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Site Response Analysis Considering Site-Affects Leading to Seismic Microzonation Map of Lahore

Maham Basharat · Ajwat Mustafa · Muhammad Umar · Mehtab Alam ⓘ · Umair Ali · Muhammad Irfan

Abstract Seismic microzonation is performed to assess the seismic risk in an area. In this paper, seismic microzonation for Lahore, Pakistan has been carried out. Firstly, the Geotechnical and geological properties of soils in the region were classified based on 119 boreholes. Two downhole tests were performed to measure the dynamic in-situ properties of soil. The design spectra for Lahore city from BCP 2007 and 2021 were used as target spectra to develop two synthetic acceleration time histories respectively. Afterward, one-dimensional non-linear site response analysis was performed at 33 sites having depth of 30 m for evaluation of parameters such as peak ground acceleration and spectral acceleration at the ground surface. Major seismic hazards considered for the seismic risk assessment are (1) peak ground acceleration at the ground surface, (2) surface spectral acceleration and (3) spectral amplification in the top 30 m of soil. All the major hazards estimated above were also used to prepare a seismic risk map of Lahore. Additionally, two site-specific design spectra were proposed in accordance with the soil classes D and E. The results of this study demonstrate the importance of micro-scale seismic studies to quantify the seismic risks associated with earthquakes.

Keywords Seismic risk · Microzonation · Earthquake · Design spectra · Site response analysis · Nonlinear analysis

M. Basharat · A. Mustafa · M. Umar
Department of Civil Engineering, National University of Computer and Emerging Sciences, Lahore, Pakistan

M. Basharat
Department of Civil Engineering, Middle East Technical University, Ankara, Turkey

A. Mustafa
Pacific Consultants, Lahore, Pakistan

M. Alam (✉)
Ghulam Ishaq Khan Institute of Engineering Sciences and Technology, Topi 23640, Pakistan
e-mail: engr_mehtab@yahoo.com

M. Alam
Department of Geotechnical Engineering, College of Civil Engineering, Tongji University, Shanghai 200092, China

U. Ali
Civil and Environmental Engineering Department, King Fahd University of Petroleum & Minerals, 31261 Dhahran, Saudi Arabia

U. Ali
Interdisciplinary Research Center for Building and Construction Material, KFUPM, 31261 Dhahran, Saudi Arabia

M. Irfan
Birudo Engineers, Lahore, Pakistan

1 Introduction

Seismic events tend to cause massive damage to infrastructure and an unprecedented loss of human lives. Therefore, it is imperative for the safety of communities to assess the risk of earthquakes to mitigate loss to infrastructure and human lives. Typically, this is achieved through a process called seismic risk assessment (Mojarab et al. 2023; Jaimes et al. 2023; Qiu et al. 2024; Aziz et al. 2024). It involves assessing the ground response against probable earthquakes using geotechnical, geological, social and economic parameters. Seismic microzonation sub-divides an area into different zones based on expected risk levels after a seismic assessment (Shah et al. 2022). Researchers and policymakers have widely accepted it accepted as one of the most efficient tools to assess the probable earthquake hazard (Nejad et al. 2018).

In Pakistan, awareness regarding seismic hazards is generally low and policy-making regarding earthquakes is not on par with the level of seismic activity (Ainuddin et al. 2014). Furthermore, infrastructure is usually not designed considering the level of earthquake hazard in the area. Additionally, various non-engineering factors also contribute to the increased risk of earthquakes such as a growing population and an increase in urban sprawl (Zhai et al. 2023; Du and Wang. 2013). Therefore, it is important to investigate the expected response of considering local soil conditions and the anticipated damages incurred from probable earthquakes (Parvez and Rosset 2014). This is especially important for all major cities of Pakistan with dense population, which could thus become hotspots of destruction in the event of an earthquake.

The Building Code of Pakistan (BCP) was first formulated in 2007 (BCP 2007). It classifies Pakistan into four zones based on the expected level of seismicity. Revisions were made to the BCP and the seismic hazard map of Pakistan in 2021 (BCP 2021). Both versions of the BCP make use of probabilistic seismic hazard analyses (PSHA) by considering the seismic source zones across the entirety of Pakistan. Meanwhile, BCP (2007) considers only one earthquake ground motion with a 10% probability of exceedance in 50 years. Whereas BCP (2021) considers earthquake ground motions with 2%, 5% and 10% probability of exceedance in 50 years. Both versions of the BCP contain only a nationwide seismic hazard map which encapsulates large areas of land into a single zone with a uniform value of seismic hazard. Generalizations over large areas and ignoring the local soil conditions may result in over-estimation or under-estimation of seismic risk, especially in large densely populated metropolitan cities.

Recent recorded data (Pakistan Meteorological Department 2023) related to earthquakes indicate that the entire region of Pakistan is becoming more seismically active. Importantly the intensity of earthquakes and the number of events with a magnitude greater than 4.0 every year. Figure 1 shows the major earthquakes (with Mw > 5.0) that occurred in the south and east Asia region from 1900 to 2022. Added to this is the fact that building regulations contain minimal guidelines regarding seismic design and are seldom enforced properly. All these factors combined present a very problematic picture.

Therefore, microzonation studies must be carried out to quantify the disparity of seismic risk within cities to have a better perception of the seismic risk (Altindal et al. 2021; Shams and Agrawal. 2024). Microzonation studies in Pakistan for cities of Islamabad and Karachi have shown that site-specific seismic risk assessments yield different results than the building codes (Khan and Khan 2018; Waseem et al. 2019). This study focuses on seismic microzonation of Lahore, one such large metropolitan city of Pakistan. It is currently the second-most populous city in Pakistan and one of the most populated cities in the world, housing a population of 11.3 million, as of 2017 (Punjab Bureau of Statistics 2022). According to the BCP (2007), it lies in zone 2A and is likely to experience a Maximum Considered Earthquake (MCE) of 0.16 g, against a return period of 475 years (BCP 2007). The updated version of the BCP states that Lahore is likely to experience an MCE of 0.23 g against a return period of 2475 years (BCP 2021). Also, the Lahore Development Authority (LDA) Building and Zoning Regulations, the seismic zone factor for the design of buildings in Lahore should be based on the seismic zoning map of Pakistan which assigns the same peak ground acceleration (PGA) to all areas of Lahore (Lahore Development Authority 2020).

In this study, a seismic risk assessment of Lahore has been carried out. Only the top 30 m of soil needs to be analyzed as this has the greatest influence on the structures present above ground and other earthquake-related phenomena such as liquefaction and

Fig. 1 Major earthquakes (Mw > 5.0) in the region from 1900 to 2022 (Pakistan Meteorological Department 2023)
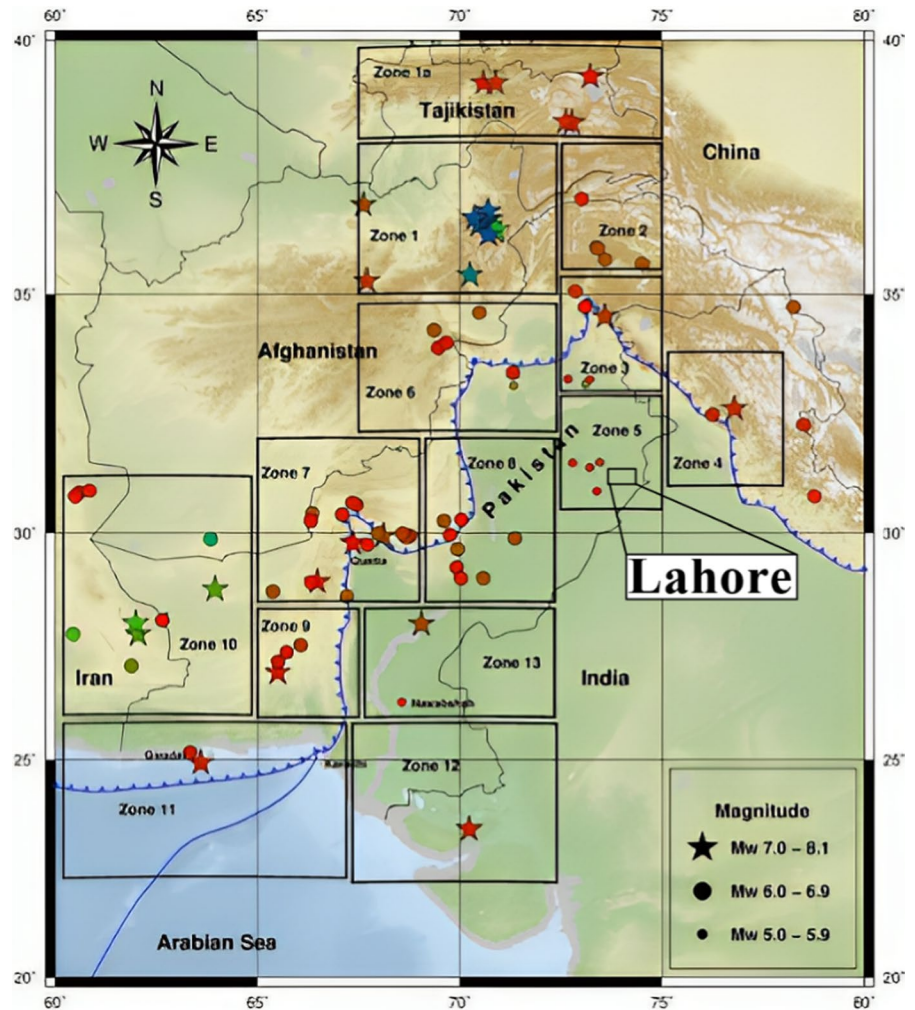

landslides (Altun et al. 2012). Geotechnical and geophysical properties of the soil in the study area were evaluated from site investigation reports and borehole logs. The BCP 2007 and 2021 design spectra were used to generate artificial earthquake time histories with a peak ground acceleration of 0.16 g and 0.23 g respectively. A one-dimensional nonlinear site response was conducted on 33 sites in the study area. Several important parameters, such as expected PGA and spectral acceleration (SA) were determined from the analyses. Finally, a risk map was developed which incorporates all the above factors and displays the qualitative level of risk throughout the city. Additionally, site-specific design spectra for Lahore have also been proposed. These can act as the basis for all future planning as well as the risk associated with existing infrastructure to mitigate damages.

2 Microzonation Methodology

Seismic hazard evaluation depends on the ground motion characteristics as well as the geotechnical, geological, and geophysical properties of the soils (Sun et al. 2024). Therefore, the first step in the site response analysis is to determine the properties of soils. The soil properties representative of the local soil condition are crucial for site response for any input motion. (Viti et al. 2017; Cïvelekler et al. 2021; Du and Wang 2014).

Therefore local soil data for the Lahore city was collected from 119 site investigation reports up to a depth of 30 m. Figure 2 shows the distribution of boreholes across Lahore. The soil investigation reports were used to extract important soil properties such as soil type, unit weight, standard penetration

Fig. 2 Location of boreholes
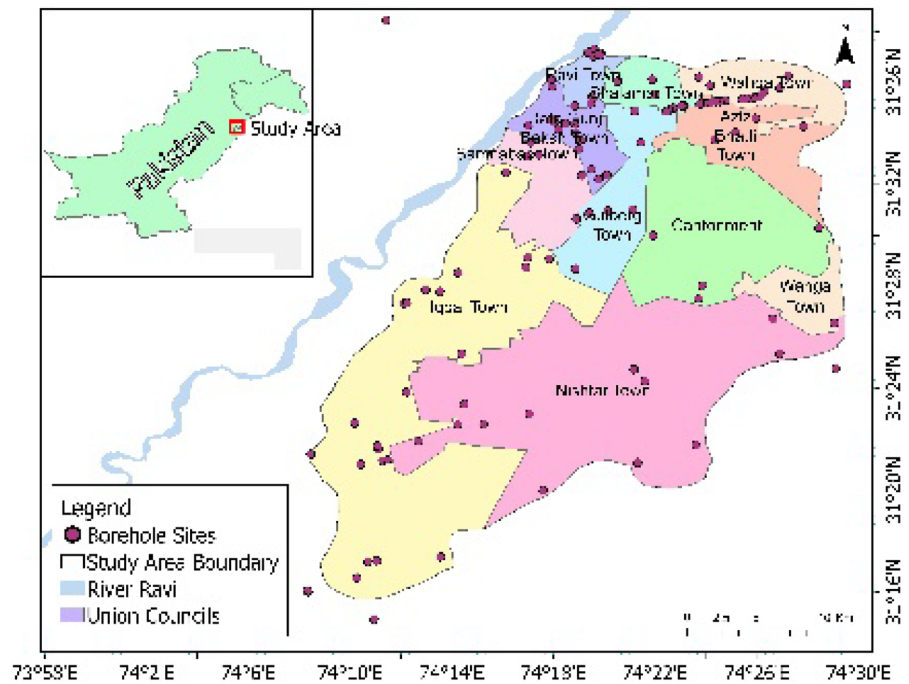
Table 1 Selected correlations between SPT-N and Vs

Developed By	Correlation	Region	Soil type
Hanumantharao and Ramana (2008)	$V_s = 82.6 \times N^{0.43}$	India	All soils
Jafari et al. (1997)	$V_s = 22 \times N^{0.83}$	Iran	All soils
Ilysian (1996)	$V_s = 51.5 \times N^{0.516}$	Turkey	All soils

test number (SPT-N), friction angle and cohesion. Generally, in each borehole, sampling was performed at 1 m intervals.

2.1 In-situ Testing for Dynamic Soil Properties

Shear wave velocity (Vs) of different soil layers is imperative for conducting site response analysis as it governs the soil behavior and, thus, the local site response (Rathje et al. 2010). In the absence of in-situ tests to measure the dynamic properties of soils, researchers typically rely on existing correlations to relate shear wave velocity to the SPT-N value (Anbazhagan et al. 2012; Sil and Haloi 2017; Adeel et al. 2023). In this study, three correlations as shown in Table 1 were selected as the geology and topography of the selected regions are similar to that of the study area (USGS 1995).

However, these correlations were developed for specific geology and need to be validated for suitability for our study area. Therefore, it is preferable to validate the shear wave velocity by correlations by through performing in-situ tests, such as the downhole test. The downhole test is an in-situ test to determine the compression and shear wave velocity values wherein values are measured at various depths, typically having a fixed interval. To validate and verify the correlation between SPT-N values and shear wave velocity suitability, two downhole tests were conducted by following ASTM D7400 2014.

Firstly, SPT tests were carried out in the boreholes, and then PVC casing was installed, keeping the final diameter of the boreholes as 150 mm. In the downhole tests, the distance between the source and borehole was kept at 5 m. This value was later used to obtain the diagonal geophone-to-source distances. Since the source was a horizontal distance of 5 m away, a correction factor was also applied to convert the diagonal path time to vertical path times. Additionally, data sampling was done at 1 m intervals, from ground level up to 30 m depth.

Furthermore, three downhole tests from near the study area were selected from the literature (Kibria

et al. 2022; Khurram et al. 2020) to improve the accuracy. Table 2 shows the location of all downhole tests. The standard penetration test was then performed in the same boreholes. The data from these two tests—i.e., the SPT and the downhole test—were used in conjunction to select an appropriate correlation based on statistical analysis, as discussed in the next section.

2.2 Selection of Correlation from Existing Literature

SPT-N values obtained from field tests were input into the selected correlations to obtain shear wave velocity values. These values were then compared with those obtained from the downhole tests. A comparison of correlation values and field values was done using regression analysis and values of regression coefficients (R^2) were obtained. The R^2 value was used to assess the accuracy of the adopted correlations. The greater the value of the correlation coefficient, the more closely it matches the values with the downhole test. Table 3 and Fig. 3 show the analysis for one of the five sites, namely site 4 as shown in Table 2.

Figure 3 shows that the correlation by Hanumantharao and Ramana (2008) has the highest value of
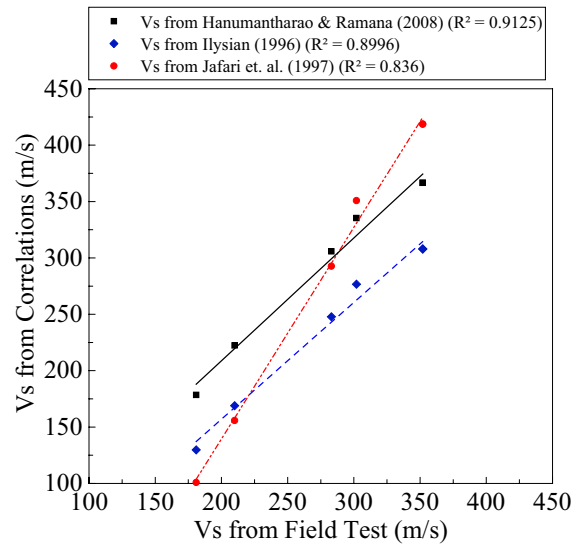

Fig. 3 Relationship between Vs from correlation and downhole tests

regression coefficient, $R^2 = 0.91$, indicating closely match with the measured shear wave velocity. Similar analyses were carried out on all five sites. For each of the three correlations, a weighted average value was calculated for the correlation coefficient, with the weight being determined by the number of points at which measurements were taken in the field tests (Table 4). The correlation with the highest weighted average value of the correlation coefficient was selected (Hanumantharao and Ramana (2008) with an R^2 value of 0.70).

Table 2 Location of downhole tests

Site no	Data source	Latitude	Longitude
1	Kibria et al. (2022)	74° 00′ 31″	31° 44′ 45″
2	Kibria et al. (2022)	74° 27′ 18″	31° 07′ 36″
3	Khurram et al. (2020)	73° 55′ 01″	31° 07′ 27″
4	Tests conducted for this study	74° 18′ 05″	31° 28′ 51″
5	Tests conducted for this study	74° 21′ 12″	31° 27′ 03″

Table 3 Comparison of shear wave velocity values from downhole tests and correlations for Site 4

Sr. No	SPT -N values	In-situ shear wave velocity	Hanumantharao and Ramana (2008)	Ilysian (1996)		Jaffari et. al. (1997)
1	10	210	222	169	156	
2	26	302	335	277	351	
3	54	352	459	403	653	
4	6	181	178	130	101	
5	21	283	306	248	293	
6	32	352	367	308	419	

Table 4 Weighted average of regression coefficients for all three correlations

Sites	No. of points	Hanumantharao and Ramana (2008)	Jaffari et. al. (1997)	Illysian (1996)
1	27	0.70	0.68	0.70
2	15	0.78	0.82	0.71
3	31	0.70	0.63	0.69
4	6	0.91	0.84	0.90
5	4	0.73	0.74	0.73
Weighted R^2-value		0.73	0.70	0.71

3 Geological and Geotechnical Properties of the Region

3.1 Local Geology

Lahore is located in the Indus Plain which has primarily quaternary sediments (Geological Survey of Pakistan 1964). The area of Lahore is dominated by older loess and floodplain deposits i.e. soil which has been primarily deposited through winds. In the vicinity of the Ravi River, there are predominantly stream-deposited soils that are deposited by the riverbed. Along the northwestern side of Lahore, there exist recent floodplain deposits.

3.2 Tectonics of the Region

Pakistan overlaps with both the Indian and Eurasian tectonic plates. As a result, it has a major tectonic plate boundary running through its entire length. This plate boundary is responsible for most of the seismic activity in the region, along with several smaller faults and fault source zones.

Shah et al. (2008) further identified all the major and minor seismogenic source zones in the vicinity of Lahore and concluded that there were a total of 14 faults and source zones that were in close enough proximity to Lahore to have the potential to cause damage if an earthquake were to occur there (see Fig. 4 and Table 5).

3.3 Groundwater Conditions

The depth of the water table in Lahore's city center—in the area of Gulberg and Cantonment—is more than 40 m. Towards the outskirts, in areas such as Iqbal Town, Wahga Town and Aziz Bhatti Town, the water table sits a little higher, at a depth of around 20-30 m. It is highest near the Ravi River, at a depth of 10-20 m. However, since the population of Lahore has a groundwater dependency of 100%—i.e. they rely entirely on groundwater for all their needs—the depth to groundwater table has been increasing gradually.

3.4 Bedrock Depth

Bedrock was not encountered in any of the boreholes, even in those with a depth greater than 30 m. Hence, the actual depth of bedrock in Lahore cannot be accurately estimated. However, for numerical modelling of soil response, bedrock was assumed at a depth of 30 m from the surface and only the top 30 m layer of soil was considered. Generally, the topmost 30 m layer of soil has the most significant impact on the site response (Ayele et al. 2021). Additionally, from the collected data at the depth of 30 m, the value of SPT-N becomes almost equal to 50 indicating the stiff soil.

3.5 Geotechnical Properties of Soils in the Region

To understand the soils in the study area and identify spatial variation in the soil properties, Fig. 5 shows the type of soils across Lahore. The soils in each borehole were classified based on the Unified Soil Classification System (USCS). Afterwards, the soil type occurred in all the boreholes were totaled with respect to depth up to to 30 m depth. From Fig. 5, it can be seen that the study area majorly contains silty sand, 918.5 m of soil out of a total depth of 2091.5 m was silty sand (i-e., 44%). The second most prominent category was sand which was present in 538 m (i-e., 26%) of the total combined borehole depths. The least commonly occurring soil was clayey silt, which was present in a total of 11.5 m depth (i-e., 0.5%).
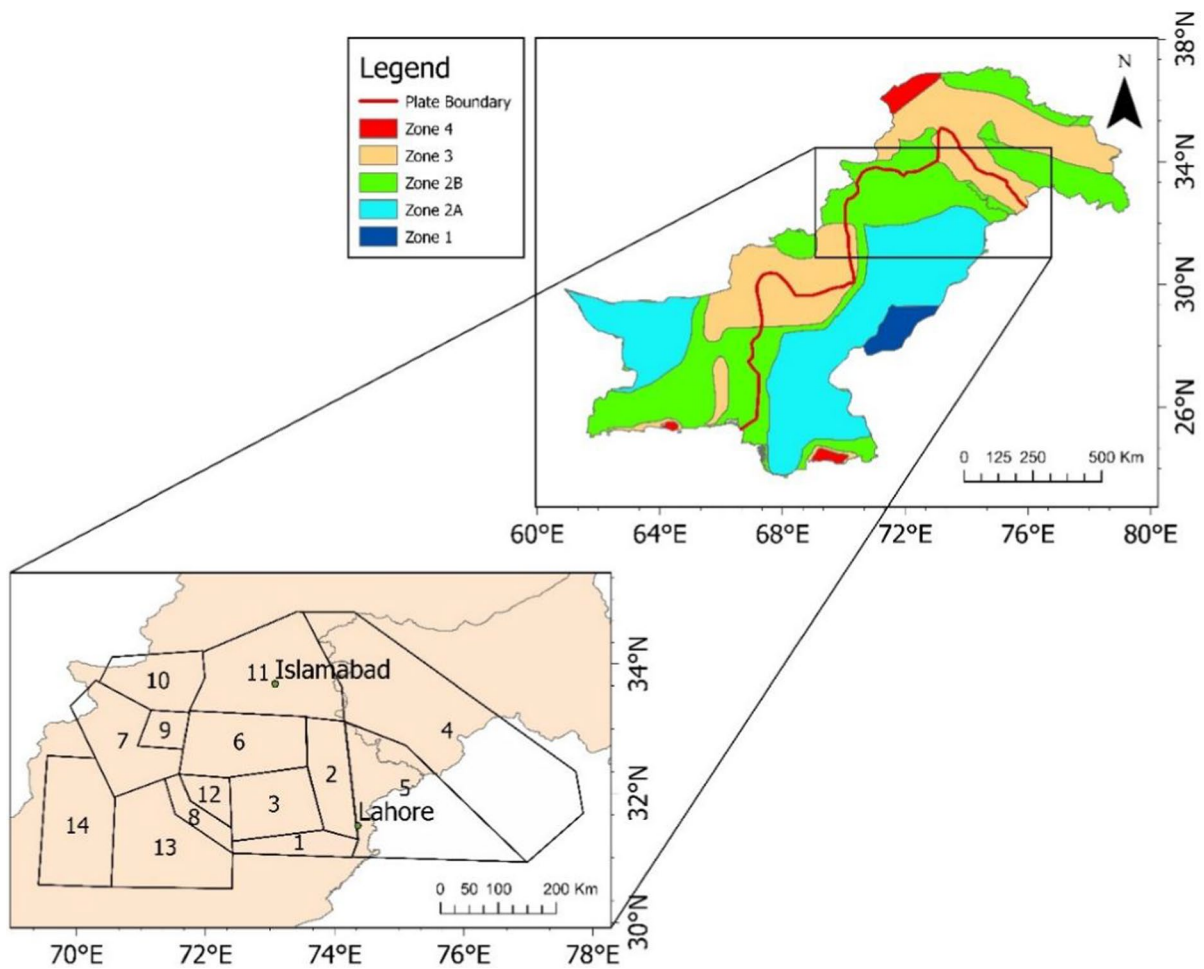
Fig. 4 Seismic zoning map of Pakistan (BCP 2007), plate boundary running through Pakistan and seismic source zones in the vicinity of Lahore (Shah et al. 2008)

Soil classification maps were being developed using various spatial interpolation techniques such as kriging and inverse distance weighting (IDW) (Ijaz et al. 2023; Yin et al. 2023). They aid in the visualization of soil properties across a region and are a particularly helpful tool for engineers and policymakers alike (Hassan et al. 2023). For this study, soil classification was done using the kriging technique and on the basis of average Vs values of the top 30 m of soil. As can be seen in Fig. 6, the highest Vs is present in the western part of the study area and values in this region range from 350 to 400 m/s. The lowest values of Vs can be seen in Ravi Town, along the Ravi River, ranging from 100 to 150 m/s. The rest of the study area has moderate values of Vs. The most commonly occurring range of values is 250-300 m/s.

Figure 7 shows the variation of soil types for three (3) boreholes i-e., BH-01, BH-40 and BH-103 at various locations across the study area. In BH-01, a weak soil layer between 21 and 27 m depth as SPT-N values decrease significantly in this range, going as low as 17. Water table was encountered in one of the boreholes only i-e., BH-40 at a depth of 14.7 m. These boreholes were located near the Ravi River.

Classification of the study area was also done on the basis of soil class, based on the guidelines provided in BCP (2021), International Building Code (IBC) (2021) and NEHRP (2020). The soils can be classified into six categories namely A, B, C, D, E

Table 5 Seismic source zones in the vicinity of Lahore (Shah et al. 2008)

S. no	Seismic source zone
1	Lahore fault source zone
2	Hafizabad fault source zone
3	Sargodha high source zone
4	Western himalaya source zone
5	Indian border region source zone
6	Salt range source zone
7	Bannu basin fault source zone
8	Bhakkar fault source zone
9	Kalabagh region source zone
10	Kohat-chirat source zone
11	Hazara-potohar source zone
12	Diffused seismicity source zone
13	Southern punjab source zone
14	Suleiman range source zone

and F based on the average SPT-N value of a site. The average SPT-N value was calculated using the formula in Eq. (1)

$$N = \frac{\sum_{i=1}^{n} di}{\sum_{i=1}^{n} \frac{di}{Nsi}} \qquad (1)$$

A soil classification map for the study areas was also developed based on soil class. As can be seen in Fig. 8, the area is dominated by Soil Class D, which is sands/silts/stiff clayey soils. These soils have SPT-N values ranging from 15 to 50. Some areas in the

southern and eastern parts of the study area contain soil belonging to Soil Class E, which has SPT-N values ranging from 0 to 15 and is labeled as 'soft soils'. It is also important to note that some soft soil regions lie close to the Ravi River.

One dimensional non-linear site response analysis was carried out on 33 sites across the study area. These sites were selected such that they collectively represent the geology of the entire study area and soil information was available for upto 30 m. This number of analyses was deemed sufficient owing to the fact that since there exists very little variability in the soils of Lahore, in both horizontal and vertical directions (Alam et al. 2018, 2024). The site response analyses were performed in open-source DEEPSOIL. Details regarding DEEPSOIL can be found in Hashash et al. (2020). Specifications of the analyses are detailed in the next section.

4 Input Earthquake and Site Response Analyses

The ground motion characteristics such as PGA are influenced by local site conditions encountered by seismic waves as they propagate from bedrock to the surface, especially the strata in the top 30 m of soil. In case the bedrock is more deeper than 30 m, the site effects on ground motion characteristics from 30 m upto the bedrock is ignored (Ayele et al. 2021; Rahman et al. 2021). Hence, in this study, site response analysis has been carried out on the top 30 m of soil present in the study area and information such as
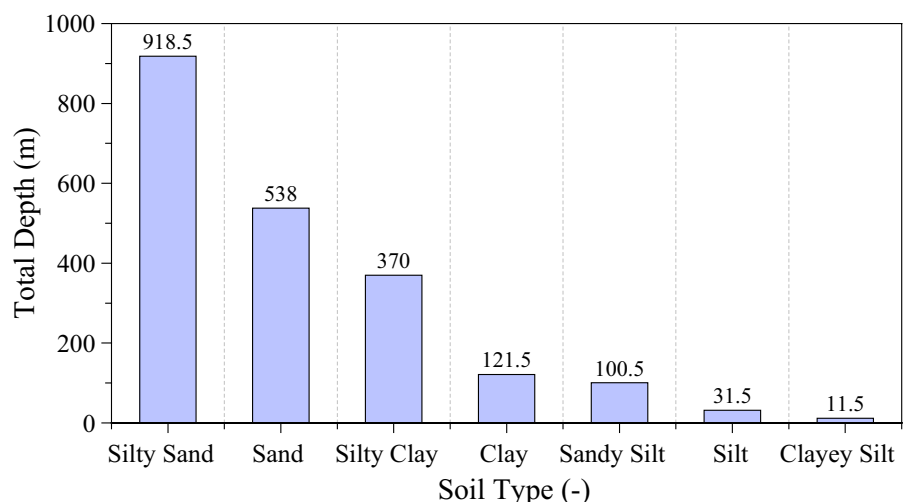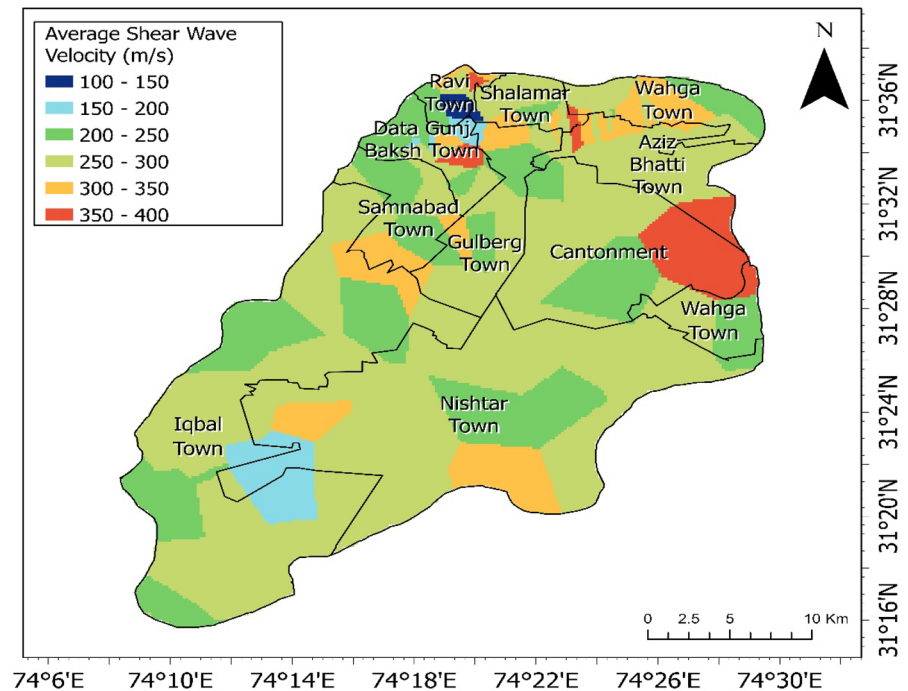

Fig. 5 Total depth of each soil type present in the study area

Fig. 6 Average shear wave velocity in m/s across the study area

PGA, SA and spectral amplification has been determined for each site.

4.1 Specifications of Numerical Analysis

Bedrock was taken at 30 m depth and soil layer depths were defined from 30 m to surface level as specified in the borehole logs. DEEPSOIL requires values of properties for each soil layer such as unit weight, shear wave velocity and effective vertical stress. Shear wave velocities for each layer were calculated from SPT-N values using the correlation specified in Sect. 2.2. Effective vertical stress for each layer was calculated using the unit weight values of all layers and the depth to the water table. This depth value to water table was also specified separately in the analysis as it affects the propagation of shear waves. The value was ignored if the water table was greater than 30 m. The General Quadratic/Hyperbolic (GQ/H) proposed by (Groholski et al. 2016) was selected in conjunction with the Non-Masing Hysteretic Re/ Unloading formulation. The GQ/H can accurately represent the nonlinear soil behavior as compared to earlier models. Darendeli reference curve and the curve fitting parameter Modulus Reduction and Damping Curve Fitting (MRDF) with the University of Illinois at Urbana Campaign (UIUC) reduction factor was employed (Phillips and Hashash 2009). Frequency-independent damping was used to define viscous/small strain damping. Flexible step control with a maximum strain increment of 0.0001% was used. The integration scheme used was the Implicit Newmark Beta Method and the time history interpolation method was selected as zero-padded in the frequency domain (Hashash et al. 2020).

4.2 Input Motion

Synthetic input motions have been developed as per local site conditions and used to conduct the site response analysis (Bhatti 2016, Bajaj & Ambazhagan 2019) due to the unavailability of input motion data for the region. Two major important parameters need to fulfill for the representative input motion to be used for the site response analysis i-e., the design spectrum of the input motion should be similar as recommended by the building codes as well as the PGA of the input motion should be similar as suggested in the building codes.

Hence, for this study, synthetic acceleration time histories of 0.16 g and 0.23 g—in line with BCP 2007 and BCP 2021, respectively—earthquakes were
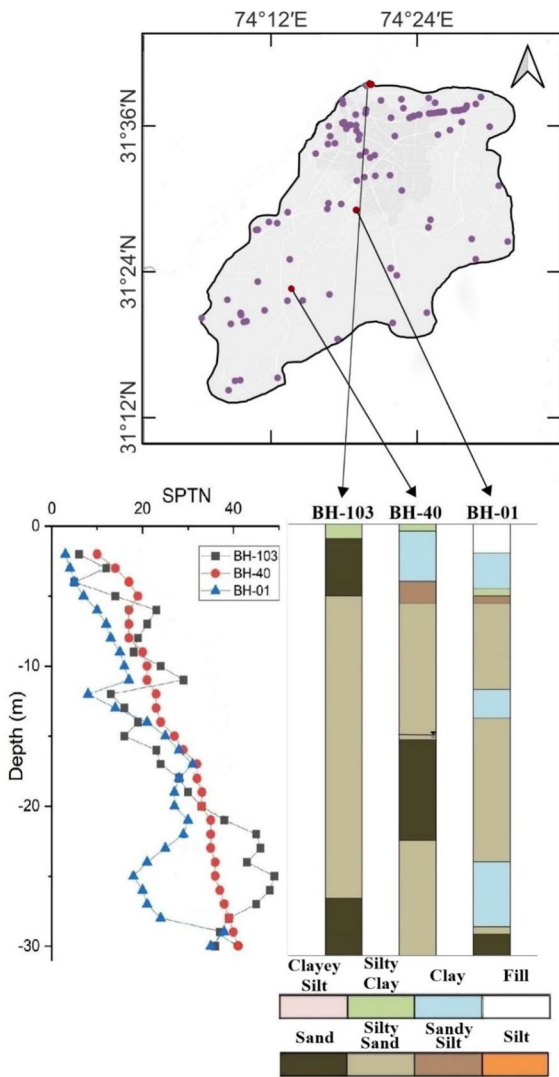
Fig. 7 Sample boreholes in various regions of Lahore

developed using Seismoartiff 2022. There are four methods in SeismoArtiff which are used to make a synthetic earthquake i-e., 1) Synthetic Accelerogram Generation and Adjustment, 2) Artificial Accelerogram Generation, 3) Artificial, Accelerogram Generation 4) Adjustment and Real Accelerogram Adjustment. Two of these methods—namely, synthetic accelerogram generation and adjustment and real accelerogram adjustment—require the input of an accelerogram recorded by a seismometer. In this study the method called artificial accelerogram generation and adjustment was used. In this process, firstly, the design spectra for Lahore from BCP 2007 and

2021 were defined as the target spectra in Seismoartiff 2022. Envelope shape was then specified as that of Saragoni and Hart and accelerograms were generated by specifying the duration (20 s), PGA (0.16 g and 0.23 g) and time-step (0.01 s) for 20 s with a damping of 5%.

The design spectra for Lahore from BCP 2007 and 2021 were used as target spectra. The whole process is iterative, and the software continues iteration until the response spectrum from artificial earthquakes matches the target response, which were design spectra from the BCP 2007 and 2021. In this way, two earthquake time histories were generated which followed the Saragoni and Hart envelope shape, each corresponding to one version of the BCP (Hart and Sragoni 2017). Figure 9 shows the synthetic time histories, one with a PGA of 0.16 g and the other with a PGA of 0.23 g.

Site response analysis was performed at 33 sites across Lahore (see Fig. 10) and a total of 66 analyses (33 sites × 2 earthquakes) were performed. All the 33 sites on which the nonlinear and equivalent linear analysis was performed, were deeper than 30 m. According to Basharat et al. (2022), non-linear analysis showed more reasonable PGA values for Lahore as compared to equivalent linear analysis. The local soil of Lahore exhibits a high strain level during input motion and consequently the equivalent linear analysis overestimate the PGA (Basharat et al. 2022). From Fig. 10, it can be inferred that the sites are scattered all across Lahore so the geospatial interpolation gives accurate results which is explained in a later section of this paper.

5 Evaluation of the Results

Site response analysis was carried out at 33 sites in Lahore and the results obtained were then evaluated. The boreholes of these sites were constructed in DEEPSOIL and the two input motions were applied at the base of each soil profile. Figure 11 shows the variation of ground acceleration with depth for both input motions. The maximum ground acceleration is calculated by averaging the peak accelerations from the responses of all the sites at different depths. The minimum ground acceleration is calculated using a similar approach. Figure 11 shows that the maximum ground acceleration is greater at all depths for

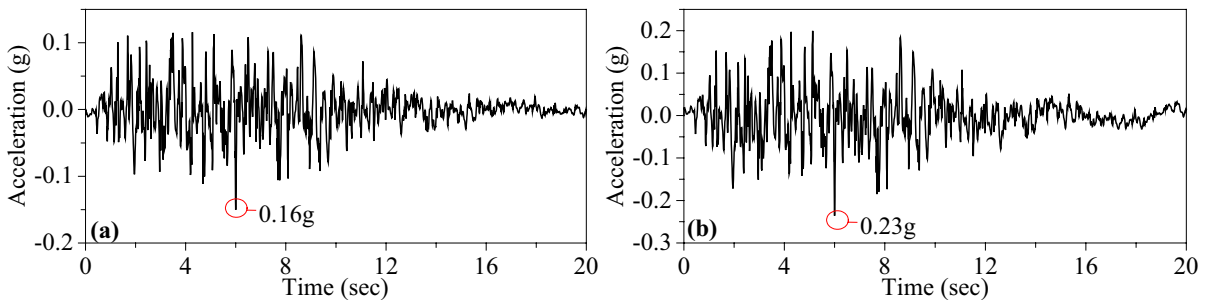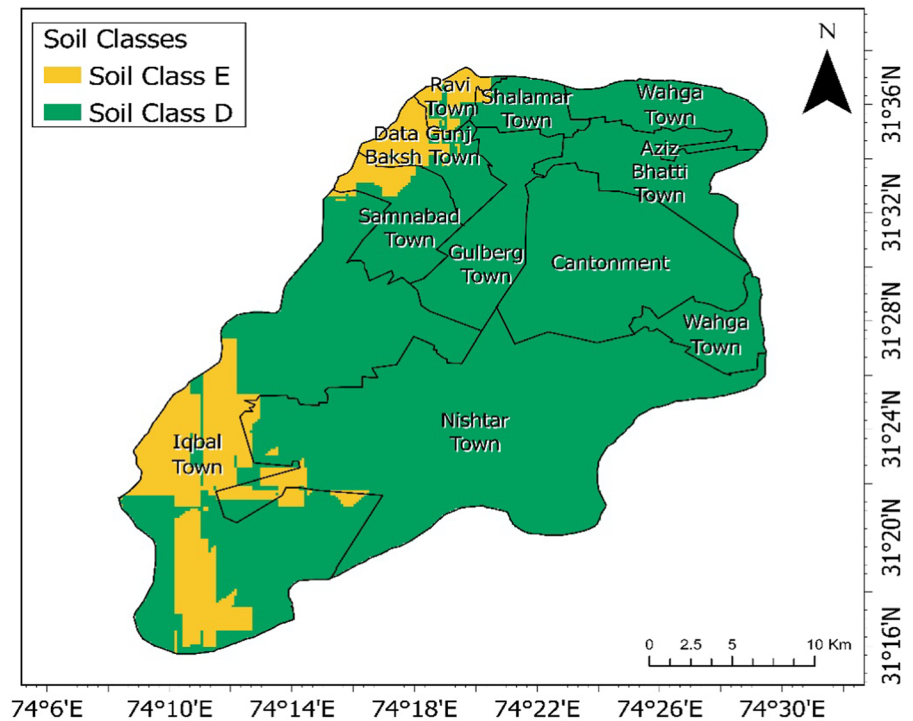**Fig. 8** Variation of soil classes across the study area

Fig. 9 Input motion time histories of **a** 0.16 g **b** 0.23 g

the 0.23 g earthquake than for 0.16 g earthquake. Whereas similar values of the PGAs were observed along the depth of minimum ground acceleration between 0.23 and 0.16 g input motions. The maximum ground acceleration observed at the surface is 0.35 g for the 0.16 g motion (52% amplification) and 0.46 g for the 0.23 g motion (100% amplification). Generally, ground acceleration decreases with the depth of the borehole. However, there is an increase in maximum ground acceleration for input motions at 27 m depth. From this, it can be inferred

that a loose layer of soil exists at the depth of 27 m in Lahore resulted in amplification of input motions.

Figures 12 a and b show the variation of short-period (0.1 s) spectral acceleration with depth for the 0.16 g and 0.23 g input motions, respectively. Figures 12 c and d depict the trends in long-period (1.0 s) spectral acceleration with depth for both earthquakes used as input. At $t = 0.1$ s, the values of minimum SA are somewhat similar for both input motions, ranging from 0.10 g to 0.14 g. However, the maximum SA values differ greatly for the same time period. A sharp

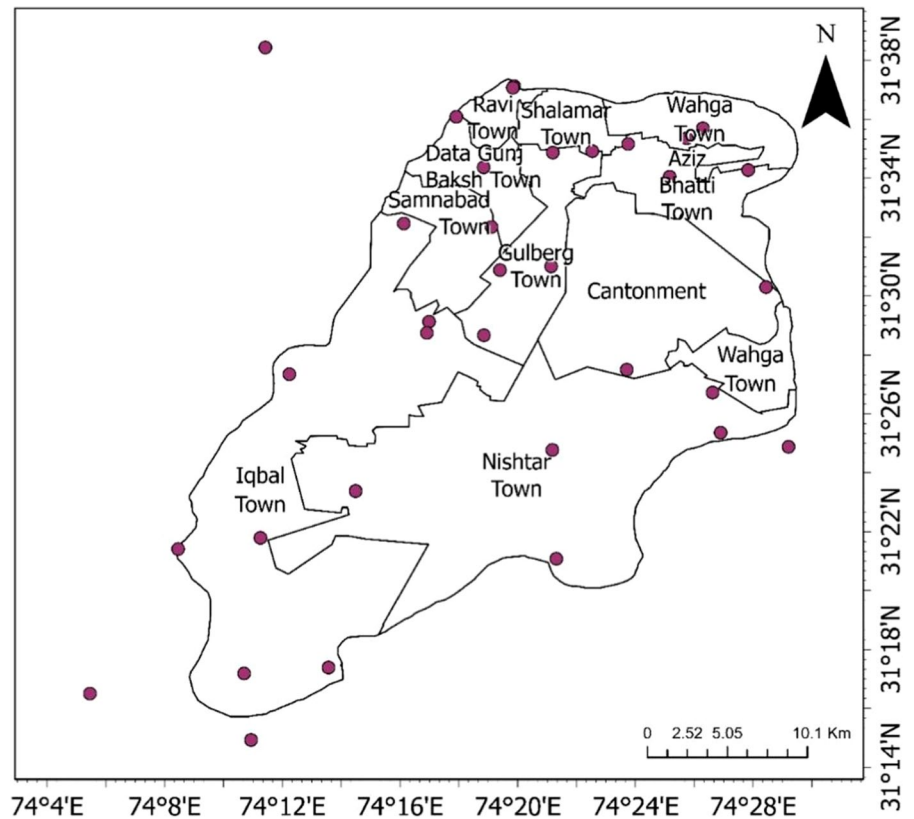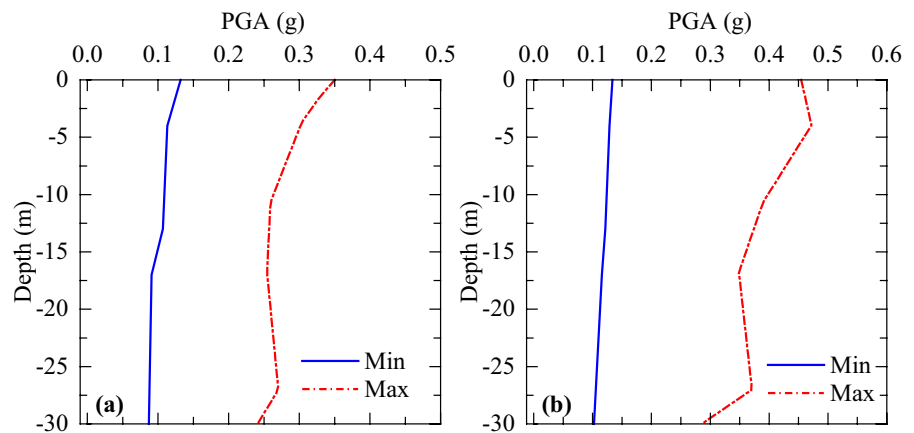**Fig. 10** Location of boreholes for site response analyses

Fig. 11 Variation of PGA with depth for **a** 0.16 g earthquake and **b** 0.23 g earthquake

increase can be observed at 27 m depth, indicating resonance. Even at the surface, the SA value for the 0.23 g earthquake is greater (0.45 g) as compared to that of the 0.16 g earthquake (0.37 g). From these results, it can be concluded that the ground motion is more intense at the depth of 27 m below Lahore and this increase in the intensity carries its effect to the surface layer.

At t = 1.0 s, the values of minimum and maximum SA display drastic differences. For the 0.16 g input motion, the values lie between 0.36 and 0.37 g at all depths whereas, for the 0.23 g input motion, the values lie between 0.10 and 0.11 g at the surface and converge to 0.104 g at 30 m depth.

Figure 13 shows the SA at the surface i-e., 0 m plotted against the natural period for the three sites

Fig. 12 Variation with depth of **a** short-period (0.1 s) SA for 0.16 g earthquake **b** short-period (0.1 s) SA for 0.23 g earthquake **c** long-period (1.0 s) SA for 0.16 g earthquake **d** long-period (1.0 s) SA for 0.23 g earthquake
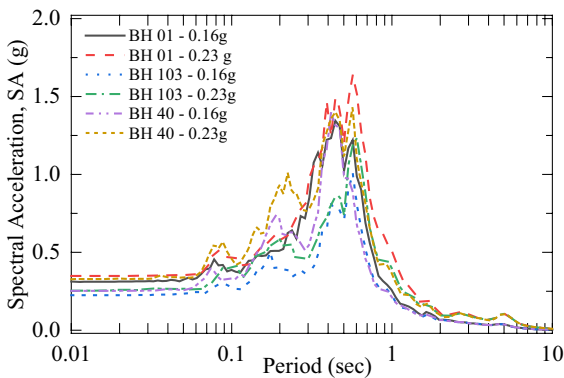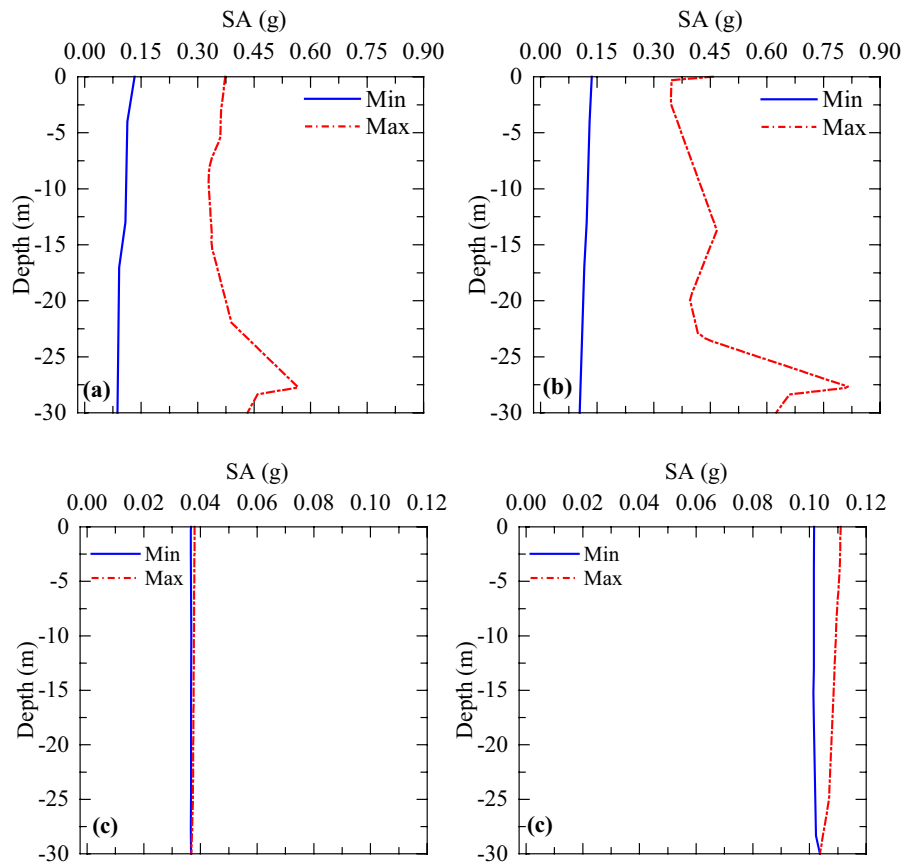

Fig. 13 Spectral Acceleration for BH-01, BH-40 and BH-103 at Surface (0 m)

BH-01, BH-40 and BH-103. The highest peak of SA was observed at BH-01 when 0.23 g input motion is applied and the lowest peak is developed by BH-103 when 0.16 g input motion is applied.

Further, heat maps were developed that display the variation in PGA at the surface, surface spectral acceleration and spectral amplification for Lahore. Figure 14 depicts the variation in PGA at the surface. Figure 14 shows that the surface PGA is higher for the 0.23 g input motion in most areas. For both input motions, most of the study area experiences a PGA in the range of 0.228 g to 0.272 g. The lowest PGA in the range of 0.140 g to 0.184 g is experienced by some regions in the southeast as well as some regions in the north for the 0.16 g input motion. For the 0.23 g input motion, the central region of the city i-e., Gulberg Town and parts of Cantonment experiences the maximum PGA. This is particularly worrisome as this region of Lahore is the most densely populated According to (The Urban Unit, 2015), population density in these areas ranges from 25,000 to 50000 people per square kilometer.

Figure 15 displays the variation in the maximum surface spectral acceleration experienced across the region. Similarly, as for the PGA, the higher values
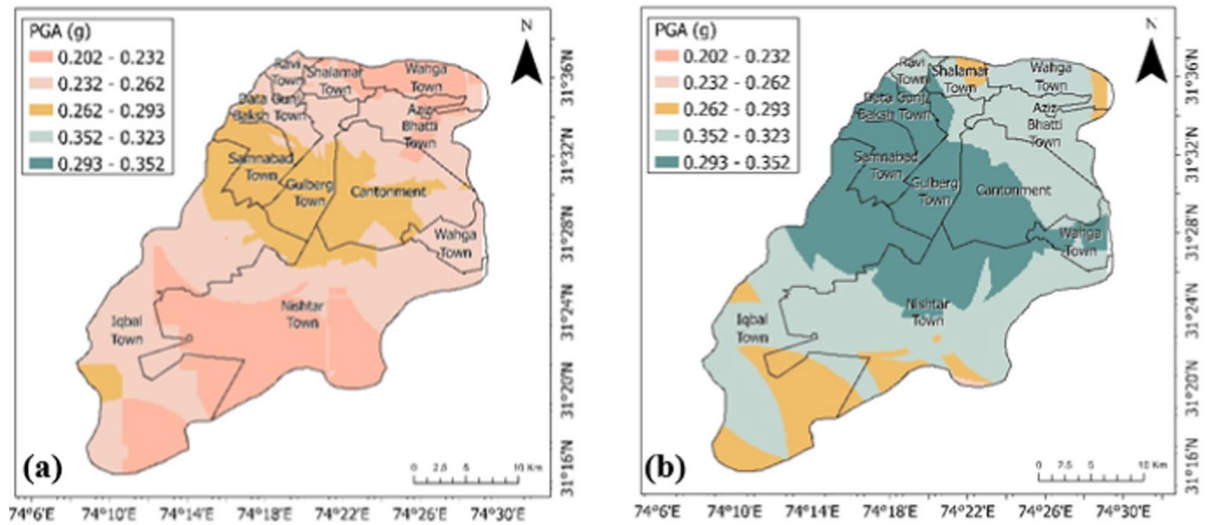
Fig. 14 Variation in PGA at surface (0 m depth) for **a** 0.16 g earthquake and **b** 0.23 g earthquake
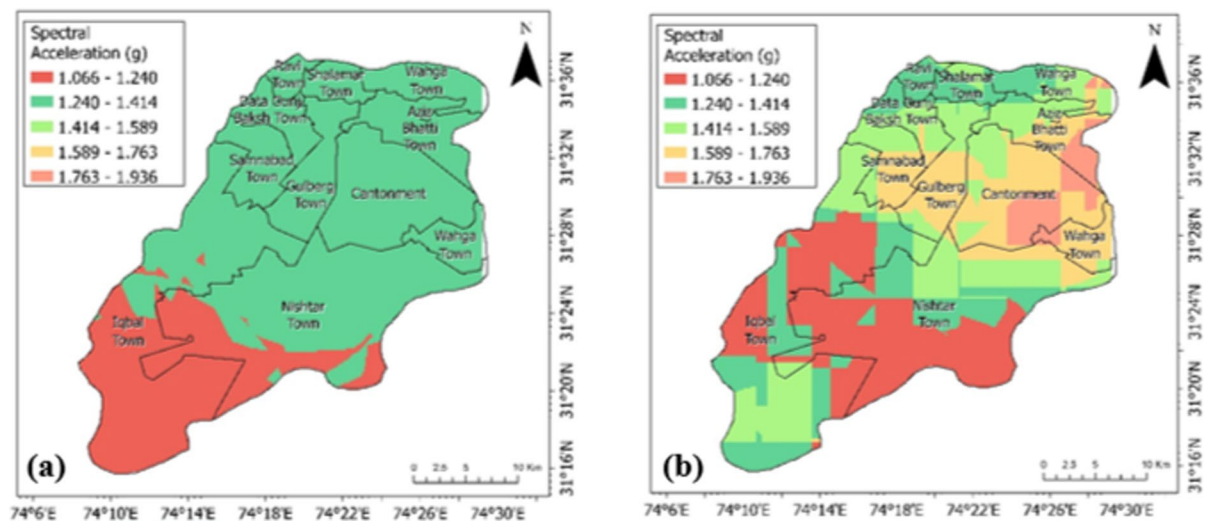

Fig. 15 Variation in surface spectral acceleration (g) for **a** 0.16 g earthquake and **b** 0.23 g earthquake

were observed mostly for the 0.23 g input motion. For the 0.16 g input motion, most of the region experiences spectral acceleration in the 1.136 g to 1.404 g range. For the 0.23 g motion, the maximum observed values lie in the range of 1.404–1.672 g.

In comparison, studies conducted in Islamabad show that it is likely to experience PGA of 0.31-0.43 over the vast majority of its area. Some areas of Islamabad are also likely to experience a PGA in the range of 0.43–0.53 g, given their proximity to seismic

sources and faults (Khan and Khan 2018). Studies conducted for Karachi demonstrate that the coastal regions are likely to experience PGAs as high as 0.710–0.861 g (Waseem et al. 2019). It is also noteworthy that none of these values (including the ones found in this study) align with the values of expected PGA mentioned in the BCP. This further highlights the shortcomings of studies conducted over large areas and points to the importance of conducting site-specific studies.

Site amplification has been one of the important parameters to assess in microzonation. It measures the increase in the SA concerning with respect to the input motion SA as earthquake waves travel through different soil layers and subsequently reach the surface. The input motion frequency and amplitude can attenuate or amplify depending on the properties of soil layers. It is the ratio of spectral SA at the surface to the SA at 30 m depth. In this case study, this is essentially a measure of how much the earthquake will amplify when travelling through deep foundations.

Figure 16 depicts that the spectral amplification was greater for the 0.16 g as compared to the 0.23 g input motion. In some regions, for the 0.16 g earthquake, the spectral amplification value can be observed to be as high as 2.7. For the 0.23 g input motion, it can be seen that for the major portion of the study area, the value of spectral amplification ranges from 1.14 to 1.92. So, it can be concluded that local soils amplify the input motion in the Lahore region. This amplification can be attributed to the presence of soft and granular soil layers through which the earthquake waves have to travel.

6 Discussion

A final risk map was developed which incorporated peak ground acceleration at the surface and surface spectral acceleration resulting from both input motions. As mentioned in Sect. 3.5, the kriging technique was employed and a map showing the spatial variation of earthquake risk was developed. This risk map, displayed in Fig. 17, indicates the level of risk faced by various regions throughout the study area. In this study, three levels of risks are defined in the risk map, i-e., low, medium and high. Low corresponds to the least PGA (0.202–0.232 g) and spectral acceleration (1.066–1.240 g) compared with other regions of Lahore and high corresponds to maximum PGA (0.293–0.352 g) and spectral acceleration (1.763–1.936 g) compared with other regions of Lahore. From Fig. 17, it can be seen that the area at the most risk is Cantonment, Gulberg Town, Wahga Town and some parts of Data Gunj Baksh Town and Aziz Bhatti Town, while there are some parts of Iqbal Town and Nishtar Town that face the least risk.

Overall, the level of risk faced by Lahore is lesser than that of Karachi and Islamabad as the latter are closer in proximity to some major seismic source zones. However, level of risk in Lahore is still significant enough to warrant concern and attention from the concerned authorities. This is especially because
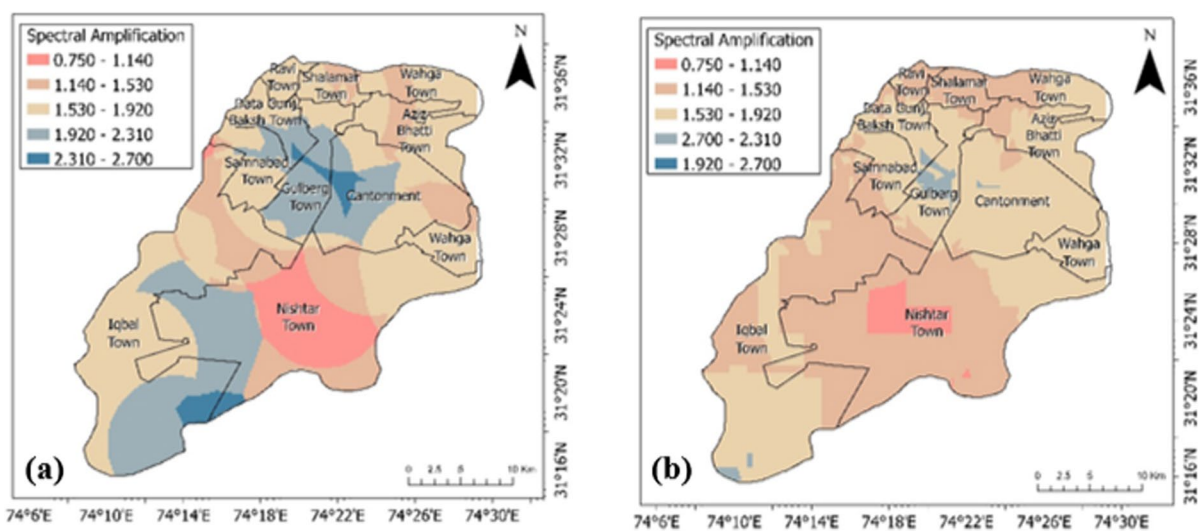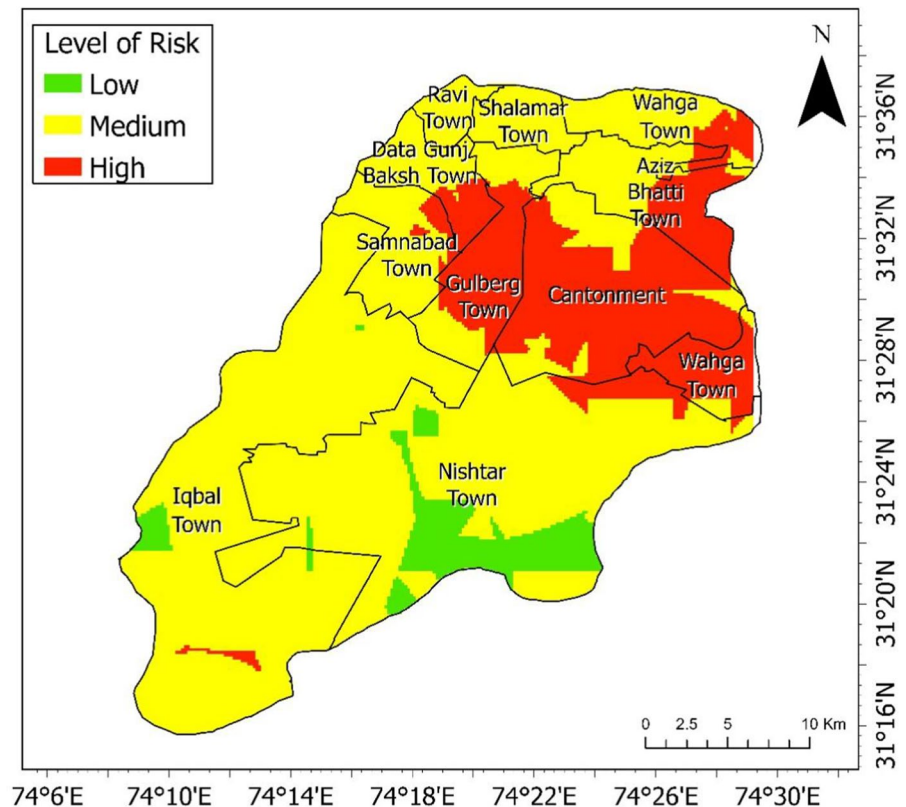

Fig. 16 Variation in spectral amplification for **a** 0.16 g earthquake and **b** 0.23 g earthquake

Fig. 17 Risk map for Lahore based on seismic risk assessment

of the ever-growing population and urban sprawl of the city, as mentioned earlier.

All major building codes contain specific guidelines for the development of site-specific design spectra. The guidelines are somewhat similar and differ only in terms of coefficients that are dependent on local soil conditions. For development of a design spectrum, the values of peak spectral acceleration—which occur at the natural time period—for short buildings and tall buildings are needed. In general, the natural time period of all buildings would differ. However, for generalization purposes, it is assumed to be 0.2 s for short buildings (seven stories or less) and 1 s for tall buildings (greater than seven stories).

For this study, two important building codes are IBC2021 and ASCE 7, since the former refers back to the latter for certain calculations. Two design spectra—corresponding to the two soil classes in Lahore—were developed using the parameters obtained from site response analysis. The development of the envelope shapes was done in accordance with the procedure outlined in the international building code 2021. The values of spectral acceleration at 0.2 s (short period) and 1 s (long period) were obtained for all sites. From these, the maximum values were selected and these were designated as Ss and S1, respectively. Using these values and site coefficients for short period (Fa) and long period (Fv) was taken from IBC2021, all the necessary values were computed using the procedure outlined in the IBC 2021. After all the necessary parameters, two design spectra were formulated, one for each site class present within the study area. These were then compared with the design spectra for site class D and E as given in BCP 2007. Further, two spectra were developed using the earthquake parameters given in BCP 2007 as well for comparison.

Figure 18 shows that the BCP spectra for both soil classes vary greatly from their site-specific counterparts. For soil class D, BCP tends to over-predict the spectral acceleration. This essentially means that buildings designed in accordance with BCP 2007 may prove to not be safe even though they are compliant with the national code. For soil class E, BCP under-predicts the spectral acceleration, leading to an increase in construction costs.

Fig. 18 Proposed design spectra for soil class d and soil class E
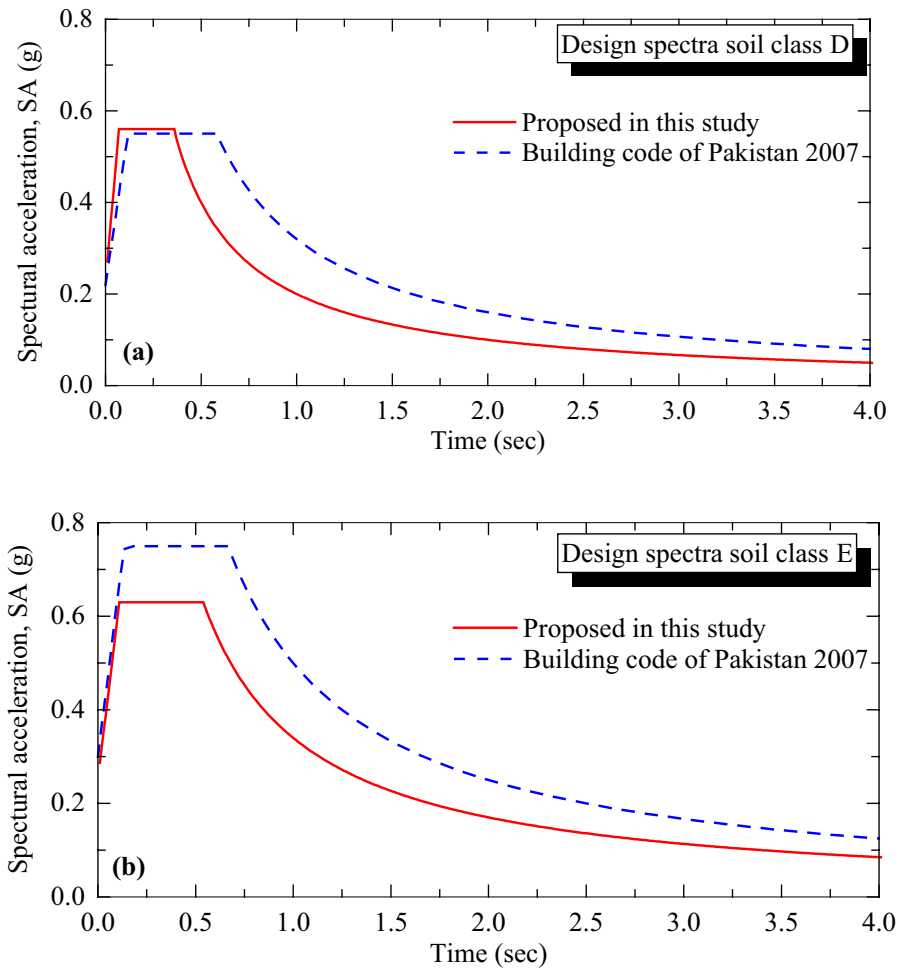
This microzonation study—and the subsequent risk map and design spectra—is meant to act as an aid for city planners, local government as well as policy-makers. This study categorize areas in Lahore and its outskirts that face the least amount of earthquake risk and, therefore, are most suitable for urban population. High-risk areas can also be easily identified from the risk map and retrofitting efforts can be carried out for structures with historical or cultural significance. Both of these things are extremely important for a city like Lahore, which is a booming metropolis as well as a place of historical significance. Furthermore, it can also be used to plan emergency evacuation routes and estimate earthquake insurance rates.

The design spectra developed as part of this study can be used to improve the BCP. The discrepancies between site-specific design spectra and their BCP counterparts point to the limitations of carrying out

seismic risk assessments over large areas. Previously, site response analysis has also been similarly used by various researchers for improving building codes (Amirsardari et al. 2017; Sonmezer et al. 2024). It is recommended that the design spectra developed in this study be incorporated into the local building codes of Pakistan to optimize the cost of construction.

This study highlights the fact that seismic risk assessments carried out over large areas tend to contain generalizations over large areas and produce less accurate results. Therefore, it is recommended that similar microzonation studies be carried out in other major cities of Pakistan. Site-specific design spectra must be developed and incorporated into the local construction industry for all such cities. Furthermore, the site coefficient for long and short period should be developed based on site response analysis by extensive site response analysis. This will lead to more

representative spectral acceleration values for the Lahore city. Also the design spectrum should be propose for different time periods to accommodate different structural requirements.

7 Conclusion

A seismic risk assessment was carried out in Lahore. The local geological and geotechnical properties of the soil were analyzed and soil classes as well as average shear wave velocities were determined. Two input motion earthquakes were developed as per the maximum PGA specified in BCP 2007 and BCP 2021. Non-linear site response analysis was then carried out at selected sites. Values of peak ground acceleration, spectral acceleration and amplification were determined from the analyses. It was observed that the central areas of Lahore (i.e. Gulberg and parts of Cantonment) experience the highest PGA, SA and amplification. This is concerning because these areas also happen to be among the most densely populated areas in the city. The central business district (CBD) of Lahore is also located in this region and is a hub of economic activity, thus increasing the risk of economic losses in the event of an earthquake.

As a result of this study, the following tools have been developed which can be of aid to local policymakers and government:

1. A risk map, displaying the qualitative risk level across the study area. The area of the Lahore was divided into three risk levels i-e. low, medium and high based on PGA and SA results
2. Two design spectra specific to Lahore, correspond to the two soil classes found in Lahore. Explain about the spectra difference here

Upon comparison with the BCP design spectra, it can be seen that BCP either over-predicts or under-predicts the acceptable spectral response. In either case, it does not align with the actual site response in the area, which can be dangerous. The discrepancies in the BCP and site-specific design spectra can likely be chalked up to the fact that the input parameters for the BCP design spectra considered incorporate the spectral acceleration values based on probabilistic seismic hazard analysis instead of local surface response based on the input motion data. The results of this study highlight the importance of site-specific risk assessments and design spectra. Generalizations over large areas do not accurately represent the site-specific characteristics of specific points within said area, as is highlighted by the results of this study.

As a result, it is recommended that the methodology of this study be replicated for other major cities in Pakistan as well as other countries in order to better understand the earthquake risk faced by these regions. The advantage of this methodology over other alternatives is that it requires minimal amounts of data and does not make use of overly complicated techniques but still delivers useful and comprehensive results. Furthermore, risk-maps are easily understandable by policy makers and local governments.

Data Availability The datasets generated during this study are not publicly available but are available on request, at the discretion of the corresponding author.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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