation maps were developed. However, as the population of Pakistan keeps growing, the need for the development of various commercial and residential infrastructures has been increased. Hence, there is a dire need for microzonation seismic amplification mapping, which can correspond to seismic site-specific scale for various cities of Pakistan (Sadiq et al., 2021). The seismic provisions proposed the seismic zoning map of Pakistan, which divided the whole country into five zones where based on their peak ground accelerations (PGA) using the seismic data from past earthquakes. It is understood that BCP (2007), even after seismic provisions, can only provide amplification factors for major sites in their predefined zones. Using generalized amplification factors for infrastructure design can result in the uneconomical and sometimes in unsafe design (de la Torre et al., 2024). This research study resolves this issue and proposes a new methodology for evaluating site-specific seismic amplification factors with the help of various correlations used for the calculation of shear wave velocity (V_s), shear wave velocity at 30m depth (V_{s30}), 1D non-linear analysis in DEEPSOIL software using General Quadratic/Hyperbolic model, sub-site classification, and proposal of results in the form of geospatial maps. For seismic analysis of soil profiles, non-linear analysis is proved to be accurate and precise in comparison with linear seismic analysis (Aaqib et al., 2025; Civelekler et al., 2024).

This study investigated local soil conditions of the Peshawar district's metropolitan area, revealing that bedrock depth of the study region lies in the range of 10 to 40 m. Whereas, the seismic provisions in the BCP are based on the data that relates to the deep soil conditions of the United States (USA) as mentioned before. The SPT data depicts that BCP is foreseeing the local site conditions and proposing macro seismic zones only based on PGA which doesn't incorporate the seismic conditions of actual local sites. With the advancements in the technology, many developing countries like Turkey, South Korea and Japan (Altun et al., 2012) are now shifting towards site specific seismic effects and major infrastructure design decisions are made accordingly. This study proposes new site-specific seismic amplification factors that can relate to the local site conditions for intended future infrastructure projects within the boundaries of study area. Moreover, the scope of this study can be expanded to the other cities

as well to eventually propose full scale site specific seismic amplification effects microzonation maps for the whole country.

2. Study Area

2.1. Location

Peshawar is one of the metropolitan cities of Pakistan and the provincial capital of Khyber Pakhtunkhwa, located at 34.0151° N, 71.5249° E, with an average elevation of 331m from the mean sea level. The district's total area is $1,280 \text{ km}^2$ with a total perimeter of 175.70 km and comprising 92 Union Councils and 346 village/neighborhood councils (PNDKP, 2017). The city has been divided into 4 main towns (tehsils) i.e. Town 1, Town 2, Town 3 and Town 4, having an area of 26.94, 429.85, 187.25 and 635.89 km^2 , respectively, as shown in Fig. 2. Moreover, Peshawar city has a commercial metropolitan area of 183.85 km^2 and a perimeter of 84.06 km (area of interest for this study). Peshawar district is expected to have many high-rise buildings and infrastructure development in the coming years. It had a population of around 4.26 million and a population density of 3394.75 persons/ km^2 in 2017, with an average annual growth rate of 3.99% since 1998 (Pakistan Bureau of Statistics, 2017), which rates this city as the 6th largest city in the country concerning population. Many ongoing mega projects include DHA (Defense Housing Authority), Peshawar, Regi Model Town, Naya Pakistan Housing Scheme, and Deans Heights.

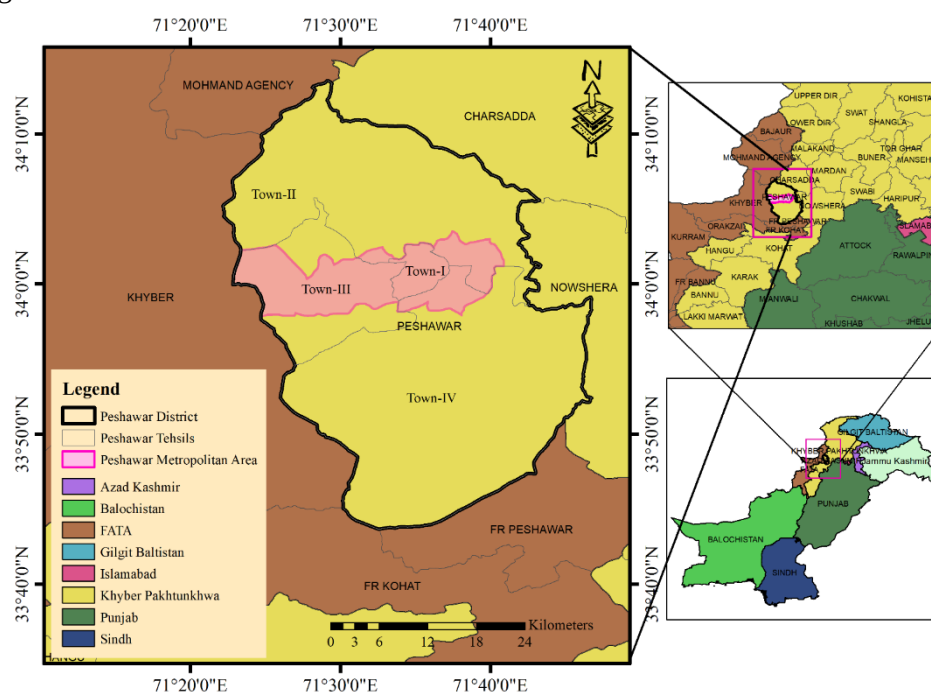


Fig. 2. Peshawar district in the context of Khyber Pakhtunkhwa province and Pakistan

2.2. Geological and Seismological Conditions

The geology of Peshawar is laid by recent floods, streams and river deposits, belonging to the Pleistocene age group. These deposits make up about 80% of the district's underlying area. These are further classed into four types: Riverine, Murree Formation, Quaternary Alluvium, and Samana Suk Formation as depicted in Fig. 3. Around 20% of the area of the Peshawar district is covered by different rock types. These rocks are typically observed in the outcrop to the district's West, Southwest, and South, comprising of tertiary, Paleozoic, Jurassic, and Precambrian Rocks (PMD and NORSAR, 2007).

Peshawar is very vulnerable due to its location on the Himalayan region's western side, which has high seismicity rates (PNDKP, 2017). The Main Boundary Thrust (MBT) fault, along which the Kashmir earthquake occurred in October 2005 is also located in the northern parts of the country. Other active regional faults, including Main Mantle Thrust (MMT) and Main Karakorum Thrust (MKT), contribute to its seismicity as shown in Fig. 4. These faults, if reactivated, can act as potential sources of seismic hazard for the region, including Peshawar. According to the seismic provisions of the building code of Pakistan (2007), Peshawar is placed in Zone 2B of seismic zonation (PMD and NORSAR, 2007) as shown in Fig. 4. Zone 2B has Peak Ground Acceleration (PGA) in the range of 0.16g to 0.24g for a return period of 475 years (PNDKP, 2017).

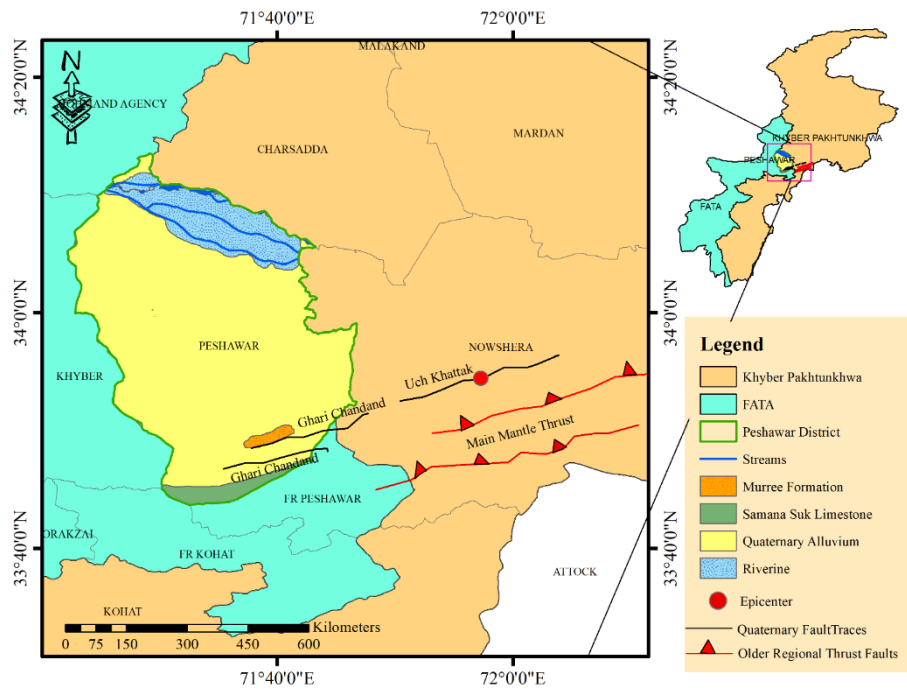


Fig. 3. Peshawar District fault line map (PNDKP, 2017)

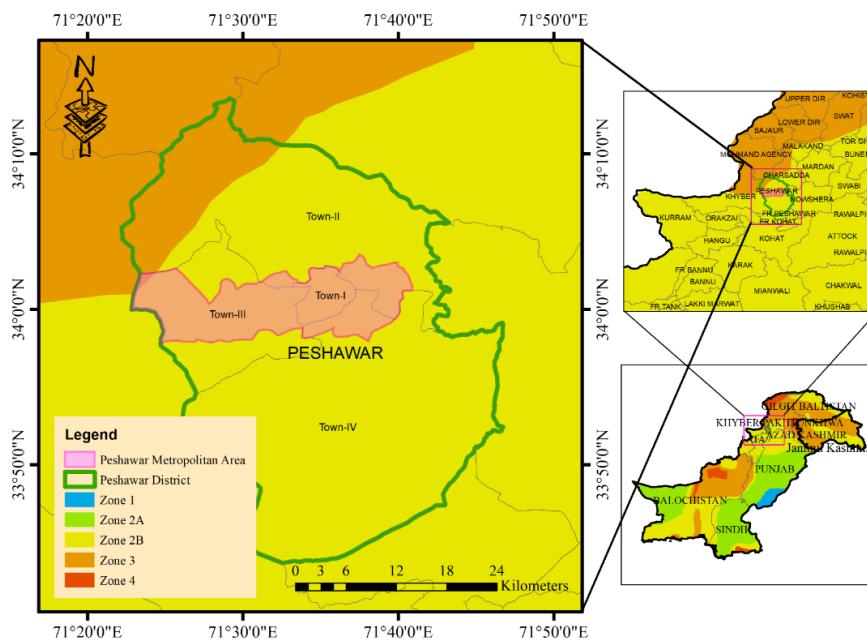


Fig. 4. Peshawar district seismic zone map in the context of Pakistan and KP province (PEC, 2007)

3. Methodology

The following Fig. 5, best depicts the research methodology adapted for this study. It is designed to be specific and accurate at the same time to increase efficiency in cost and time consumed. This study is based on the geotechnical engineering data set of 42 Standard Penetration Test (SPT) boreholes mainly with some other field and laboratory test results of the local soil samples. The 50 most suitable shear wave velocity and SPTN (SPTN- V_s) equations were used to calculate each soil layer's average shear wave velocity (V_{sz}). Later, shear wave velocity at 30m depth (V_{s30}) is calculated using Boore's equation. This study proposes a subsite classification system to micro zone the study area, and 16 new sub-site profiles were developed. After all the necessary data calculations, sub-profiles were analyzed in the DEEPSOIL using 1D non-linear analysis and GQ/H modeling for seismic site response analysis. This analysis led to the actual site-specific seismic amplification factors in the form of F_a and F_v . In the end, this study also proposes ArcGIS based geospatial maps for enhancing the applicability of the results and methodology adapted.

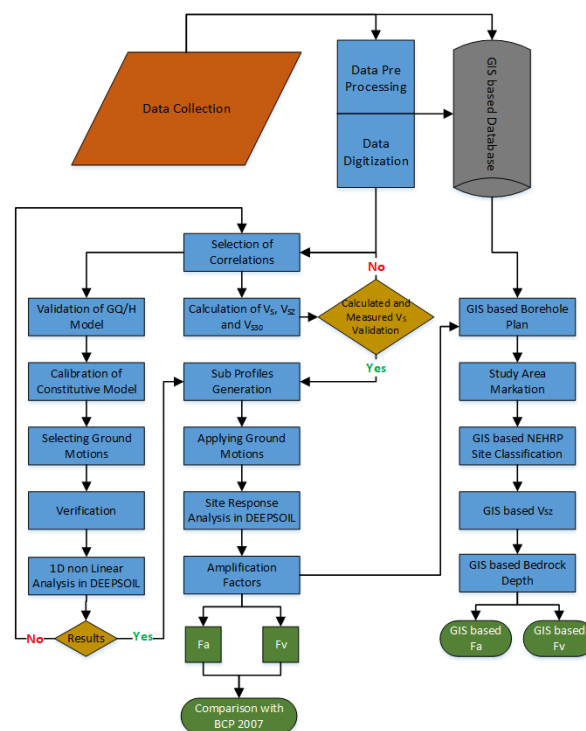


Fig. 5. Technical Research path

3.1. Data Selection

Primarily, the available geotechnical data was collected from the region, which was also covered by the Peshawar BRT (Bus Rapid Transit) project. The available data comprises the soil investigation characteristics such as standard penetration test (SPT) data, soil gradations, and Atterberg's limits, etc. A total of 42 boreholes were dug, the logs of these were used for other soil investigations and findings. A standard penetration test (SPT) is a subsurface exploration test that is used worldwide to find out the soil properties and use as a base for structural design (ASTM International, 1999). In these tests, SPT-N values were counted, which are the number of blows of dropping hammer during the penetration of 12 inches. The SPT-N values directly relate to the strength of soil and shear wave velocity (V_s) calculation as a result (Shibata, 1970; Sil and Sitharam, 2014). In this study, borehole site data has been collected for the metropolitan area of the Peshawar district. Fig. 6 shows the exact location of SPT boreholes on the map area.

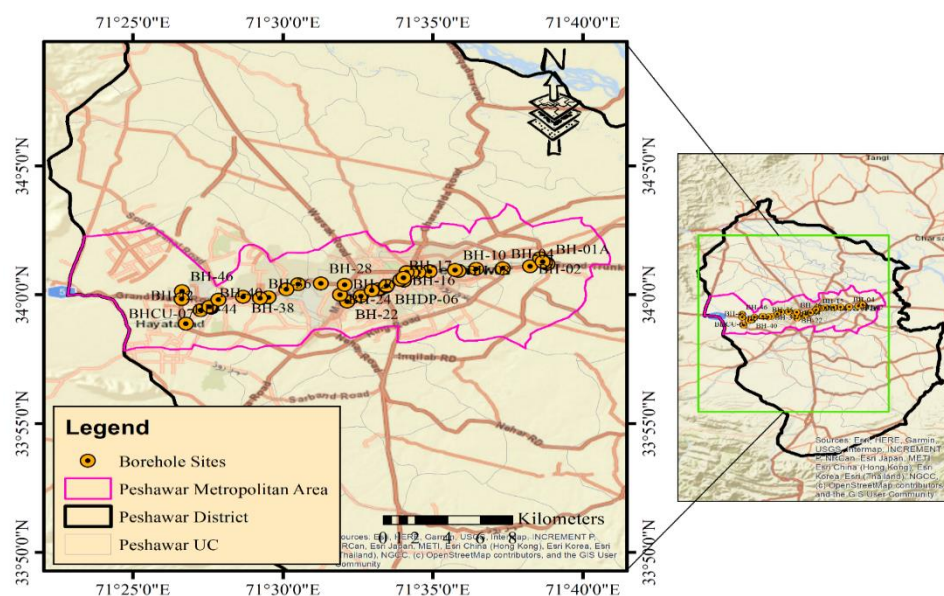


Fig. 6. Study area and borehole sites representation in the context of the Peshawar district

3.2. Calculations of Shear Wave Velocity from SPT-N Values and Site Classification

Shear wave velocity is widely used for the seismic analysis of any site. The ground shaking is inversely proportional to the shear wave velocity; for the higher values of shear wave velocity the ground response shaking will be less. In total, fifty (50) equations, as mentioned in Table 1, are used in various publications to calculate shear wave velocity, depending on the soil layer.

Shear wave velocity (V_s) was calculated using SPT-N along the depth of each layer using 50 correlations in total. Specific correlations according to the geological properties of soil in specific layers were used for the calculation of (V_s).

Since the metropolitan area of Peshawar contains different subsurface materials, including clay, silt, sand, gravel, and mixed deposits, the use of one generalized correlation for all layers could lead to systematic underestimation or overestimation of shear-wave velocity. Therefore, a broad set of published empirical correlations was compiled from the literature and applied according to the engineering description of each soil layer. Also, the difference among correlations for the same soil type reflects the fact that those equations were developed from different regional datasets, regression ranges, and geotechnical conditions. Therefore, their coefficients are not expected to be identical even when the general soil description is similar. This approach was adopted to reduce dependence on a single empirical model and to better capture the uncertainty associated with (V_s) estimation in a shallow-bedrock environment. A similar need to assess multiple empirical correlations before site response analysis has also been highlighted in recent Pakistani shallow-bedrock studies (Aaqib et al., 2025).

The calculated (V_s) at each layer of the borehole were compared with the measured shear wave velocity values at BH-02, BH-32, and BH-36. After the validation of the results of (V_s), average shear wave velocities (V_{savg}) were calculated. (V_{savg}) was then used to calculate (V_{sz}) to convert it to the overall depth of a single borehole. After calculations of the (V_{sz}) of each borehole, (V_{s30}) was calculated using Boore's equation with $C_0 = -1.349$, $C_1 = 1.120$, and $C_2 = -0.02810$ (Boore, 2006). (V_{s30}) was then used to assess the study area's National Earthquake Hazards Reduction Program (NEHRP) site classes. Furthermore, using Wolf's equation, the friction angle was calculated for each soil layer along the boreholes (Wolff, 1989). However, this study found that Peshawar was mainly placed in the (S_C and S_D) site classification according to (V_{s30}) ranges proposed by NEHRP, which are mentioned in

Table 2. Furthermore, this study proposes sub-site classifications as the function of bedrock depth and (V_{sz}) data, which are presented later in Section 4.1 and mentioned in Tables 6 and 7.

Table 1. Correlations for calculating VS using SPT-N values and D depth of layer

S. No.	Soil type	Vs based on un-corrected N values	Reference
1	Clay	$85.6 N^{0.34}$	(Ohta and Goto, 1978)
2	Clay	$93.1 N^{0.25}$	(Ohta and Goto, 1978)
3	Clay	$134.8 N^{0.25}$	(Ohta and Goto, 1978)
4	Clay	$107 N^{0.27}$	(Tonouchi et al., 1982)
5	Clay	$128 N^{0.26}$	(Tonouchi et al., 1982)
6	Clay	$138.4 (N+1)^{0.24}$	(Lee, 1992)
7	Clay	$132 N^{0.27}$	(Pitilakis et al., 1999)
8	Clay	$27 N^{0.73}$	(Jafari et al., 2002)
9	Clay	$97.9 N^{0.27}$	(Hasancebi and Ulusay, 2007)
10	Silt and Clay	$116.1 (N+0.32)^{0.2}$	(Jinan, 1987)
11	Silt and Clay	$129.4 (N+1)^{0.26}$	(Lee, 1992)
12	Silt and Clay	$104 (N+1)^{0.33}$	(Lee, 1992)
13	Clay	$62.1 N^{0.22} D^{0.23}$	(Ohta and Goto, 1978)
14	Clay	$68.8 N^{0.17} D^{0.20}$	(Ohta and Goto, 1978)
15	Clay	$89.6 N^{0.17} D^{0.20}$	(Ohta and Goto, 1978)
16	Clay	$86.1 N^{0.12} D+1^{0.20}$	(Lee, 1992)
17	Silt	$82.8 N^{0.13} D+1^{0.23}$	(Lee, 1992)
18	Silt and Clay	$84.5 N^{0.12} D+1^{0.25}$	(Lee, 1992)
19	Sand	$18.9 N^{0.6}$	(Kanai et al., 1967)
20	Sand	$31.7 N^{0.5}$	(Shibata, 1970)
21	Sand	$87.8 N^{0.29}$	(Tonouchi et al., 1982)
22	Sand	$110 N^{0.29}$	(Tonouchi et al., 1982)
23	Sand	$100.6 N^{0.29}$	(Sykora and Stokoe, 1983)
24	Sand	$88.4 (N+1)^{0.3}$	(Dickenson, 1994)
25	Sand	$90.8 N^{0.32}$	(Hasancebi and Ulusay, 2007)
26	Silty sand and Sand	$56.4 N^{0.5}$	(Seed et al., 1983)
27	Silty Sand	$104.7 N^{0.30}$	(Lee, 1992)
28	Fine Sand	$67.8 N^{0.22} D^{0.23}$	(Ohta and Goto, 1978)
29	Medium Sand	$63.9 N^{0.22} D^{0.23}$	(Ohta and Goto, 1978)
30	Coarse Sand	$66.7 N^{0.22} D^{0.23}$	(Ohta and Goto, 1978)
31	Fine Sand	$74.7 N^{0.17} D^{0.20}$	(Ohta and Goto, 1978)
32	Medium Sand	$73.3 N^{0.17} D^{0.20}$	(Ohta and Goto, 1978)
33	Coarse Sand	$78.1 N^{0.17} D^{0.20}$	(Ohta and Goto, 1978)
34	Fine Sand	$97.3 N^{0.17} D^{0.20}$	(Ohta and Goto, 1978)
35	Medium Sand	$95.5 N^{0.17} D^{0.20}$	(Ohta and Goto, 1978)
36	Coarse Sand	$101.7 N^{0.17} D^{0.20}$	(Ohta and Goto, 1978)
37	Sand and Gravel	$89.7 N^{0.34}$	(Ohta and Goto, 1978)
38	Sand and Gravel	$99.7 N^{0.25}$	(Ohta and Goto, 1978)
39	Sand and Gravel	$144.1 N^{0.25}$	(Ohta and Goto, 1978)
40	Gravel	$104.6 N^{0.34}$	(Ohta and Goto, 1978)
41	Gravel	$113.7 N^{0.25}$	(Ohta and Goto, 1978)
42	Gravel	$164.6 N^{0.25}$	(Ohta and Goto, 1978)
43	Gravel	$75.4 N^{0.35}$	(Tonouchi et al., 1982)
44	Gravel	$136 N^{0.25}$	(Tonouchi et al., 1982)
45	Sand and Gravel	$71.5 N^{0.22} D^{0.23}$	(Ohta and Goto, 1978)
46	Gravel	$92.3 N^{0.22} D^{0.23}$	(Ohta and Goto, 1978)
47	Sand and Gravel	$79.3 N^{0.17} D^{0.20}$	(Ohta and Goto, 1978)
48	Sand and Gravel	$99.6 N^{0.17} D^{0.20}$	(Ohta and Goto, 1978)
49	Sand and Gravel	$103.3 N^{0.17} D^{0.20}$	(Ohta and Goto, 1978)
50	Gravel	$129.8 N^{0.17} D^{0.20}$	(Ohta and Goto, 1978)

Table 2. NEHRP site classification

Site Class	V_{s30} (m/s) Ranges
A	>1500
B	760 - 1500
C	360 – 760
D	180 – 360
E	<180

3.3. Validation of Empirically Calculated Shear Wave Velocity (V_s) Results

The Empirical calculated shear wave velocity results are validated by using data from in situ shear wave velocity measurement of three boreholes (BH-02, BH-32, and BH-36) using the downhole method (non-destructive method) (Du and Pan, 2016). Fig. 7 shows the exact location of the mentioned boreholes.

The downhole method (ASTM International, 2008) for measuring (V_s) is widely used globally because it is very economical and uses the same borehole. On the other hand, the cross-hole method (ASTM International, 1999) is also very common, but an additional borehole is needed to measure the (V_s). Hence, it is considered to be uneconomical. In the downhole method, shear waves are generated at the surface of the borehole that travels through various soil layers underneath the surface. Measured results of (V_s) by the downhole method were compared with the results of five single equations (upper bound, lower bound, and random) for the respective soil layer and an average of 50 correlations simultaneously.

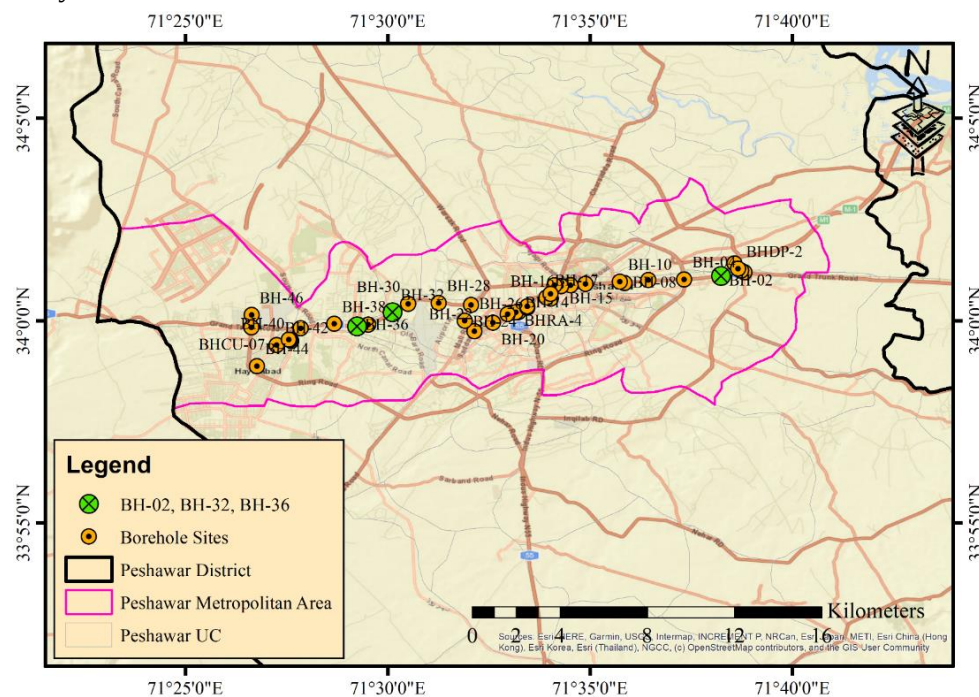


Fig. 7. Borehole plan with the representation of BH-02, BH-32, and BH-36 used for V_s result validation

Fig. 8 represents the comparison of measured values, five different correlation values and average values of (V_s) of all fifty correlations which used in this study. This figure also illustrates that the pattern followed by shear wave velocity remains almost the same throughout the depth of the boreholes. The maximum of 12.8%, 22% and 11.7% while the minimum of 1.5%, 1.1% and 0.4% differences were observed between the measured and calculated average values of (V_s) in the BH-02, BH-32, and BH-36, respectively.

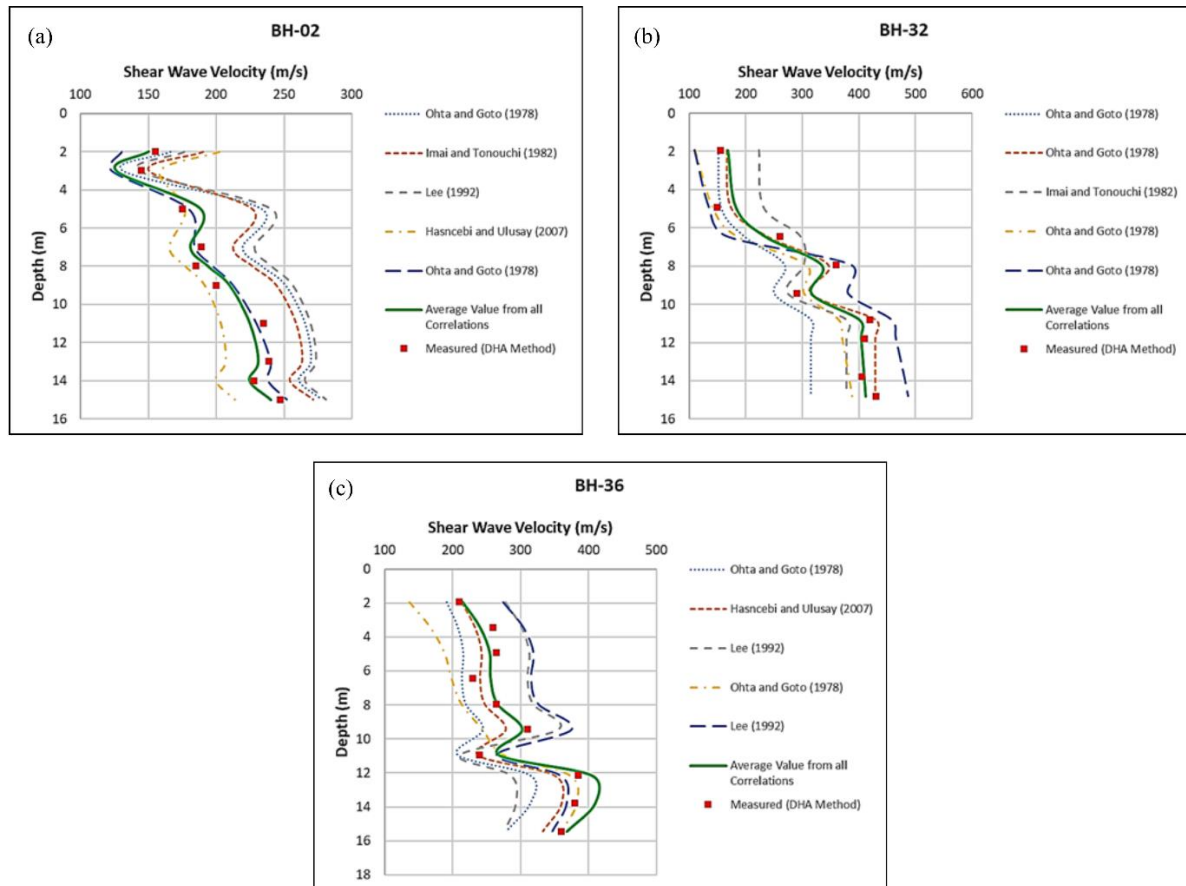


Fig. 8. Comparison of measured and calculated VS at BH-02 (a), BH-32 (b) and BH-36 (c)

By analyzing the empirically calculated and measured shear wave velocity data of these three boreholes (BH-02, BH-32, and BH-36), it is concluded that the real measured (V_s) values are closer to the average values of all correlations and follow the identical pattern, considered in this research study. Therefore, this comparison can be extended to all other boreholes for their (V_s) calculations. Hence, the (V_s) calculated using the proposed research process was further used for the study.

3.4. Calculation of V_{SZ} and V_{S30}

The correlations presented in Table 1 are used to estimate the shear wave velocities from the digitized borehole log data at each interval. The average shear wave velocity up to the depth “z” can be calculated from (Eq. 1) given as below:

$$V_{SZ} = \frac{z}{\sum_{i=1}^N \frac{h_i}{V_i}} \quad (1)$$

Where, “ h_i ” is layer thickness and “ V_i ” is the respective (V_s). The calculated average shear wave velocities for all sites are tabulated in Table 3. For the calculation of V_{S30} , (Eq. 2) was used as given below:

$$\log V_{S30} = C_0 + C_1 \log V_{SZ} + C_2 (\log V_{SZ})^2 \quad (2)$$

The above Boore equation (Boore et al., 2011) is used to calculate the V_{S30} from V_{SZ} for all borehole sites of this study. (V_{S30}) was calculated using Boore’s equation with $C_0 = -1.349$, $C_1 = 1.120$, and $C_2 = -0.02810$. The calculated values are tabulated in Table 3 against each borehole. From the calculated (V_{SZ} , and V_{S30}), estimated NEHRP site classes against each borehole are also mentioned in (Table 3) according to the ranges mentioned in Table 2.

Table 3. Calculation of V_{sz} , V_{s30} , and NEHRP site classification of the understudy region

Name	Northing	Easting	BH depth (m)	V_{sz} (m/sec)	$\log V_{s30}$	V_{s30} (m/sec)	NEHRP Site class
BH-01A	3767512	744428	27	229.0518	2.379575	239.6488	D
BH-02	3767330	743540	15	189.9761	2.297297	198.2881	D
BH-04	3767128	742144	15	196.701	2.312622	205.41	D
BH-06	3767069	740781	15	218.2487	2.358353	228.2196	D
BH-08	3766897	739881	15	202.4208	2.325241	211.4663	D
BH-10	3766959	739692	20	226.0678	2.373817	236.4923	D
BH-12	3766824	738391	26	230.0536	2.381491	240.7085	D
BH-14	3766751	737823	15	324.7927	2.53238	340.7065	D
BHDP-01	3767907	744044	30.45	253.8902	2.424732	265.9083	D
BHDP-1	3767589	744304	30.15	244.4534	2.408129	255.9347	D
BHDP-2	3767666	744182	10.37	185.2857	2.286277	193.3202	D
BHDP-3	3667487	744004	10.37	182.2282	2.27894	190.0814	D
BH-15	3766706	737461	35.3	218.7226	2.359306	228.721	D
BH-16	3766124	737087	15.44	315.1281	2.519205	330.5257	D
BH-17	3766173	736920	35.15	338.0573	2.549826	354.6715	D
BH-19B	3765474	735875	35.15	306.6399	2.507289	321.5802	D
BH-20	3764966	734910	30.3	292.8403	2.48718	307.0294	D
BH-22	3764558	734211	35.44	378.2241	2.598684	396.903	C
BH-24	3765032	733835	35.44	275.2538	2.460103	288.4717	D
BH-26	3765751	734064	32.2	288.5194	2.480684	302.4713	D
BHRA-1	3766738	737216	35.15	267.1452	2.447019	279.9102	D
BHRA-2	3766334	737075	35.45	290.5526	2.483753	304.6162	D
BHRA-3	3765434	735561	35.26	332.4522	2.542541	348.7716	D
BHRA-4	3765464	735777	15.15	343.3475	2.55659	360.2386	C
BHRA-5	3765373	735465	35.15	290.9376	2.484332	305.0223	D
BHDP-04	3765679	736198	10.45	313.6316	2.517128	328.9488	D
BHDP-05	3765701	736187	34.95	344.9317	2.558595	361.9053	C
BHDP-06	3765742	736205	9.22	369.3573	2.58837	387.5878	C
BH-28	3765820	732827	35.3	335.8758	2.547006	352.3754	D
BH-30	3765747	731660	35.3	272.8046	2.456193	285.886	D
BH-32	3765353	731070	14.8	261.1281	2.437045	273.5551	D
BH-34	3764757	730164	15.3	259.7645	2.434752	272.1146	D
BH-36	3764675	729732	15.44	282.4414	2.471377	296.0581	D
BH-38	3764762	728864	15.3	287.1386	2.478587	301.0145	D
BH-40	3763944	727249	35.3	411.1925	2.634983	431.5021	C
BH-42	3763745	726697	15.3	331.69	2.541541	347.9691	D
BH-44	3762764	725970	15.15	376.5375	2.596742	395.1315	C
BH-46	3765092	725711	13.65	352.64	2.568218	370.0137	C
BHDP-07	3763996	727212	10.45	352.3459	2.567855	369.7044	C
BHDP-08	3764004	727152	10.45	331.7659	2.54164	348.049	D
BHAD-6	3764529	727601	20.15	379.1946	2.599798	397.9223	C
BHCU-07	3764525	725715	35.15	384.1519	2.605443	403.1283	C

3.5. Selection of Ground Motions

The selection of ground motions for site response analysis is a crucial step in understanding the seismic behavior for a particular site. It involves a careful process of choosing representative historical earthquake records that capture the spectral characteristics and intensity of ground shaking expected at the local site. Factors such as the region's seismicity and the site's geological features play significant

roles in this selection process. Given the unique tectonic setting and seismicity of the region, encompassing the interaction of the Indian Plate with the Eurasian Plate, selecting time histories that closely align with the local tectonic environment, expected earthquake magnitudes and distances, as well as site-specific response spectral characteristics becomes vital. Although Peshawar lies in a seismically active region, with no past events like the Kashmir earthquake of 2005 (Mw 7.6), comprehensive instrumental recordings are limited. Alternatively, intra-plate recordings from related regions worldwide, compiled by seismic experts, become necessary to approximate the ground motion characteristics pertinent to a Peshawar's geological profile. As per the Pakistan Building Code, Peshawar is categorized under seismic zone 2B, implying a moderate to high seismic hazard level with a Peak Ground Acceleration (PGA) ranging from 0.16g to 0.24g for a return period of 475 years. However, due to the scarcity of specific ground motion data for Peshawar, twenty representative ground motions have been precisely selected for conducting site response analysis in DEEPSOIL. The selected motions span short, intermediate, and long-period characteristics, while the inclusion of pulse motions from 0.1 g to 0.4 g helps evaluate the sensitivity of the shallow profiles under varying input intensity levels. Similar approaches have also been adopted in recent Pakistani shallow-bedrock studies, where (13) multiple input motions were used to obtain representative nonlinear site response trends rather than relying on a single earthquake record (Aaqib et al., 2025). Therefore, the use of (20) ground motions in the present study was intended to reduce record-specific bias and to derive more reliable average values of short-period and long-period amplification factors for each representative sub-profile. The input ground motions are summarized (Table 4) as given below, whereas their spectral acceleration characteristics are presented in Fig. 9.

Table 4. Input ground motions

Ground Motion Symbol	Ground Motion Name	Predominant frequency	Predominant Period
GM1	Chichi	0.69580078	1.43719298
GM2	Nahanni	16.0583496	0.0622729
GM3	NR	1.62353516	0.61593985
GM4	Parkfield	2.63061523	0.38013921
GM5	Landers	9.42993164	0.10604531
GM6	Loma	0.90332031	1.10702703
GM7	Kobe	0.82397461	1.21362963
GM8	Mirpur Ch_EW	0.45471191	2.19919463
GM9	Mirpur CH_NS	0.43029785	2.32397163
GM10	Capetown	1.42211914	0.70317597
GM11	Coyote	2.39868164	0.41689567
GM12	Duzce	1.84326172	0.54251656
GM13	Tabas	2.64892578	0.37751152
GM14	Kocaeli	5.35888672	0.18660592
GM15	Imperial Valley	2.35595703	0.42445596
GM16	Hector	0.79956055	1.25068702
GM17	Pulse 0.1g	3.99780273	0.25013740
GM18	Pulse 0.2g	3.99780273	0.25013740
GM19	Pulse 0.3g	3.99780273	0.25013740
GM20	Pulse 0.4g	3.99780273	0.25013740

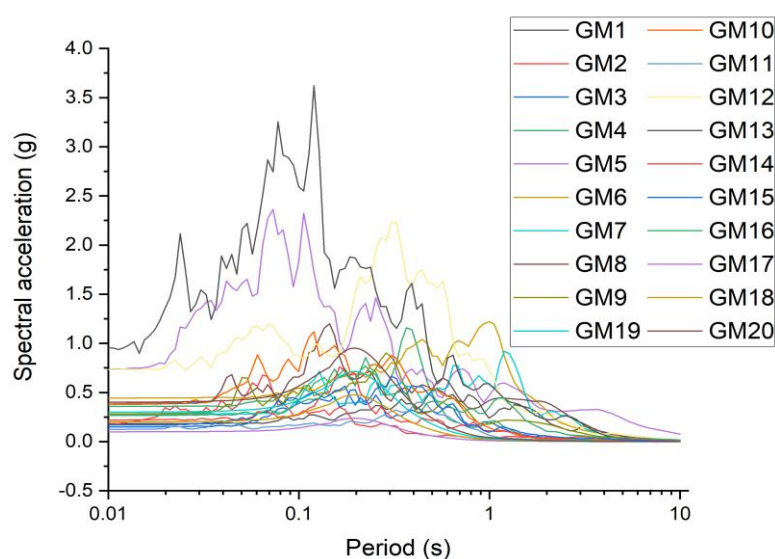


Fig. 9. Spectral Acceleration of Twenty Ground Motions

3.6. Seismic Site Response Analysis

DEEPSOIL software was used to run the simulation of borehole data. For this purpose, the General Quadratic/Hyperbolic (GQ/H) model was used instead of the MKZ (Modified Kondner Zelesko hyperbolic) model because, when compared the given results to the MKZ model, the GQ/H model estimates lower shear stresses and larger amplification factors than the MKZ model. The values of seismic coefficient for shorter and longer periods (F_a and F_v) were calculated using the GQ/H model, were similarly found to be greater than those calculated with the MKZ model (Pehlivan et al., 2017). By applying 1D non-linear analysis in DEEPSOIL software under 20 ground motions, this study was analyzed all 16 sub-profiles. Surface response spectra is then used to calculate short-period amplification factors “ F_a ” and long-period amplification factors “ F_v ”. The comparison is also made with the existing values proposed by the Building Code of Pakistan, as discussed later in Section 4.2 (Table 9).

DEEPSOIL is a one-dimensional site response analysis software developed in 1998, with or without pore water generation, linear and nonlinear response analysis can be performed. For this study, the general quadratic/hyperbolic model (GQ/H) is adopted instead of the pressure-dependent Modified Kondner Zelesko (MKZ) model. MKZ, compared to the GQ/H model, over estimates the damping ration and shear modulus (Du and Pan, 2016). One-dimensional non-linear analysis was performed without the generation of pore water pressure on all (16) sub-profiles using the (20) ground motions.

Three main types of soil settings were defined in DEEPSOIL. (1) Sand (SW, SC, and SM). (2) Clay (ML and CL) and (3) Gravels (GW, GM, and GC). In case of the Sand (SW, SC and SM), (Darendeli, 2001) reference curve was used with $OCR=1$ and $Ko=0.5$. in the case of Clay (ML and CL), the plasticity index was taken as 10, and (Vucetic and Dobry, 1991) reference curve was used. Additionally, Gravel (GW, GM and GC) was assigned user-defined values proposed by (Rollins et al., 1998), as mentioned in Table 5 below. The plasticity index was taken as 10 and MRDF-Darendeli (Modulus Reduction and Damping Curve) curve fittings were used for analysis. Further, for this study, the number of iterations was limited to 15 and the effective shear strain ratio was selected as 0.65 for analyzing all soil types and proposed sub profiles.

Table 5. User-defined values for Gravels (Rollins et al., 1998)

Strain (%)	G/Gmax	Damping (%)
0.0001	0.9960204	0.95
0.0002	0.9920815	1.04
0.0005	0.9805021	1.24
0.0010	0.9619595	1.50
0.0020	0.9274719	1.91
0.0050	0.8409544	2.80
0.0100	0.7359079	3.89
0.0200	0.6051865	5.45
0.0500	0.4317364	8.28
0.1000	0.3125000	10.79
0.2000	0.1984126	13.23
0.5000	0.0909082	15.76
1.0000	0.0476190	17.01

Additionally, using ArcGIS, various geospatial maps were generated. Maps showing NEHRP site classes, GIS-based VSZ, GIS-based bedrock depth, and ArcGIS-based short-period (F_a) and long-period (F_v) amplification factors were generated using kriging extrapolation; these are presented later in Section 4.3 (Figs. 13 to Fig. 17).

4. Results and Discussions

The following section shows the calculated results by the methodology adapted as mentioned above. The results were produced in the form of site-specific amplification factors (F_a and F_v) after analyzing each sub-profile under (20) ground motions.

4.1. Development of Sub-Site Classification System

Sub-classes need to be defined for microzonation. After finding the NEHRP classes for all profiles (which are “D” and “C” in this case), are then sub-classified on the basis of depth to bedrock and average shear wave velocity (V_{sz}). According to the depth, six sub-classes are created and assigned as (1-6 numeric digits), comprising 5-10m, 10-15m, 15-20m, 20-25m, 25-30m and 30-35m in the order as mentioned in Table 6 below. On the other hand, according to the average shear velocity (V_{sz}), the research area was divided into four groups a, b, c and d, which follow the range from 150-200 m/s, 200-250 m/s, 250-300 m/s and greater than 300 m/s respectively as mentioned in Table 7. Some of these classes have more than one profile, so, for further analysis, the average of all these profiles is then taken. For this, the adopted nomenclature is in the form of “SXyz”. Where, “S” is sub site, “X” is the NEHRP site class. Meanwhile, “y” and “z” define sub-class in a way the “y” value represents the bedrock depth and “z” represents the (V_{sz}).

Table 6. Sub site classification w.r.t bedrock depth

Range of bedrock depth (m)	Nomenclature (x)
5-10	1
10-15	2
15-20	3
20-25	4
25-30	5
30-35	6

Table 7. Sub site classification w.r.t V_{sz}

Range of V_{sz} (m/s)	Nomenclature (y)
150-200	a
200-250	b
250-300	c
>300	d

Table 8, however, represents sub-site classifications with respect to the SPT boreholes data and (V_{zs}) values.

Table 8. NEHRP and sub-site classifications

S. No.	Classification	BH No	Bedrock Depth (m)	V _{SZ} (m/s)	V _{S30} (m/s)	NEHRP Site class
NEHRP Site Classification “C”						
1	SC1d	BHDP-06	9.22	369.3573	387.5878	C
2	SC2d	BH-46	13.65	352.64	370.0137	C
		BHDP-07	10.45	352.3459	369.7044	C
3	SC3d	BHRA-4	15.15	343.3475	360.2386	C
		BH-44	15.15	376.5375	395.1315	C
4	SC4d	BHAD-6	20.15	379.1946	397.9223	C
		BHDP-05	34.95	344.9317	361.9053	C
5	SC6d	BH-22	35.44	378.2241	396.903	C
		BH-40	35.3	411.1925	431.5021	C
		BHCU-07	35.15	384.1519	403.1283	C
NEHRP Site Classification “D”						
6	SD2a	BH-02	15	189.9761	198.2881	D
		BH-04	15	196.701	205.41	D
		BHDP-2	10.37	185.2857	193.3202	D
		BHDP-3	10.37	182.2282	190.0814	D
7	SD2b	BH-06	15	218.2487	228.2196	D
		BH-08	15	202.4208	211.4663	D
8	SD2c	BH-32	14.8	261.1281	273.5551	D
		BH-14	15	324.7927	340.7065	D
9	SD2d	BHDP-04	10.45	313.6316	328.9488	D
		BHDP-08	10.45	331.7659	348.049	D
10	SD3b	BH-10	20	226.0678	236.4923	D
		BH-34	15.3	259.7645	272.1146	D
11	SD3c	BH-36	15.44	282.4414	296.0581	D
		BH-38	15.3	287.1386	301.0145	D
12	SD3d	BH-16	15.44	315.1281	330.5257	D
		BH-42	15.3	331.69	347.9691	D
13	SD5b	BH-01A	27	229.0518	239.6488	D
		BH-12	26	230.0536	240.7085	D
14	SD6b	BHDP-1	30.15	244.4534	255.9347	D
		BH-15	35.3	218.7226	228.721	D
		BHDP-01	30.45	253.8902	265.9083	D
		BH-20	30.3	292.8403	307.0294	D
15	SD6c	BH-24	35.44	275.2538	288.4717	D
		BH-26	32.2	288.5194	302.4713	D
		BHRA-1	35.15	267.1452	279.9102	D
		BHRA-2	35.45	290.5526	304.6162	D
		BHRA-5	35.15	290.9376	305.0223	D
		BH-30	35.3	272.8046	285.886	D
		BH-17	35.15	338.0573	354.6715	D
16	SD6d	BH-19B	35.15	306.6399	321.5802	D
		BHRA-3	35.26	332.4522	348.7716	D
		BH-28	35.3	335.8758	352.3754	D

Fig. 10. The movement of average shear wave velocity within the depth of a proposed sub-profiles

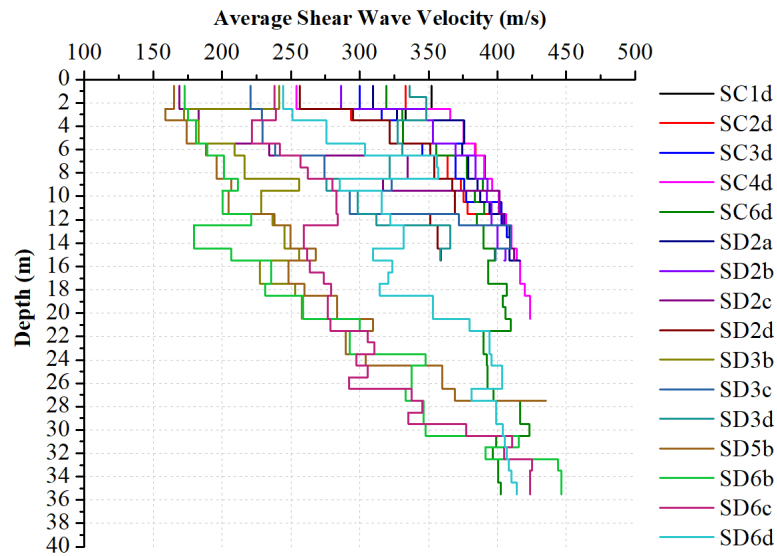


Fig. 100. Developed shear wave velocity sub-profiles

4.2. Site-Specific Seismic Amplification Factors and Comparison with BCP-2007

From the site response analysis, the amplification factors for all representative sub-profiles were calculated. The amplification factor is the ratio of ground motion at the free field surface to the ground motion at the bedrock (Kramer, 1996). The empirical value of the site coefficient is commonly presented in short periods ($T = 0.2$ s) and long periods ($T = 1.0$ s) (Pawirodikromo et al., 2019) which is generally abbreviated as (F_a and F_v), respectively.

Fig. 11 represents the calculated short-period amplification factors “ F_a ” for all representative sub-profiles of NEHRP site class C and D along the suggested values of BCP-2007 for specific locations. One sub-profile was given 20 ground motions, and all results were then averaged to represent one value of “ F_a ” for each sub-profile as shown in Table 9 below. BCP-2007 suggested the value of “ F_a ” for NEHRP site class C was “1.2” and value of “ F_a ” for NEHRP site class D was “1.4”.

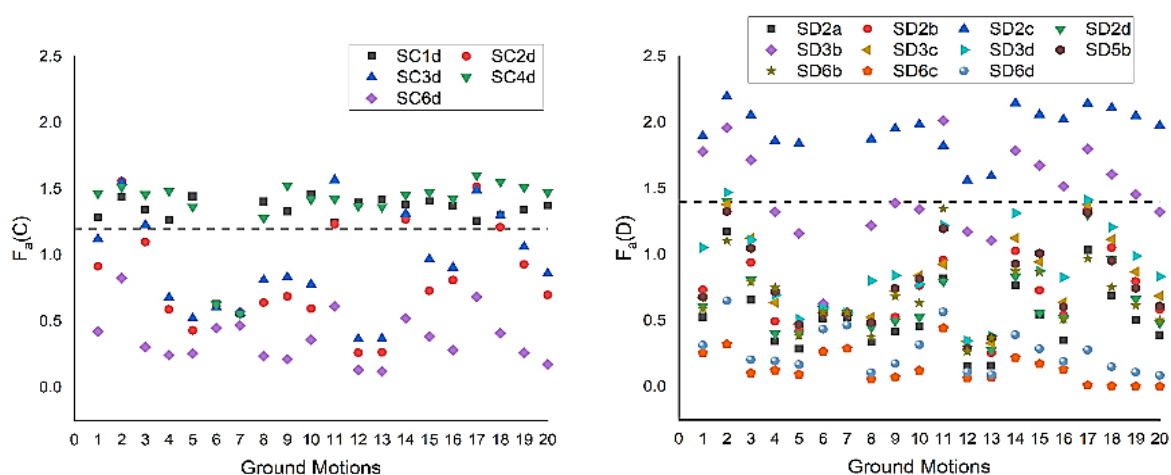


Fig. 11. “ F_a ” values for NEHRP “C” and “D” class along with BCP suggested values (dashed lines: BCP-2007 reference values, $F_a = 1.2$ for class C and $F_a = 1.4$ for class D)

Similarly, Fig. 12 represents the calculated long-period amplification factors “Fv” for all representative sub-profiles of NEHRP site class C and D along the suggested values of BCP-2007 for a specific location. Again, one sub-profile was given 20 ground motions, and all the results were then averaged to represent one value of “Fa” for each sub-profile as shown in Table 9. BCP-2007 suggested the value of “Fv” for NEHRP site class C was “1.6” and the value of “Fv” for NEHRP site class D was “2”. However, in the light of this study, the Building Code of Pakistan (BCP) designs short-period and long-period seismic coefficients is concluded. Proposed new site-specific amplification factors can result in more economical and safe buildings and other infrastructure designs. Table 9 also shows the percent change in the values of amplification factors proposed by BCP-2007 and this study.

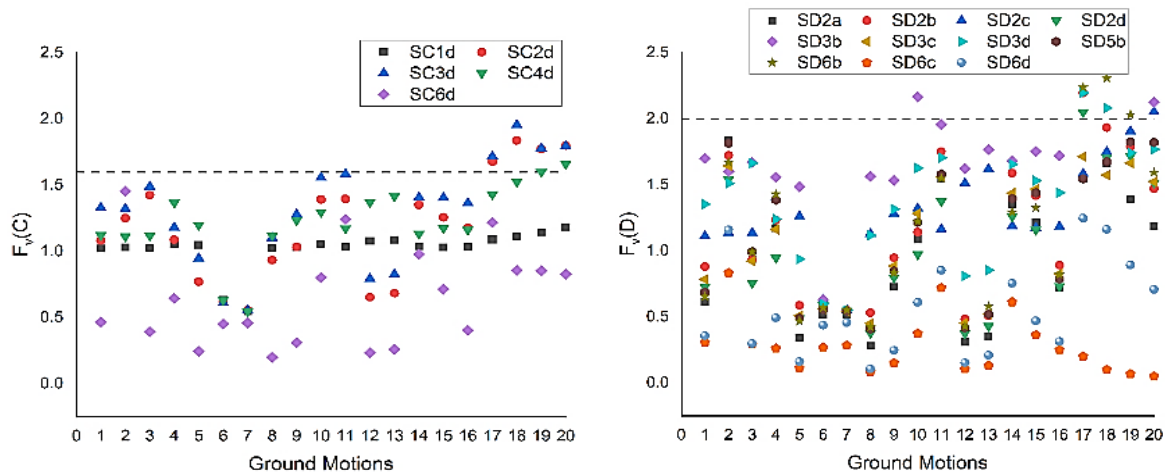


Fig. 12. “Fv” values for NEHRP “C” and “D” class along with BCP suggested values (dashed lines: BCP-2007 reference values, Fv = 1.6 for class C and Fv = 2.0 for class D)

Table 9. The comparison between BCP-2007 suggested values and the values of Fa and Fv with the percentage difference

Sub Profiles	NEHRP Site Class	BCP-2007 Suggested		This Research Study		Percent Difference (%)	
		Fa	Fv	Fa	Fv	Fa	Fv
SC1d	C	1.2	1.6	1.284	1.015	-7.0	36.6
SC2d				0.834	1.187	30.5	25.8
SC3d				0.946	1.3	21.2	18.8
SC4d				1.37	1.22	-14.2	23.8
SC6d				0.37	0.65	69.2	59.4
SD2a	D	1.4	2	0.534	0.965	61.9	51.8
SD2b				0.721	1.156	48.5	42.2
SD2c				1.818	1.304	-29.9	34.8
SD2d				0.648	1.002	53.7	49.9
SD3b				1.428	1.737	-2.0	13.2
SD3c				0.794	1.073	43.3	46.4
SD3d				0.893	1.484	36.2	25.8
SD5b				0.772	1.096	44.9	45.2
SD6b				0.677	1.148	51.6	42.6
SD6c				0.143	0.278	89.8	86.1
SD6d				0.266	0.553	81.0	72.4

Table 9 reflects the mismatch between generalized code-based amplification factors and the actual local response of shallow-bedrock sites in Peshawar proposed by this study, because BCP-2007 adopts fixed coefficients for broad site classes. These results prove that BCP-2007 cannot capture the influence of local bedrock depth, stiffness variation, and impedance contrast identified in this study. As a result, profiles such as SD6c and SD6d, which exhibit relatively low computed amplification, show 86.1% and 72.4% percentage differences when compared with the higher generalized code values.

4.3. Microzonation Seismic Hazard Maps of the Study Area

Kriging spatial interpolation technique was used to develop seismic hazard maps for the areas under study. Fig. 13 illustrates the NEHRP site classes based on the NEHRP recommended (V_{s30}) ranges within the target area of this study. Fig. 14, on the other hand, shows the (V_{sz}) map of Peshawar metropolitan area. The (V_{sz}) lies in the range of 150 to 400 m/s. The lowest values are observed at Musazai region which is in range of 150 to 200m/s. The (V_{sz}) kept increasing while moving towards western region and the highest values were observed at Hayatabad region. Fig. 15, on the other hand, represents bedrock depth, that the Peshawar metropolitan area lies in the shallow region, with a minimum depth of 10m and deepest up to 40m. More than 90% area of Peshawar metropolitan has less than 30m bedrock depth.

Figs. 16 and 17 represent the spatial variation of seismic coefficients for short-period (F_a) and long-period (F_v) respectively. The seismic coefficient for the short-period (F_a) is from 0.266 to 1.818 with the minimum value observed in the Peshawar Cantt-I and Tehkal area. The eastern and western regions mostly lie in the range of 0.5 to 1. Some of the region such as University Town and Sikandar Town mainly observed maximum amplification which is from 1 to 1.5. Similarly, the seismic coefficient for long-period (F_v) is from 0.278 to 1.737 with the minimum values observed in Peshawar Cantt-I and Tehkal area. Most of the area of Hayatabad lies in the range of 0.5 to 1, while for the Gulbahar and Chamakni region was from (1 to 1.5).

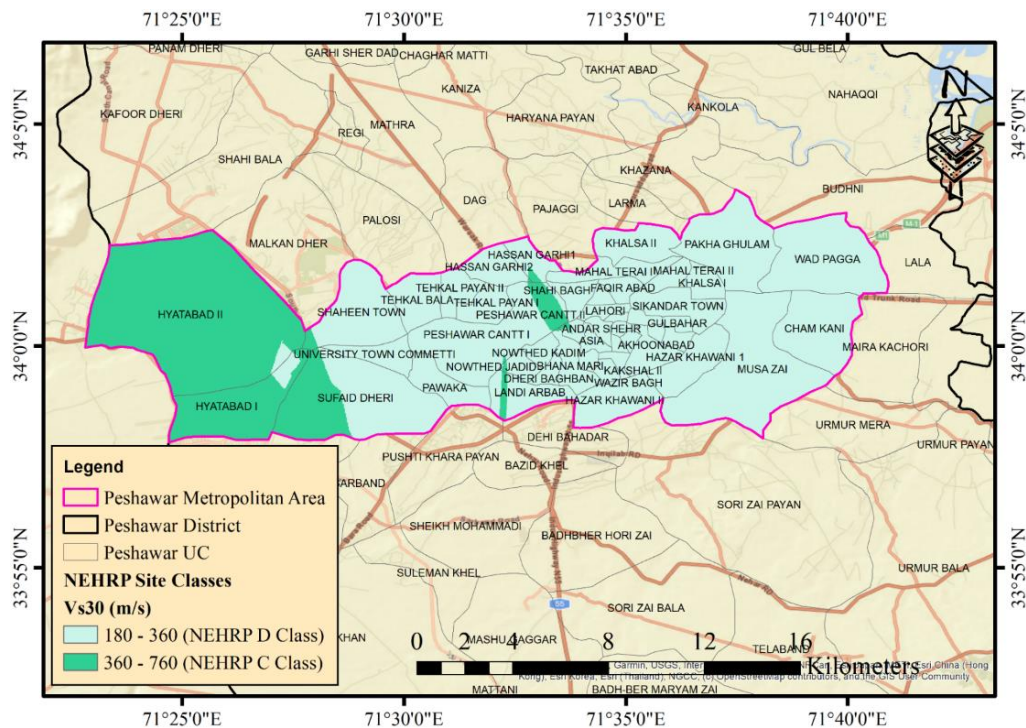


Fig. 13. Proposed NEHRP site class map for the Peshawar Metropolitan Area

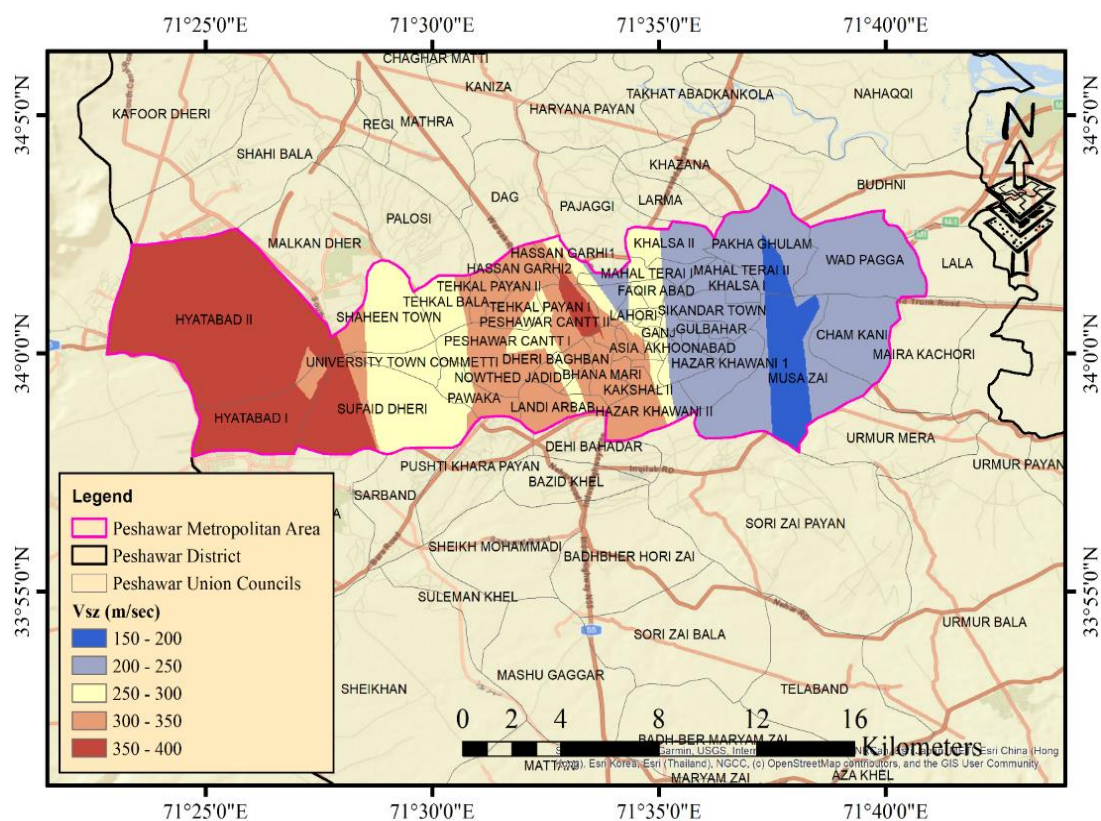


Fig. 14. Proposed V_{sz} map of the Peshawar metropolitan area

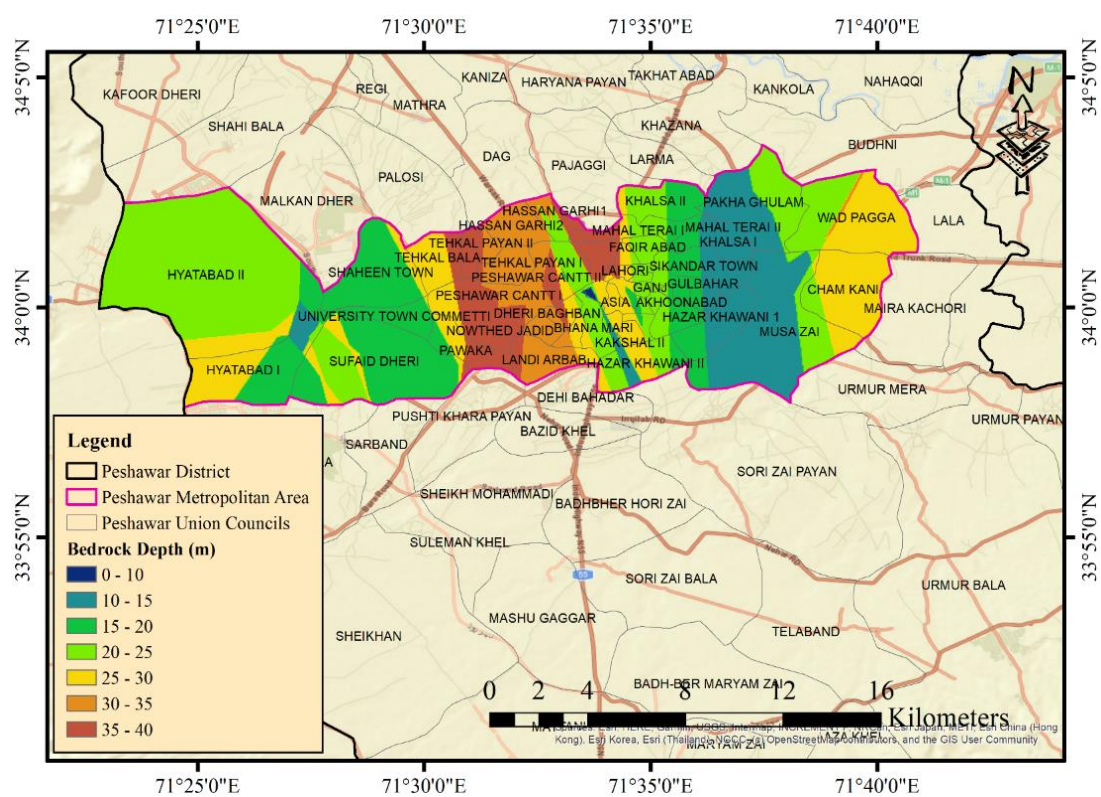


Fig. 15. Proposed bedrock depth map of the Peshawar metropolitan area

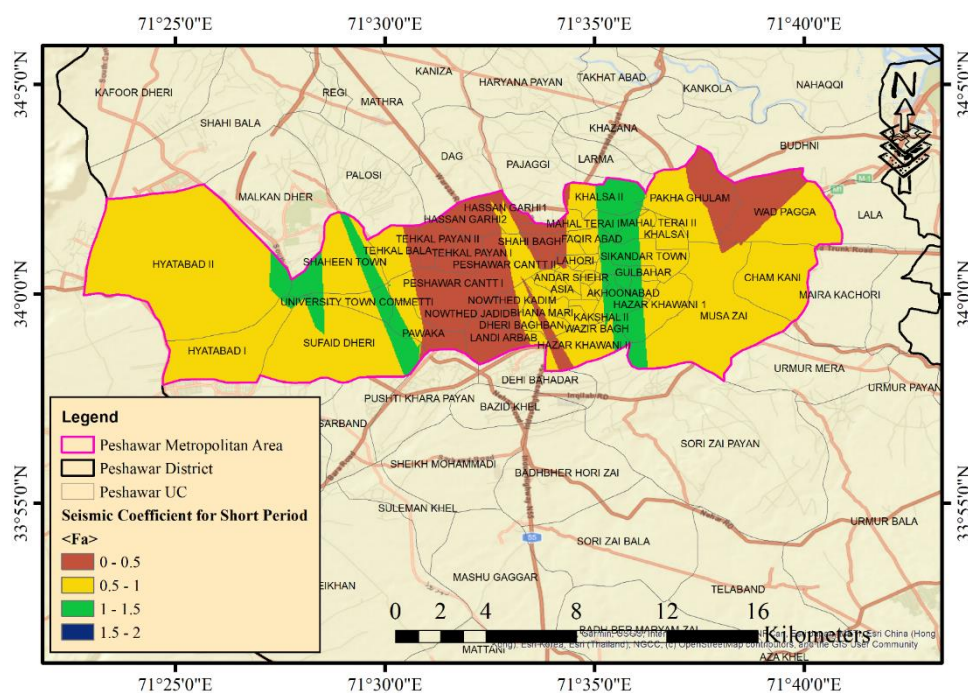


Fig. 16. Seismic coefficients for short period of Peshawar metropolitan Area

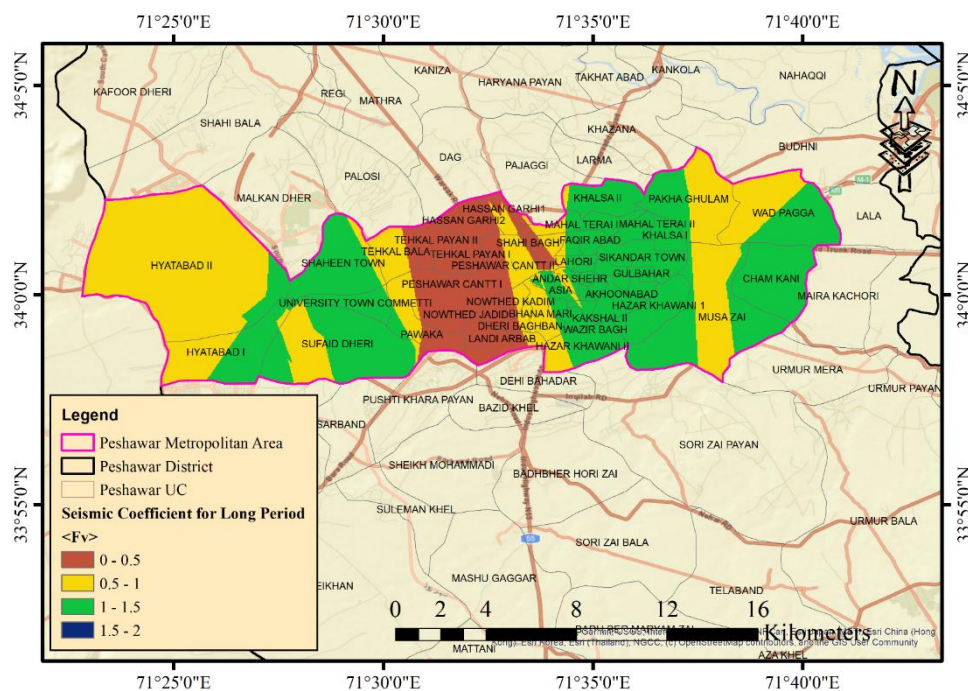


Fig. 17. Seismic coefficients for long period of Peshawar metropolitan Area

4.4. Discussion of the Results and Its Comparison with Previous Studies

The results indicate that the seismic response of the Peshawar metropolitan area is mainly governed by shallow bedrock depth, local stiffness variation, and impedance contrast between overlying soils and the underlying rock. The comparison with BCP-2007 shows that the code-based values overestimate (F_a) for 12 out of 16 representative sub-profiles and overestimate (F_v) for all 16 sub-profiles. The largest differences are observed for the deeper D-class shallow bedrock profiles, particularly (SD6c and SD6d), where both (F_a and F_v) are substantially lower than the corresponding (BCP-2007) values. This

behavior suggests that the generalized coefficients of (BCP-2007) overestimates the dynamic response of shallow-bedrock sites in Peshawar metropolitan area and may therefore lead to uneconomical and unsuitable seismic design estimates.

These findings are consistent with the previous studies that applied site-specific seismic response analysis to shallow-bedrock regions. (Sadiq et al., 2021) reported that shallow-rock sites in Islamabad required site-specific evaluation of amplification factors and showed notable differences from the generalized seismic provisions from the building code of Pakistan. (Anbazhagan et al., 2013) even demonstrated that shallow bedrock conditions can significantly influence site classification and amplification behavior, especially where the top 30 m alone does not fully represent the seismic response of the soil-rock system. More recent studies have similarly emphasized that nonlinear site response analysis provides a more realistic representation of local amplification behavior than generalized subsurface conditions as they vary significantly from site to site.

A particularly relevant and recent comparison is provided by (Aaqib et al., 2025), where their study evaluated empirical SPT-N-Vs correlations for shallow-bedrock sites in Islamabad, Pakistan, with six representative profiles selected from 62 boreholes. In that study, the developed profiles covered a (V_{s30}) range of 227-597 m/s and a natural-period range of 0.098-0.656 s, and a total of 546 one-dimensional nonlinear DEEPSOIL analyses were carried out using 13 input ground motions scaled to a PGA of 0.31 g. Their results showed clear variability even within the same shallow-bedrock environment. For instance, site class SC, the (F_a) generally varied from 1.4 to 1.8 and (F_v) from 1.75 to 2.05. Whereas, for site class SD, the (F_a) was varied from about 1.4 to 1.9 and (F_v) reached as high as 3.1. Their comparative assessment further showed that for SC sites, the AEA15 correlation produced the lowest percentage differences from the code, generally less than 25% for both (F_a and F_v), while for (SD) sites the (OG78) outputs gave lower differences, generally less than 40% for (F_a and 50% for F_v), although discrepancies remained at longer periods. These statistical findings support the present results for Peshawar, where (F_a) ranges from 0.266 to 1.818 and (F_v) from 0.278 to 1.737, and where (BCP, 2007) overestimates (F_a) for 12 of the 16 representative sub-profiles and (F_v) for all 16, with the largest deviations observed for (SD6c and SD6d). Together, both studies demonstrate that shallow-bedrock sites in Pakistan do not respond uniformly and that reliable amplification estimates require locally constrained (V_s) characterization and site-specific nonlinear response analysis rather than generalized code-based coefficients.

Moreover, the spatial distribution maps developed in this study significantly enhance the practical applicability of the results. By presenting the variation of NEHRP site classes, (V_{sz}), bedrock depth, (F_a , and F_v) in spatial form, the study makes it possible to evaluate local seismic response more efficiently across the Peshawar metropolitan area. These maps work as a feasible tool for preliminary engineering assessment, urban planning, and regional seismic microzonation, particularly in data-limited conditions where site-specific nonlinear analysis cannot be performed for every individual location.

For the proper evaluation of the results in the form of site-specific short period seismic amplification factors (F_a) and long period seismic amplification factors (F_v) for any site in the understudy region, the following method must be adopted:

1. Check NEHRP site class with the help of (Fig. 13).
2. Check (V_{sz}) range with the help of (Fig. 14).
3. Check bedrock depth range with the help of (Fig. 15).
4. Check value of short period seismic amplification factor (F_a) with the help of (Fig. 16).
5. Check value of long period seismic amplification factor (F_v) with the help of (Fig. 17).
6. The values of (F_a and F_v) can also be determined directly with the help of Table 9 if a standard sub-site profile is encountered.

5. Conclusions

This study demonstrates that the seismic response of the Peshawar metropolitan area cannot be represented adequately by generalized amplification factors alone and instead it requires site-specific evaluation that is based on local subsurface conditions. The metropolitan area is characterized predominantly by shallow bedrock conditions, with bedrock generally occurring at depths of about 10-40 m depth and more than 90% of the area having bedrock shallower than 30 m. Under these conditions, the calculated seismic amplification factors vary significantly across the study area, indicating that the local stiffness variation, bedrock depth, and impedance contrast strongly influence the seismic response.

The main conclusion of this study is that the generalized seismic amplification coefficients of (BCP, 2007) are not fully representative of the actual site response of Peshawar metropolitan area. The comparison with the proposed site-specific factors shows that (BCP-2007) overestimates short-period amplification factors (F_a) for 12 out of 16 representative sub-profiles and long-period amplification factors (F_v) for all 16 sub-profiles. This indicates that direct use of generalized code-based coefficients may lead to uneconomical and overly conservative seismic design estimates for the study area. Therefore, the proposed microzonation framework, based on (V_{sz} , V_{s30}), bedrock depth, and one-dimensional nonlinear site response analysis, provides a more realistic basis for evaluating local seismic effects and for improving future seismic design practice in Peshawar.

In addition, the study confirms the practical value of combining multiple SPTN- V_s correlations, in situ validation, nonlinear DEEPSOIL analysis, and spatial mapping to produce engineering-useful microzonation outputs in a data-limited urban environment. The proposed site-specific spatial maps and tabulated amplification factors provide a feasible basis for preliminary seismic assessment, urban planning, and future revision of seismic design criteria for shallow-bedrock regions of Pakistan. Overall, the study establishes that reliable seismic microzonation of Peshawar requires local geotechnical characterization and site-specific nonlinear analysis rather than reliance on uniform macro-level code. Moreover, this study is unique in both the calculation of (V_s) using 50 various SPTN- V_s correlations and the calculation of site-specific seismic amplification factors for the Peshawar metropolitan area using 1D non-linear analysis and GQ/H modeling. However, chances for improvement are present. This study strengthens the idea of revising seismic design criteria in the Building Code of Pakistan.

Recommendations

It is recommended that the study can be strengthened by adding further data on the under-study area, or the same maps can be generated for the whole Peshawar district if more data is available. It is also recommended that site-specific correlations may be developed to estimate site-specific shear wave velocities, which will uplift confidence in the results of this research study.

Author Contributions: CRediT

- Ahmad Iqbal: Conceptualization, methodology, software, formal analysis, investigation, data curation, visualization and writing original draft.
- Muhammad Shahkar: conceptualization, methodology, software, validation.
- Fahd Saeed Alakbari: supervision, project administration and resources.
- M. Hamza Sabir: data curation, resources, writing, review and editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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Data Availability

The geotechnical borehole data which analyzed in this study were obtained from the Peshawar Development Authority and associated consultancy firms under a data-sharing agreement, and are available from the corresponding author upon reasonable request with the permission of the data providers. The DEEPSOIL software used for one-dimensional nonlinear site response analysis is publicly available through the University of Illinois Urbana-Champaign.

References

- Aaqib, M., Nguyen, V.Q., Javaid, O., Khan, A.H., Ashraf, M. A., Bhusal, B., 2025. Evaluation of empirical SPT N-Vs correlations using 1D site response analysis for shallow bedrock sites in Islamabad, Pakistan. *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, 49, 2947–2963. <https://doi.org/10.1007/s40996-024-01621-4>
- Ahmad, I., Hashash, Y.M.A., Khan, A.N., Waseem, M., 2011. Site Amplification Factor at Mardan. *Geological Bulletin, University of Peshawar*, 44, 81-90.
- Altun, S., Sezer, A., Burak Göktepe, A., 2012. A preliminary microzonation study on Northern Coasts of Izmir: Investigation of the local soil conditions. *Soil Dynamics and Earthquake Engineering*, 39, 37–49. <https://doi.org/10.1016/j.soildyn.2012.02.006>
- Anbazhagan, P., Sheikh, M. N., Parihar, A., 2013. Influence of rock depth on seismic site classification for shallow bedrock regions. *Natural Hazards Review*, 14 (2), 108–121. [https://doi.org/10.1061/\(ASCE\)NH.1527-6996.0000088](https://doi.org/10.1061/(ASCE)NH.1527-6996.0000088)
- Apriadi, D., Mandhany, A., Sahadewa, A., Basarah, Y.I., Sengara, W., Hakim, A.M., 2023. Scaling factors for 1-D ground response amplification in a soft soil basin. *Frontiers in Built Environment*, 9, 1275425. <https://doi.org/10.3389/fbuil.2023.1275425>
- ASTM International, 1999. ASTM D1586-99: Standard Test Method for Penetration Test and Split-Barrel Sampling of Soils. West Conshohocken, PA. <https://doi.org/10.1520/D1586-99>
- ASTM International, 2008. ASTM D7400-08: Standard Test Methods for Downhole Seismic Testing. West Conshohocken, PA. <https://doi.org/10.1520/D7400-08>
- Bhatti, A.Q., Hassan, S.Z.U., Rafi, Z., Khatoon, Z., Ali, Q., 2011. Probabilistic seismic hazard analysis of Islamabad, Pakistan. *Journal of Asian Earth Sciences*, 42, 468–478. <https://doi.org/10.1016/j.jseaes.2011.05.006>
- Boore, D.M., 2006. Determining subsurface shear-wave velocities: a review, in: *Proceedings of the Third International Symposium on the Effects of Surface Geology on Seismic Motion*. Grenoble, France, 1–21.

- Boore, D.M., Thompson, E.M., Cadet, H., 2011. Regional correlations of VS30 and velocities averaged over depths less than and greater than 30 meters. *Bulletin of the Seismological Society of America*, 101, 3046–3059. <https://doi.org/10.1785/0120110071>
- Civelekler, E., Afacan, K.B., Okur, D.V., 2024. Effect of site-specific soil characteristics on the nonlinear ground response analysis and comparison of the results with equivalent linear analysis. *Journal of Applied Geophysics*, 220, 105250. <https://doi.org/10.1016/j.jappgeo.2023.105250>
- Darendeli, M.B., 2001. Development of a new family of normalized modulus reduction and material damping curves. University of Texas at Austin.
- De la Torre, C.A., Bradley, B.A., Kuncar, F., Lee, R.L., Wotherspoon, L.M., Kaiser, A.E., 2024. Combining observed linear basin amplification factors with 1D nonlinear site-response analyses to predict site response for strong ground motions: application to Wellington, New Zealand. *Earthquake Spectra*, 40, 143–173. <https://doi.org/10.1177/87552930231209726>
- Dickenson, S.E., 1994. Dynamic Response of Soft and Deep Cohesive Soils During the Loma Prieta Earthquake of October 17, 1989. University of California, Berkeley.
- Di Filippo, G., Biondi, G., Casablanca, O., Cascone, E., 2023. Seismic amplification factors for low plasticity medium-stiff soil deposits. *Soil Dynamics and Earthquake Engineering*, 173, 108094. <https://doi.org/10.1016/j.soildyn.2023.108094>
- Du, W., Pan, T.C., 2016. Site response analyses using downhole arrays at various seismic hazard levels of Singapore. *Soil Dynamics and Earthquake Engineering*, 90, 169–182. <https://doi.org/10.1016/j.soildyn.2016.08.033>
- Ge, Y., Gu, Y., Deng, W., 2010. Evaluating China's national post-disaster plans: the 2008 Wenchuan earthquake's recovery and reconstruction planning. *International Journal of Disaster Risk Science*, 1, 17–27.
- Hasancebi, N., Ulusay, R., 2007. Empirical correlations between shear wave velocity and penetration resistance for ground shaking assessments. *Bulletin of Engineering Geology and the Environment*, 66, 203–213. <https://doi.org/10.1007/s10064-006-0063-0>
- International Code Council Inc., 2000. International Building Code. International Code Council, Inc., Falls Church, VA.
- International Conference of Building Officials, 1997. Uniform Building Code. Volume 2: Structural Engineering Design Provisions. International Conference of Building Officials, Whittier, CA.
- Jafari, M.K., Shafiee, A., Razmkhah, A., 2002. Dynamic properties of fine grained soils in south of Tehran. *Journal of Seismology and Earthquake Engineering*, 4, 25–35.
- Jinan, Z., 1987. Correlation between seismic wave velocity and the number of blow of SPT and depth. Selected Papers from the Chinese Journal of Geotechnical Engineering, ASCE 92–100.
- Kanai, K., Tanaka, T., Morishita, T., Osada, K., 1967. Observation of Microtremors.XI. : Matsushiro Earthquake Swarm Area.
- Kim, D.S., Yoon, J.K., 2006. Development of new site classification system for the regions of shallow bedrock in Korea. *Journal of Earthquake Engineering*, 10, 331–358. <https://doi.org/10.1080/13632460609350600>
- Kim, H.S., Chung, C.K., Kim, J.J., 2018. Three-dimensional geostatistical integration of borehole and geophysical datasets in developing geological unit boundaries for geotechnical investigations. *Quarterly Journal of Engineering Geology and Hydrogeology*, 51, 79–95. <https://doi.org/10.1144/qjegh2016-012>
- Kim, H.S., Sun, C.G., Cho, H.I., 2019. Site-specific zonation of seismic site effects by optimization of the expert GIS-based geotechnical information system for western coastal urban areas in South Korea. *International Journal of Disaster Risk Science*, 10, 117–133. <https://doi.org/10.1007/s13753-018-0208-3>
- Kramer, S.L., 1996. *Geotechnical Earthquake Engineering*. Prentice Hall, Upper Saddle River, NJ.
- Lee, S.H.H., 1992. Analysis of the multicollinearity of regression equations of shear wave velocities. *Soils and Foundations*, 32, 205–214. <https://doi.org/10.3208/sandf1972.32.205>
- Ohta, Y., Goto, N., 1978. Empirical shear wave velocity equations in terms of characteristic soil indexes. *Earthquake Engineering and Structural Dynamics*, 6, 167–187. <https://doi.org/10.1002/eqe.4290060205>
- Ozmen, H.B., 2023. An investigation on soil amplification through site factors used in seismic design codes. *Advances in Civil Engineering*, 2023, 6858371. <https://doi.org/10.1155/2023/6858371>
- Pakistan Bureau of Statistics, 2017. PBS Pakistan Bureau of Statistics [WWW Document]. <https://www.pbs.gov.pk/>

- Pawirodikromo, W., Makrup, L., Teguh, M., Suryo, B., Hartantyo, E., 2019. Site coefficient of short Fa and long period Fv maps constructed from the probabilistic seismic hazard analysis in Yogyakarta Special Province. MATEC Web of Conferences, 280, 1001. <https://doi.org/10.1051/mateconf/201928001001>
- PEC, 2007. Building Code of Pakistan: Seismic Provisions. Islamabad, Pakistan.
- Pehlivan, M., Park, D., Sadiq, S., Hashash, Y.M.A., 2017. Seismic site response of shallow sites in moderate seismicity regions, in: Proceedings of the 19th International Conference on Soil Mechanics and Geotechnical Engineering (ICSMGE). Seoul, Korea, 1569–1572.
- Pitilakis, K., Raptakis, D., Lontzetidis, K., Tika-Vassilikou, T., Jongmans, D., 1999. Geotechnical and geophysical description of EURO-SEISTEST, using field, laboratory tests and moderate strong motion recordings. Journal of Earthquake Engineering, 3, 381–409. <https://doi.org/10.1080/13632469909350352>
- PMD, NORSAR, 2007. Seismic Hazard Analysis and Zonation for Pakistan, Azad Jammu and Kashmir. Islamabad, Pakistan.
- PNDKP, 2017. Urban Policy and Planning Unit – Provincial Land Use Plan (PLUP): Final Land Use Plan of District Peshawar. Peshawar, Pakistan.
- Rollins, K.M., Evans, M.D., Diehl, N.B., Daily III, W.D., 1998. Shear modulus and damping relationships for gravels. Journal of Geotechnical and Geoenvironmental Engineering, 124, 396–405. [https://doi.org/10.1061/\(ASCE\)1090-0241\(1998\)124:5\(396\)](https://doi.org/10.1061/(ASCE)1090-0241(1998)124:5(396))
- Sadiq, S., Aaqib, M., Mandokhail, S.J., Rehman, M.U., Mehtab, A., Muhammad, N., Adeel, M.B., 2021. Evaluation of site amplification factors for shallow rock sites of Islamabad, Pakistan. Kuwait Journal of Science, 48(2), 1-15. <https://doi.org/10.48129/kjs.v48i2.7772>
- Seed, H.B., Idriss, I.M., Arango, I., 1983. Evaluation of liquefaction potential using field performance data. Journal of geotechnical engineering, 109, 458–482. [https://doi.org/10.1061/\(ASCE\)0733-9410\(1983\)109:3\(458\)](https://doi.org/10.1061/(ASCE)0733-9410(1983)109:3(458))
- Shahkar, M., Khan, S., Khan, M.A., 2021. GIS based V_{s30}, V_{sz} and D_{bedrock} mapping for the shallow sites of Islamabad, Pakistan. Journal of Applied and Emerging Sciences, 11, 43–50.
- Shibata, T., 1970. Relation between shear wave velocity of ground and N value of standard penetration test, in: Proceedings of the 5th Annual Meeting of the Japan Society of Soil Mechanics and Foundation Engineering. Tokyo, Japan, 121–124.
- Siddique, M.S., Schwarz, J., 2015. Elaboration of multi-hazard zoning and qualitative risk maps of Pakistan. Earthquake Spectra, 31, 1371–1395. <https://doi.org/10.1193/042913EQS114M>
- Sil, A., Sitharam, T.G., 2014. Dynamic site characterization and correlation of shear wave velocity with standard penetration test 'N' values for the city of Agartala, Tripura State, India. Pure and Applied Geophysics, 171, 1859–1876. <https://doi.org/10.1007/s00024-013-0754-y>
- Sykora, D.W., Stokoe, K.H., 1983. Correlations of in-situ measurements in sands of shear wave velocity, soil characteristics and site conditions. Austin, TX.
- Tonouchi, K., Sakayama, T., Imai, T., 1982. S wave velocity in the ground and the damping factor. Bulletin of the International Association of Engineering Geology - Bulletin de l'Association Internationale de Géologie de l'Ingénieur, 26, 327–333. <https://doi.org/10.1007/BF02594237>
- Vucetic, M., Dobry, R., 1991. Effect of soil plasticity on cyclic response. Journal of Geotechnical Engineering, 117, 89–107. [https://doi.org/10.1061/\(ASCE\)0733-9410\(1991\)117:1\(89\)](https://doi.org/10.1061/(ASCE)0733-9410(1991)117:1(89))
- Wolff, T.F., 1989. Pile capacity prediction using parameter functions, in: Predicted and Observed Axial Behavior of Piles, Results of a Pile Prediction Symposium, ASCE Geotechnical Special Publication. American Society of Civil Engineers, Reston, VA, 96–106.