Newly developed site-specific response spectrum for site in Abbottabad city, Pakistan and its comparison with building code of Pakistan, 2021

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Abstract

Using a site-specific response spectrum has become an integral part of seismic hazard analysis to incorporate the effects of soil beneath the structure. The current study has been performed as a result of a lesson learned from the recent devasting Turkey earthquake of 6th February 2023, where design ground motions were greatly exceeded. This study presents the development of a site-specific response spectrum and its comparison with the recently published Building Code of Pakistan, 2021 (BCP-2021). The results of this study indicate that mobilized shear strength of input motions increased along depth due to the development of different shear strains in various soil layers which affected the shear modulus showing its resistance to deformation by exerted shear stress. Input bedrock motions with peak ground acceleration (PGA) of 0.31g amplified at the surface up to 0.36g due to the response from the soil profile used. After comparison with the design spectrum of Building Code of Pakistan, 2021, it is further validated that the development of site-specific response is very relevant and has significance when using the design spectrum of BCP-2021 developed for a return period of 475 years under currently used soil/site conditions.

Keywords: PSHA, earthquake, response spectrum, ground motion, amplification

Introduction

The current study has been performed as lessons learned from the recent devastating Turkey earthquake of 6th February, 2023, where design ground motions were greatly exceeded. Considering this recent tragedy in focus, this study has been performed to ensure existing margins in the design spectrum suggested by the recently published building code of Pakistan 2021. For this purpose, the current study is performed for a site in the Mandian area of Abbottabad city (Fig.1). The site has been chosen due to its location and the presence of important structures around like Ayub Medical Complex (AMC), which is biggest hospital and medical institute of Hazara division. The Kashmir earthquake of October 8, 2005, severally damaged the AMC structure and resulted in a structural review and heavy repairs afterwards. This earthquake was one of the most devastating earthquakes in the region leaving more than 74,000 people dead [1]. In order to calculate peak ground acceleration levels for any site or area one of well-defined methodologies of seismic hazard analysis is used globally which is called Probabilistic Seismic Hazard Analysis (PSHA). PSHA is used to quantify the rate (or probability) of exceeding various ground motion levels at a particular site considering all possible earthquakes with proper quantification of uncertainties. According to the recently published building code of Pakistan, Abbottabad city is placed in seismic zone 3 with a PGA value of 0.33g for a 10% probability of exceedance in 50 years with a return period of 475 years and a PGA value of 0.69g has been recommended for 2% probability of exceedance for 50 years with a return period of 2475 years. Building codes are normally developed considering regional models and do not account into detailed site-specific studies, therefore site-specific studies become necessary for soils where bedrock is not exposed or not close to the surface. Therefore, capturing detailed site responses against any input bedrock motion becomes necessary to provide the best estimates of spectral acceleration for structural design [2]. To ensure the design adequacy in the design spectrum proposed BCP-2021, Site-Specific Probabilistic Seismic Hazard Analysis (PSHA) has been performed with site response analysis. PSHA for the study area is performed using a classical approach by utilizing area sources and considering all potential fault sources [3]. Recently published building code recommended PGA values of 0.33g and 0.69g for 475 years and 2475 years of return period for the study area [4].

These PGA values are based on PSHA studies performed as part of BCP-2021. Considering the importance of the study area, an updated seismic hazards analysis was needed. Therefore, PSHA study incorporating site response effects was performed for the first time considering importance of areas like Abbottabad, as it is located in a seismically active zone. It defines surface ground motions for the development of design response spectra preliminary to evaluate the distribution of dynamic stresses and strains and other dynamic forces induced by earthquakes which can affect the stability of the site and structures on it respectively [5]. The Kashmir earthquake of October 8, 2005, has shown the importance of local soil conditions which play a key role in understanding the site response. It has been observed that such earthquakes produced severe damage to structures due to varying responses in soil medium beneath the structures like the collapse of Margalla tower in Islamabad and secondary effects produced by the Fukushima Earthquake of March 11, 2011. To capture the response of soil against input earthquake motion soil profile for the site has been developed using borehole data for a depth of up to 25 meters. The site response analysis has been conducted with an equivalent linear approach using DEEPSOIL software Version 7.0.5. Peak acceleration value for bedrock has been determined using PSHA and compatible time histories were selected using de-aggregation results like most contributing distance, magnitude given by de-aggregation plots, and shear wave velocity. Since the recent building code of Pakistan was revised in 2021, therefore, an initiative in the form of this study has been taken to compare the site-specific response spectrum with the design response spectrum of BCP-2021 to provide an in-depth critical view of both spectrums.

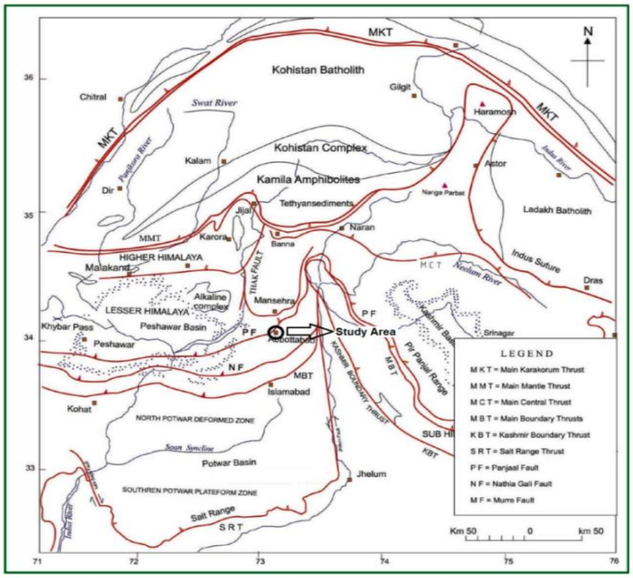


Figure 1. Location and Tectonic map of Study Area (Modified after Naveed et al., 2013)

Geology and Seismotectonics of Study Area

The Abbottabad district is located in Lesser Himalayas, eastern Hazara division. This zone is bounded to the north by the Main Mantle Thrust (MMT) and to the south by the Main Boundary Thrust (Fig.2). The compressional forces being experienced in the NW Himalayan fold and thrust belt are believed to be a result of the ongoing collision of the Eurasian and Indo- Pakistan plates that took place in the late Eocene to Early Oligocene [6]. The Indo-Pakistan plate, relative to the Eurasian plate is still moving northwards at a rate of about 2 mm/yr [7]. The southeast Hazara, being very close to the MBT (to the north of MBT), has undergone intense deformation. In Abbottabad city, it is evident that this deformation is marked by southeast verging thrust faults and northeast trending anticlines. This northeast orientation of the major structures suggests that the area has been undergone northwest-southeast-oriented stresses. The hinge lines of most of the folds in the study area are found to be northeast-southwest trending which also suggests that the area is subjected to northwest-southeast compressive stresses [8]. The style and deformation in the western limb of Hazara Kashmir Syntaxis differs from that of the eastern limb. The Salt Range Formation acts as a ‘decollement’ under the western limb of Hazara Kashmir Syntaxis and is absent under the eastern limb. Due to the presence of the Salt Range Formation, the Hazara thrust system has low-angle faults and low topography. The angle of these thrust faults gradually increases from south west to north east where the thickness of the Salt Range Formation decreases. In the eastern limb of the Hazara Kashmir Syntaxis, the absence of Salt Range Formation developed the high angle thrust faults (MBT, etc.) and high topography [9]. There is a strong coupling between sediments and the basement on the eastern limb side as compared to the western limb of the Syntaxis. Due to the collision between the Indian and Eurasian plates crystalline basement has been overridden by slices of its northern margin. The south-eastern stresses on the western limb and south-western stresses on the eastern limb developed the thin-skin thrust faults in the sedimentary wedge. These thrust sheets have contact with the different lithological units [9]. The area is located in a fold and thrust belt and has undergone intense deformation and shortening as manifested by several thrust faults and various large- and small-scale folds (Fig.2). The overall trend of these structures is northeast-southwest, indicating northwest-southeast compressive stresses. The exposed stratigraphic sequence in the Abbottabad district consists of about a half km thick succession of rocks of Precambrian to Eocene age (Fig. 2). The Hazara Formation is the oldest rock sequence in the area and represents the Precambrian sequence consisting of Slates. The Permian and Triassic sequences are missing in this area. The Jurassic sequence comprises Samana Suk Formation which is composed of Limestone which has unconformable. contact with Hazara Slates, whereas the Cretaceous sequences exposed are the Chichali, Lumshiwal, and Kawagarh formations, Chichali Formation is Shale and its overcontact is with the Samana Suk formation and Lumshiwal Formation is mainly sandstone the upper rock unit of this Kawagarh Formationwhich is Limestone and its lover contact is with Lumshiwal Formation.

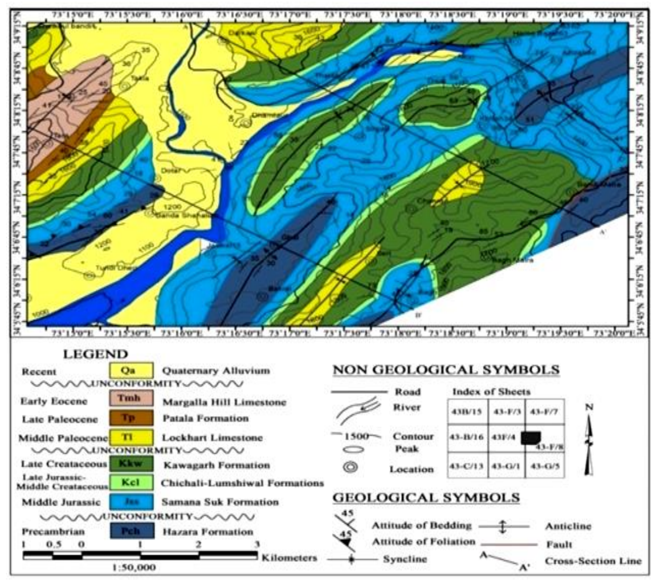


Figure 2. Geologic Map of Abbottabad District Hazara Pakistan (Shamim et al. 2019)

The Paleocene sequence is composed of Hangu and Lockhart formations, Hangu is mainly comprised of sandstone and coal seams whereas the Lochkart is limestone. The Eocene sequence consists of Nammal and Sakessar formations. In light of borehole data acquired for the study area, it is found that soil beneath the study area is mainly composed of silty clay, gravel sand, and silt mixture up to a depth of 30 meters.

Source characterization

In this study concept of a large area source has been used based on seismicity, tectonic setting, and faults present in the area [3]. A total of seven area source zones have been selected for this study considering most contributing potential faults like (MBT: main boundary thrust, MKT, main Karakoram thrust, MMT, main mantle thrust, MCT: main central Thrust, UF: Udhampur fault, JF: Jhelum fault etc.). Distance around the study area has been considered based on engineering judgment and the impact of the earthquake which is around 300km in this case (Fig. 3). Area source zone 1 contains the study area and important fault segments like MBT B, MBT C, etc. The fault depth in this zone ranges from 5-20 km with an average dip ranging from 25-45 degrees. The area source zone 2 marks most western regions having MBT A, MCT A, and Hazara fault mainly. Faults in this zone have an average depth of 10-20 km with an average dip angle of 15-40 degrees. Area source zone 3 marks the North Eastern portion having various seismic events. Area source zone 4 consists of MMT A, MMT B, MMTC, and MMT D fault segments which mark the interface boundary. This zone has faults with greater depths ranging from 40-55km. However, the average dip of these faults ranges between 35-40 degrees. Area source zone 5 has a segment of MKT fault marks suture zone and area source zone 6 has seismic events. Area source zone 7 mostly consists of the Hindu Kush region with intermediate to deep seismicity having regional faults like MKT A, and MKTB.

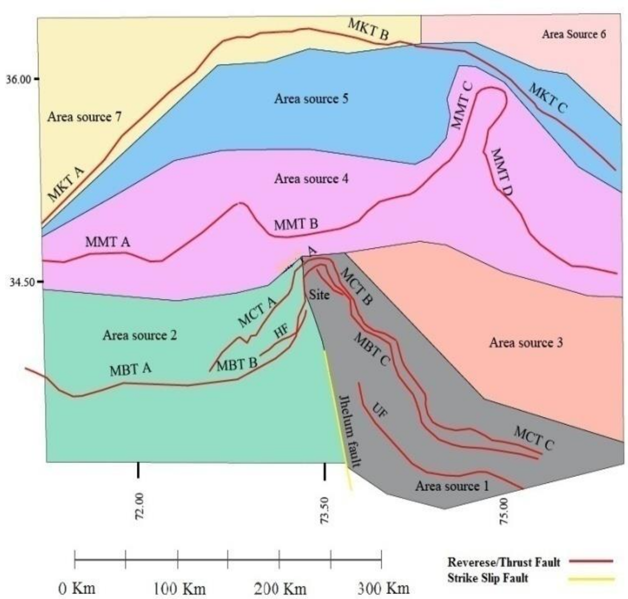


Figure 3. Area source zone map for PSHA of study area, Abbottabad (MBT: main boundary thrust, MKT, main Karakoram thrust, MMT, main mantle thrust, MCT: main central Thrust, UF: Udhampur fault)

Earthquake catalogue for the study area

Reliability and processing of seismicity data are key to having more accurate seismic hazard estimates. In the current study, a composite earthquake catalogue is compiled by using an earthquake catalogue from the International Seismological Centre (ISC) and the United States Geological Survey (USGS) for some time from 1905 to 2019. The catalogue is transformed into a uniform magnitude scale called moment magnitude (Mw) using different empirical conversion relations [10,11,12]. The comparison of these relations has been done with the events in the Mb scale which revealed that the relationship developed by Akkar (2010), seems more suitable and used for the hazard analysis (Fig. 4). After the conversion of the catalogue in Mw, declustering is performed by an algorithm proposed by Reasenberg [13]. After the declustering of the catalogue was further analyzed for a period of completeness for different values of magnitudes [14]. Similarly, histograms were developed for depth, Mw, and time to analyse the distribution of seismicity throughout the time from 1905 to 2019. The catalogue was further assessed through a, and b value plots through different methods like likelihood, least square, and by Weichert [15], which are used to calculate the recurrence parameters Fig.5(a)&Fig.5(b). a-value represents total seismicity rate of the region. However, b-value is used for regional stress analysis, activity rates calculations and earthquake prediction. Both a, b values can be calculated through Gutenberg-Richter (GR) law. The detail of completeness analysis for Mw 4.5 & 5.5 is given (Fig.6(a)) & Fig.6 (b), and for Mw 6 & 6.5 is given in Fig. 7(a) & (b). The depth plot showing the distribution of earthquakes with respect to depth is also presented (Fig.8).

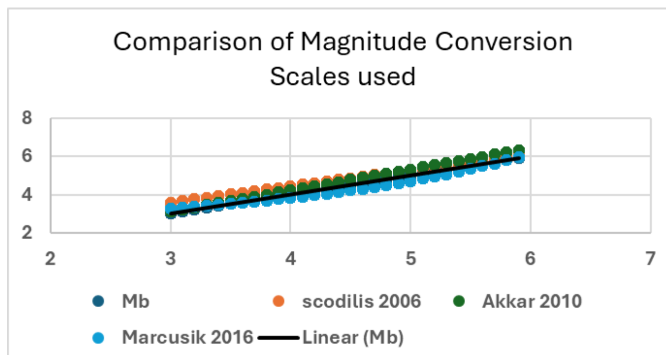


Figure 4. Comparison of Magnitude conversion relations used in the study

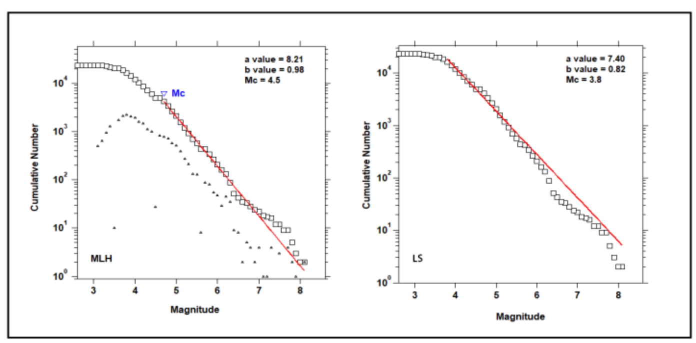


Figure 5(a). a, b values for the whole catalogue through the Maximum Likelihood Method (MLH) Figure 5(b). a, b values for the whole catalogue through the Least Square Method (LS)

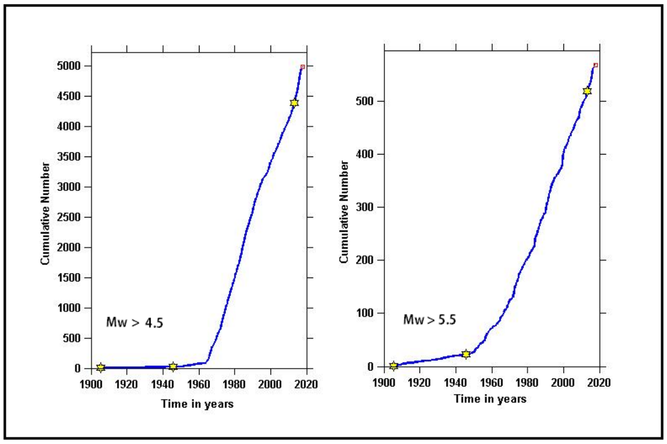
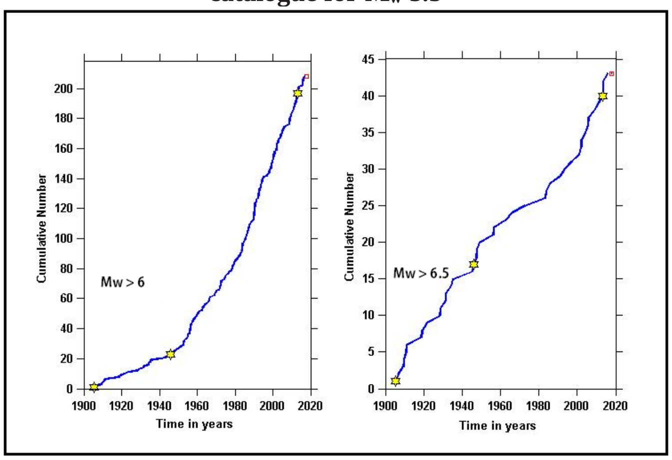


Figure 6(a). Magnitude Completeness of catalogue for M_w 4.5 & Figure 6(b). Magnitude Completeness of catalogue for M_w 5.5



Calculation of maximum magnitude for areal sources

Recent earthquakes of magnitude 7.8M_w and 7.7M_w in 2023 in Turkey opened up many questions about how we assign and calculate the maximum magnitude of the faults. The determination of M_{max} is a tricky job due to uncertainties associated especially in terms of earthquake rupture process and segmentation etc., [19] which needs to be addressed in detail. In the current study, M_{max} has been calculated based on the latest data set and methodologies. Careful consideration has been given to dividing these faults into segmentations based on their historic seismicity pattern and geometry. Three widely accepted relationships [WC: Wells & CopperSmith (1994)],[HB: Hanks & Bukun (2014)] and Gupta (2002) have been used to calculate M_{max} [16,17,18]. Surface rupture length has been used considering a 100% rupture scenario. An incremental value of 0.5 was added to the observed magnitude as suggested by Gupta (2002). However, for the calculation of Mmax for diffused zones, the Bayesian approach has been used [19]. Maximum likelihood, least square, and methodology proposed by Weichert have been used to calculate recurrence parameters as given in (Table 1). Since in almost every area source seismicity is controlled by faults, therefore, magnitude for each area source is assigned based on faults postulating maximum magnitudes. Maximum magnitudes calculated for each potential fault source are presented in (Table 2).

Figure 7(a). Magnitude Completeness of catalogue for Mw 6 & Figure 7(b). Magnitude Completeness of catalogue for Mw 6.5

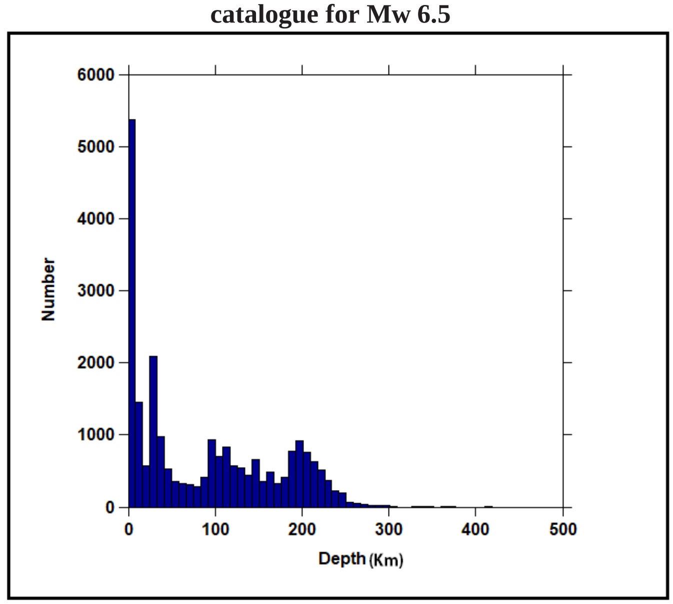


Figure 8. Depth profile of earthquakes occurrence for 300km region around the study area

Table I

Recurrence parameters (a, b values and activity rates calculated for area source zones from MLH, LS and Weichert method

Area sources	MLH[(a)]	LS[(b)]	Weichert	MLH	LS	Weichert
	b value	b value	b value	Activity Rate	Activity Rate	Activity Rate
Area source1	0.88	0.76	0.95	0.93	0.87	1.100
Area source2	0.77	0.75	0.93	0.75	0.76	0.960
Area source3	0.94	0.85	1	0.26	0.25	0.410
Area source4	0.83	0.87	1	1.67	1.52	1.940
Area source5	1	0.77	1	2.94	0.61	1.440
Area source6	1.1	0.92	1.2	0.16	0.03	0.030
Area source7	0.91	0.87	1.1	5.05	4.71	6.370

[(a)]Maximum likelihood method

[(b)]Least square method

Table II

Fault/Planner sources used in the study with their geometric parameters

Fault Name	Mechanism	Fault Length (km)	Average Dip (degrees)	Maximum Observed M_w	Mmax WC 1994	Mmax HB 2014	M_{max} Gupta 2002
Balakot - Bagh Fault, BBF	R	100	95	7.6	7.8	7.7	8.1
Main Central Thrust segment A, MCT A	R	122	40	5.4	7.1	7.2	5.9
Main Central Thrust segment B, MCT B	R	107	32	5.7	7.0	7.1	6.2
Main Central Thrust segment C, MCT C	R	160	28	5.1	7.2	7.2	5.6
Udhampur Fault, UF	R	168	32	4.5	7.1	7.2	5.0
Main Boundary Thrust segment A, MBT A	R	130	15	6.3	7.4	7.5	6.8
Main Boundary Thrust segment B, MBT B	R	142	40	5.2	7.1	7.1	5.7
Main Boundary Thrust segment C, MBT C	R	270	39	5.1	7.3	7.5	5.6
Main Mantle Thrust segment A, MMT A	R	183	40	5.3	8.0	8.4	5.8
Main Mantle Thrust segment B, MMT B	R	114	40	5.2	7.9	8.2	5.7
Main Mantle Thrust segment C, MMT C	R	134	40	6.3	8.0	8.3	6.8
Main Mantle Thrust segment D, MMT D	R	106	40	5.1	7.8	8.2	5.6
Main Mantle Thrust segment E, MMT E	R	123	40	5.3	7.9	8.3	5.8
Main Karakorum Thrust, segment A, MKT A	R	200	40	5.1	8.2	8.6	5.6
Main Karakorum Thrust segment B, MKT B	R	142	40	5.0	8.1	8.5	5.5
Main Karakorum Thrust segment C, MKT C	R	186	40	4.5	8.1	8.6	5.0

Selection of ground motion prediction equations

In the case of Pakistan, country-specific attenuation models have not been developed yet. However, in this study attenuation model developed by the Pacific Earthquake Engineering Research (PEER) called NGA-WEST 2 is used after comparing them with conditions given by Campbell and Bozorgnia (2014; hereafter, CB14; Chiou and Youngs (2014)., hereafter, CY14; Boore and Atkinson (2014); hereafter, BA14; Abrahamson and Silva (2014); hereafter, AS14 and BC Hydro (2012) [20,21,22,23,24]. A general applicability criterion suggested by the developers as given below, has been used which a particular site/study should meet:

- Mw with a range of 3 to 8.5 (strike-slip earthquakes) and 5 to 8 (reverse and normal earthquakes
- Site region distance, 0 to 300 km
- 150 m/sec ≤ VS30 ≤ 1500 m/sec

Probabilistic Seismic Hazard Analysis results for study area

PSHA results in the current study have been presented in the form of hazard curves, uniform hazard spectra (UHS), and de-aggregation plots for bedrock level at 30m depth from the surface. The hazard curves for peak acceleration for various annual rates of exceedance for 5% damping are shown in (Fig.9). These hazard curves can be used as input for design based on requirements from the designer for different probability of exceedance levels like 2% and 10% probability of exceedance (PE) in 50 years. The (Fig.9) also indicates that “zone 4 and 5” have the largest contribution and controls the hazard. As the hazard level decreases, the contribution of the other zones becomes more significant. The de-aggregation results for 475 & 2475 years return periods have been presented in (Fig.10(a)) and (Fig.10(b)) showing which particular seismic source zone controls the hazard at the site. UHS development for the site has been developed at bedrock level for both 475 and 2475 years which is given in (Fig.11). To account for uncertainties related to the model used, a logic tree approach has been used to account for uncertainties at different stages like calculating Mmax, using GMPEs, etc. The same has been given (Fig.12).

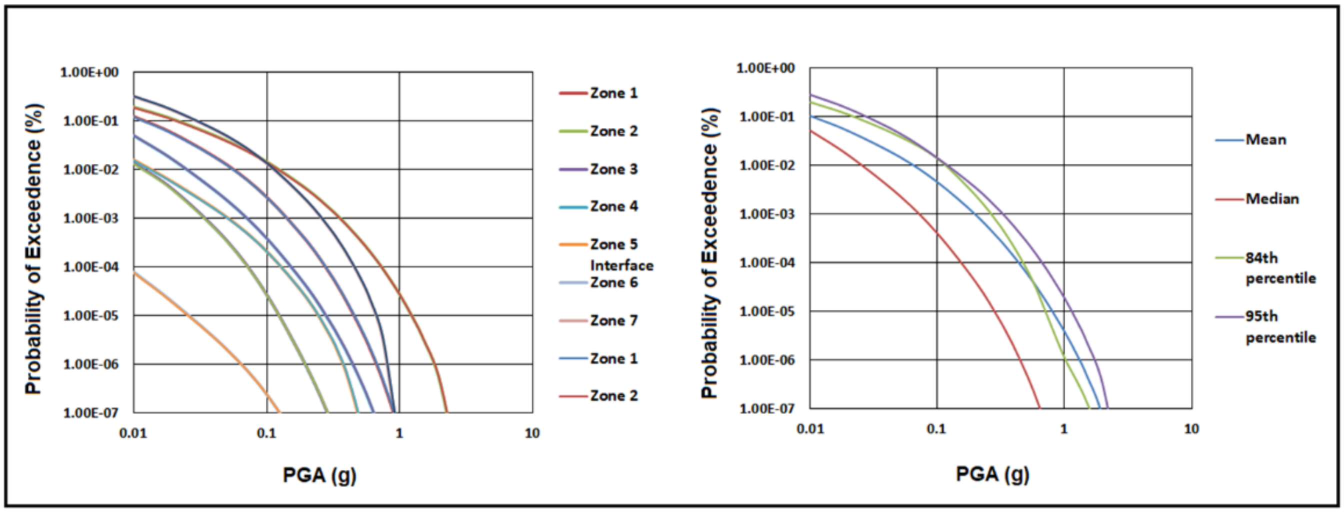
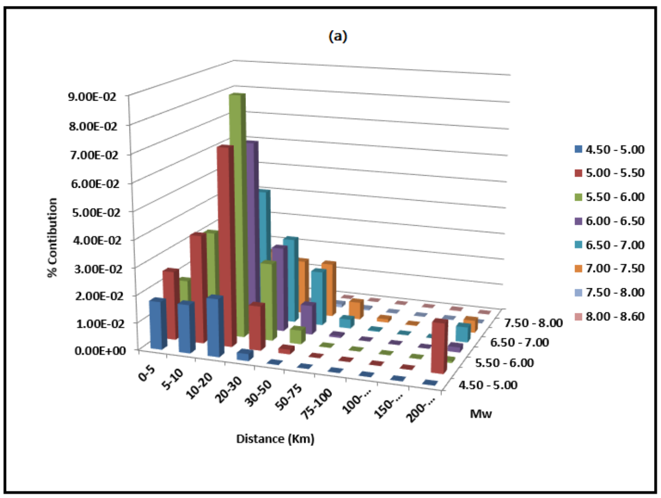


Figure 9. Seismic Hazard Curves for the study area



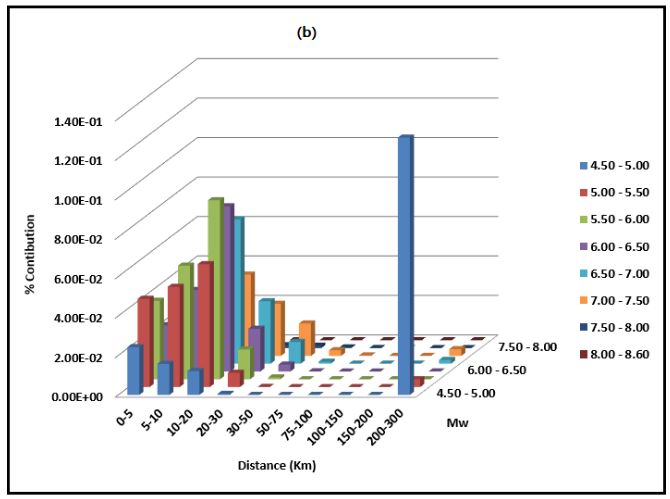


Figure 10 (a). De-aggregation plot for 475 years Figure 10(b). De-aggregation plot for 2475 years

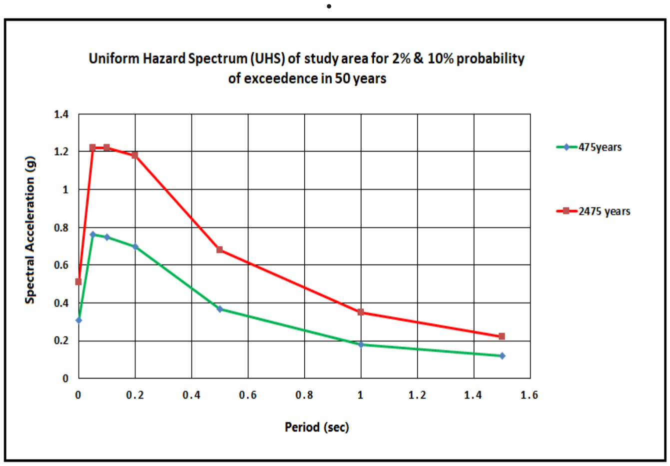


Figure 11. Uniform Hazard Response Spectrum at rock level of return periods 2475 and 475 years of study area

Input motions

Input motions have been selected based on the de-aggregation results of PSHA. In most of the cases, it is unknown, as strong motion records for site-specific conditions are not available widely. In the case of Pakistan, the availability of originally recorded strong motion records for a particular site is very rare.

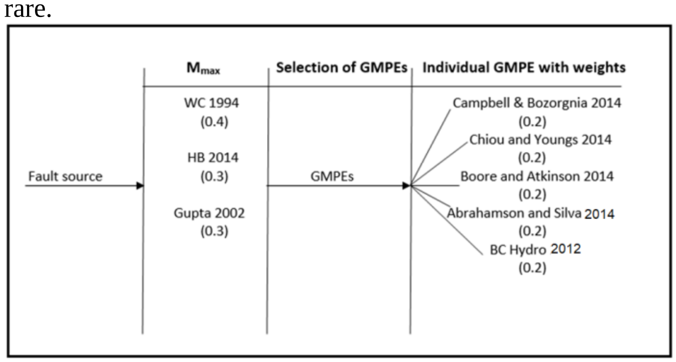


Figure 12. Logic tree used for M_{max} and GMPEs in hazard model

Therefore, in the current study most compatible input motions/time histories based on de-aggregation results and other site-specific parameters like shear wave velocity have been used. A total of eleven compatible strong motion records from the Pacific Earthquake Engineering Research (PEER) Centre strong motion database have been selected (Fig.13). The Fourier amplitude spectra for these bedrock motions show high response at a lower frequency range (0.03 to 1.5 Hz) (Fig.14). The response spectra of these time histories at bedrock corresponding to 0.31g value are given (Fig.15).

Site Response Analysis

Site response analysis for the current site has been carried out using a one-dimensional equivalent linear approach with DEEPSOIL Version 7.0.5 software developed by Hashash (2017) [25]. The site response analysis helped to understand the vertical transmission of seismic waves through horizontal soil layers. One of the most important inputs of the 1-D site-specific ground response analysis using an equivalent linear approach is the modulus degradation and damping curves that represent the soil layers properly. Modulus reduction behavior is influenced by the mean effective confining pressure for cohesionless soils [26]. Borehole data and site classification revealed that modulus reduction curves for the site are similar to that of the Vucetic and Dobry (1991) model. Physical parameters for soil encountered at the site are given in (Table 3). [27].

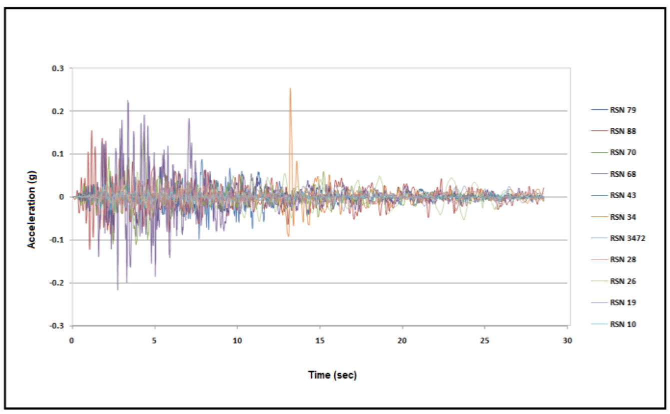


Figure 13. Time histories used as input motion for bedrock

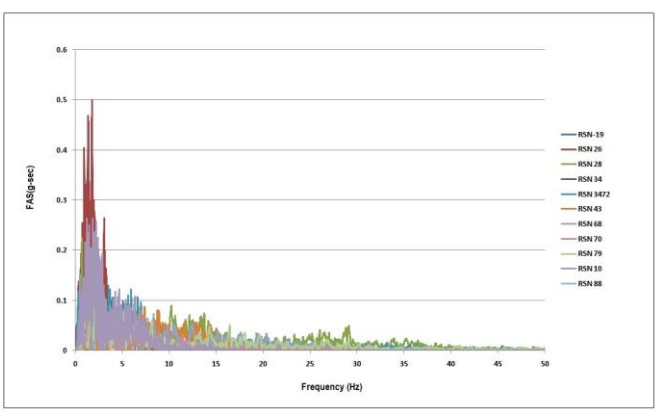


Figure 14. The Fourier amplitude spectrum of bedrock motions

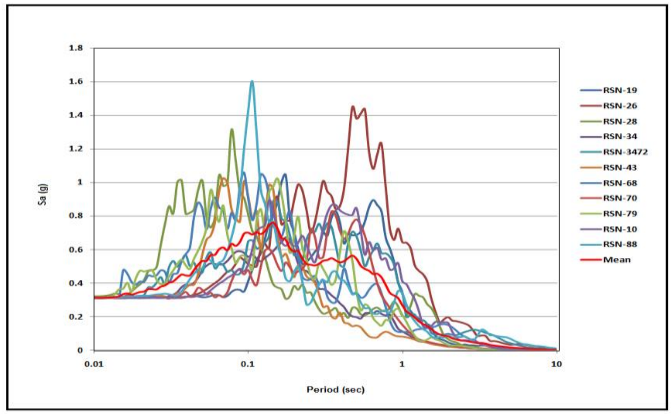


Figure 15. The response spectrum of input motions bedrock

Table III

Physical parameters of soil at the site

Depth (m)	SPT N Values	shear wave velocity (m/sec)	Soil Type	Soil Profile	Soil Composition
1	8	206.82	S_D	stiff soil	silty clay
5	4	185.00	S_D	stiff soil	silty clay
10	16	264.29	S_D	stiff soil	Clay sand silt mixture
15	12	360.72	S_D	stiff soil	Clay sand silt mixture
20	17	410.02	S_D	stiff soil	Clay sand silt mixture
25	22	470.00	S_D	stiff soil	Clay sand silt mixture
30	25	560.00	S_D	stiff soil	Clay sand silt mixture

Therefore, based on above mentioned properties for the topsoil and the layers beneath the topsoil layer, the modulus degradation and damping curves for clay and silt proposed by Vucetic and Dobry (1991) are employed in Fig.16(a) and Fig.16(b). Based on these facts, the current site was classified as class S_D. The geotechnical properties for the bedrock were used as a unit weight of 22KN/m^3 and, a shear wave velocity of 560m/sec assuming it is an engineering bedrock. Using the geotechnical properties of soil at the site, the fundamental natural period of the site is calculated by the equivalent shear wave velocity of the deposit. The fundamental natural frequency was then calculated as the reciprocal of the fundamental natural period. In light of above mentioned fundamental natural period and frequency for the site was thus determined as 0.23 sec and 4.32 Hz respectively. The amplification ratio calculated at the surface for all input motions is shown in (Fig.17). The site amplification based on the representative soil profiles and selected ground motions is presented in terms of maximum acceleration vs depth graphs for the site (Fig.18). This (Fig.18) is clearly shown amplification of input motions at the ground surface. The change in impedance in various soil layers at various depths can also be observed. For most of the accelerograms with input motion of 0.31g at bedrock, it can be seen that these input motions are amplified at the surface with a mean amplification factor of 1.16 resulting mean PGA value of 0.36g. This amplification in PGA values can be due to higher/stronger amplitude at lower and fundamental frequencies of the site. The shear strength and damping for the soil layers are calculated based on modulus reduction and damping curves. Shear strain develops in the soil layers which affects the shear modulus due to seismic wave transmission through the soil profile (Fig.19). The mobilized shear strength of the soil is found higher for all input motions showing its resistance to deformation by exerted shear stress. It also showed the resistance and response of soil with depth which can be used as one of the important considerations for the foundation design of the structure in the study area. In the current study, a single degree of freedom (SDOF) system is assumed. Therefore, response spectra are developed for all input motions assuming SDOF structure as a function of period/frequency for damping of 5%. The ground response spectra for 5 % damping for input motions along with the mean are shown in Fig.20. The Mean site-specific ground response spectrum has shown higher spectral acceleration near the fundamental period of 0.23 sec of the site.

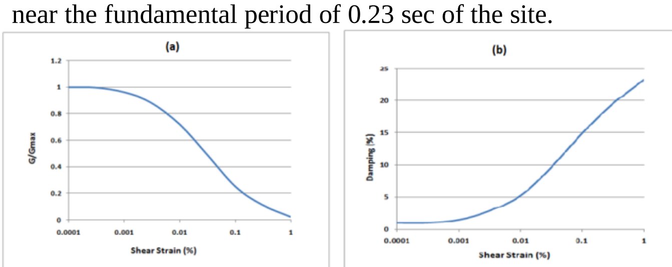


Figure 16 (a). Modulus reduction curve & Figure 16(b). Damping curve used in the study

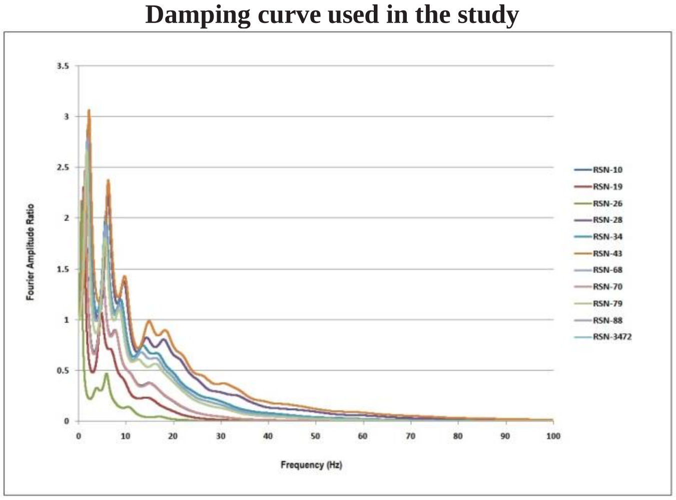


Figure 17. Fourier amplitude ratio of accelerograms used in the study

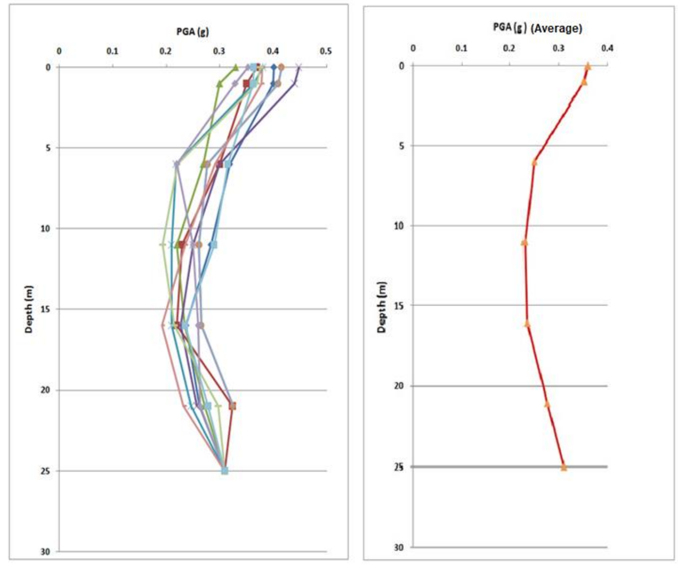


Figure 18. PGA depth profile showing amplification/de amplification through different soil layers used for the study area/site

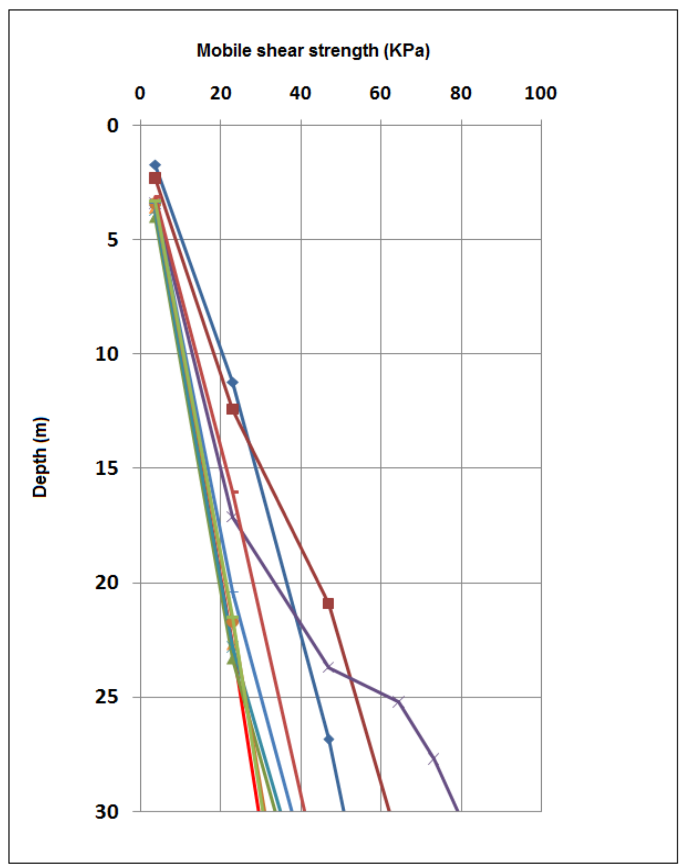


Figure 19. Mobilized shear strength (kPa) of the soil layers with depth for the study area

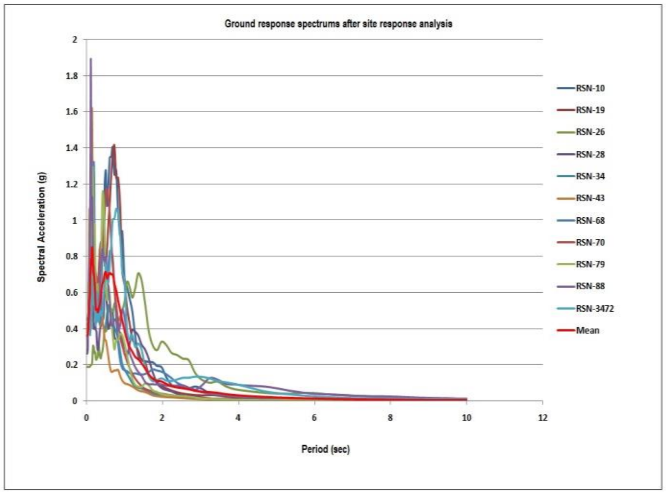


Figure 20. Site-specific response spectrum of eleven input motions

Comparison of Site-Specific Response Spectrum with Design Spectrum of Building Code of Pakistan-2021

The site-specific ground response spectrum developed has been compared with design spectra of the building code of Pakistan for soil class SD as shown in (Fig.21). As per the building code of Pakistan, Abbottabad city lies in seismic zone 3 with a PGA value of 0.33g for 475 years and 0.69g for 2475 years. Based on the provision of BCP -2021 which followed the design philosophy of International Building Code IBC (2021) and ASCE 7 -05[28], a design spectrum keeping in view a multi-story building (5 stories) has been developed. For this purpose, the design spectrum is modified according to site class and general seismic zonation of the building code. In this study, since the site is characterized as class SD, therefore parameters Ssand S1 are determined based on ASCE 7 -05 section 11.4.1 In this design spectrum, Ss represents the mapped maximum credible earthquake (MCE) for short-period spectral response acceleration parameter, and S1represents long period spectral response acceleration parameter. The design spectrum plays an important role and is useful for designing new structures and for the safety re-evaluation of existing structures. A comparison of both spectra revealed that the site-specific response spectrum has a maximum spectral acceleration of 0.84g at 0.14sec and a second peak with a maximum spectral acceleration of 0.71g at 0.5sec. However, the design spectrum developed for 475 years revealed a maximum spectral acceleration of 0.68g at 0.09-0.47sec. Similarly, a design spectrum corresponding to 2475 years has also been developed showing a maximum spectral acceleration of 1.03g for 0.09-0.47sec. Zero period acceleration for site-specific response spectrum has been calculated as 0.36g, for design spectrum for 475 years as 0.27g, and for 2475 years as 0.41g respectively. It has been observed that the design spectrum developed for 475 years does not have enough margin to provide seismic safety margin when compared with site site-specific response spectrum. For the period range from 0.09 to 1.05sec site-specific spectrum overlaps the design spectrum (475 years), which needs to be considered carefully in the design and construction of the multi-story building in the study area. However, the design spectrum developed for 2475 years overlaps completely the site-specific response spectrum, which means that using such a design spectrum can provide a higher seismic safety margin for design and construction in the study area.

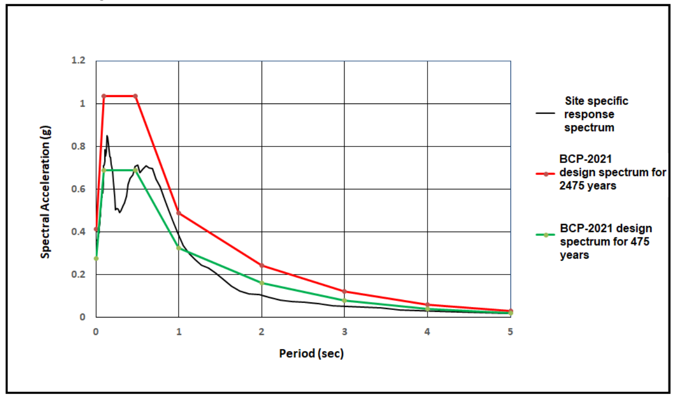


Figure 21. Comparison of site-specific response spectrum with both design spectra of BCP-2021 for 475 and 2475 years

Discussion

The main challenge of the study was to establish input motions for the bedrock for the site. For this purpose, a site-specific PSHA study was conducted for the site to determine the maximum acceleration value for bedrock. The PSHA study was conducted for 2 % & 10% probability of exceedance in 50 years for 475 and 2475 years. It is important to mention that in this study one dimensional site response analysis has been carried out using an equivalent linear approach using DEEPSOIL 7.0.5 software. The equivalent linear approach is considered the most conservative approach that can approximate the non-linear response [29,30]. The results obtained from equivalent linear ground response analysis can indicate overestimated results for peak acceleration. Additionally, equivalent linear results are dependent on site-specific geotechnical conditions [31]. Comparison of site-specific response spectrum with design spectra has shown that the design spectrum in the current case for 475 years needs care consideration when used as a design spectrum for civil structures due to its lower spectral and zero period acceleration values for various period ranges. However, the design spectrum for 2475 years has shown enough seismic margin against site-specific response spectrum over an entire range of periods. Therefore, site-specific response spectrum and design spectrum for 2475 years can be a better choice for seismic design in the study area.

Conclusions

The current study developed a site-specific response spectrum for 475 years of return period. To prevent future structural damage and humans in and around the study region this study suggests an updated site-specific response spectrum. Site class was defined as stiff soil (SD) based on borehole data and the NEHRP (National Earthquake Hazard Reduction

Program) soil classification system. Bedrock motion of 0.31g was determined for bedrock level through PSHA. Eleven compatible time histories scaled to 0.31g have been used. The soil profile was modelled using the 1D equivalent linear approach with the time history method. Based on this study following conclusions are drawn.

- Site-specific response spectrum determined through PSHA has been found on the higher side as compared to the design spectrum of BCP-2021 for a 10% probability of exceedance in 50 years with 475 years of return period. This finding indicates the importance of site response analysis to be performed.
- This analysis revealed bedrock motion of 0.31g from PSHA for a 10% probability of exceedance with 475 years of return period.
- Eleven-time histories scaled to input motion were used in 1D equivalent linear site response analysis, after carefully defining soil layers.
- The soil under study area has been classified as stiff soil SD, and analysis revealed amplification of input time histories with an average amplification factor of 1.16.
- The mean amplified motion calculated at the surface was found with peak ground acceleration value of 0.36g
- The mobilized shear strength for accelerograms is higher along depth due to the development of different shear strains in various soil layers which affected the shear modulus.
- A comparison of both spectra revealed site-specific response spectrum has a maximum spectral acceleration of 0.84g at 0.14sec and a second peak with a maximum spectral acceleration of 0.71g at 0.5sec. However, the design spectrum developed for 475 years revealed a maximum spectral acceleration of 0.68g at 0.09-0.47sec.
- Similarly, a design spectrum corresponding to 2475 years has also been developed showing a maximum spectral acceleration of 1.03g for 0.09-0.47sec.
- Zero period acceleration for site-specific response spectrum has been calculated as 0.36g, for design spectrum it is 0.27g, and for 2475 years as 0.41g.
- It has been observed that the design spectrum developed for 475 years does not have enough margin to provide seismic safety margin when compared with the site-specific response spectrum. For periods ranging from 0.09 to 1.05sec site-specific spectrum overlaps design spectrum developed for 475 years.
- Finally, the comparison of the site-specific response spectrum with the design spectrum of BCP-2021 was done which showed that the BCP-2021 design spectrum based on a 2% probability of exceedance with 2475 years of return period has enough margins and overlaps the site-specific response spectrum which can be used as design input for structures. However, if the design spectrum of BCP-2021 for a 10% probability of exceedance in 50 years with 475 years of return period is used, it should be used carefully, and site response analysis may be performed.

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Disclaimer

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