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DETERMINISTIC SEISMIC HAZARD ANALYSIS (DSHA) OF DHA PHASE-1, RAWALPINDI

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Abstract
Rawalpindi and Islamabad are two of the most seismically active areas, located near the main boundary thrust (MBT). Alongside this thrust zone are several faults: Murree, Margalla, Hazara, Jhelum, Rawat, and Riasi, which define the boundary between the Sub-Himalayan and Potwar Thrust (Monalisa et al., 2007; Khan & Khan, 2018). Due to the Destruction of high-rise buildings in Rawalpindi, the urgency for specific site seismic hazard assessment after the catastrophic earthquake of 2005 (Kashmir) was strongly felt in Islamabad & Rawalpindi. This study presents the deterministic seismic hazard analysis (DSHA) methodology for DHA Phase-1 Rawalpindi, located on the Potwar Plateau and an evolving commercial & residential region near the MBT system. This study summarizes the depth & foundation of DSHA by synthesizing and concluding existing seismic hazard studies for Islamabad and surrounding regions. The main four-step detailed process of DSHA is Determination of Source, Representation of source-to-site distance, and Selection of Ground-motion Estimation. In the literature, MBT Faults and Rawat Faults are located between 10 km and 30 km from the surroundings of DHA Phase-1 to control deterministic hazards, and these faults record Peak Ground Acceleration (PGA) estimated in the range of 0.15 g to 0.4 g based on controlling the fault. This analysis and results review form the methodological approach to give seismic microzonation and code compliance for DSHA for Site DHA Phase-1.

INTRODUCTION

Earthquakes are the most destructive and least predictable natural hazard, underscoring that the built environment relies on both ground shaking and exposure (Vaziri et al., 2022). For the design and construction of safe building structures, it is very important to estimate the expected ground shaking a site is likely to experience to ensure disaster risk reduction in urban housing development near an active fault system. There are two main approaches for these tasks: Deterministic Seismic Hazard Analysis (DSHA) and Probabilistic Seismic Hazard Analysis (PSHA) (Reiter, 1990; Cornell, 1968). The main difference between DSHA and PSHA, In PSHA all outcomes includes earthquake sources and magnitude calculated distances of each source is weighted by occurrence probability over a specified period of exposure, on the other hand DSHA focuses on the worst-case scenario like the maximum ground shaking and earthquake is produced by near by earthquake sources is able to produce and the

distances from the source to site (Reiter, 1990; Krinitzsky, 1995; Kramer, 1996).

Main Boundary Thrust (MBT) and Main Mantle Thrust (MMT) are basically the northern part of the country, including Islamabad and Rawalpindi metropolitan area, which is crisscrossed by many active thrust systems such as Jhelum fault, Murree Thrust, Rawat Fault and Panjal Thrust (Monalisa et al., 2007; Khan & Khan, 2018). Due to the severe earthquake in Kashmir on 8th October, 2005, the vulnerability of the region was substantiated, with a magnitude of 7.6; considering that, as it was 100 km away, the structural damage in Islamabad was felt as strongly and caused ground shaking and cracking (Bhatti et al., 2011). On the other hand, moderate earthquakes, such as the one on 24th July, 2015, with a magnitude of 5.1 near Rawat, have caused ground cracking and structural damage in the Rawalpindi region, confirming the activity and presence of local fault sources (Khalid et al., n.d.). Based on the Defense Housing Authority (DHA) development, DHA Phase-1 is one of the largest populated phases along the Islamabad Highway / Grand Trunk Road Corridor in Rawalpindi, underlain by Potwar Plateau sediments located within a few kilometers from the MBT and Rawat Fault (Khalid et al., n.d.; Ahmed et al., 2022). From time to time, as the development and construction of residential and commercial areas increase, it is very important to conduct site-deterministic seismic hazard assessments to determine design-basis ground motion parameters, especially in northern Pakistan, where earthquake recurrence data are used as worst-case design bases (Hashash et al., 2012).

The aim of this study is: (1) Analysis of the theoretical development and the methodological steps of a deterministic seismic hazard analysis report; (2) Deriving the seismogenic source framework consisting of faults controlling their maximum magnitude and their distance from the site that will support the deterministic seismic hazard evaluation of DHA Phase-1 Rawalpindi.

LITERATURE REVIEW

Theoretical Basis of Deterministic Seismic Hazard Analysis

The DSHA method was first developed in the late 1960s for the siting and design of critical facilities such as nuclear power plants, and was later extended to other sites, including dams, bridges, and other high-consequence infrastructure (AEIS-IGN, 1979; NRC, 1973, cited in Beltré et al., 2025). Reiter (1990) formally developed the DSHA into four distinct steps: (i) identify and characterize all seismic sources capable of significant ground motion at the site — generally this requires faults or seismogenic zones; (ii) choose a parameter that measures the distance between the seismic source and the site, typically the closest distance between the source and the site; (iii) select the Maximum Credible Earthquake (MCE) for each source, defined as the largest magnitude the source is likely to generate; and (iv) calculate the resulting ground motion parameter (e.g., Peak Ground Acceleration or spectral acceleration) at the site for each source's MCE using an appropriate Ground Motion Prediction Equation (GMPE), with the site hazard finally governed by the "controlling" source producing the highest ground motion (Reiter, 1990; Kramer, 1996; Vaziri et al., 2022).

One of the most vocal proponents of the method is Krinitzsky (1995), who contended that DSHA provides a more physically transparent and defensible basis for critical structures than PSHA, because direct evidence of surface rupture from the past 12,000 to 500,000 years is used in establishing these bases, instead of relying on statistically derived recurrence relationships that are often poorly constrained in areas with limited historical earthquake catalogs. Krinitzsky also argued that the key advantage of DSHA is that it eliminates some of the epistemic uncertainties associated with probabilistic recurrence modeling and built this case in a series of subsequent papers (Krinitzsky, 1995, 2002; Wang, 2011). In his popular geotechnical earthquake engineering book, Kramer (1996) also describes DSHA as a simple four-step process that is useful when the goal is to define a conservative single design-basis ground motion for a particular critical facility.

The DSHA approach has also been the focus of methodological debate for years. Bommer (2002) termed this deterministic-versus-probabilistic dichotomy "exaggerated and obstructive" and suggested a deterministic-probabilistic framework to achieve balanced, engineering-relevant design ground motions. Wang et al. (2012) also noted that the two approaches can be combined to validate hazard estimates, and that DSHA is especially useful for providing worst-case or maximum-credible scenarios to complement the PSHA framework, which is based on exceedance probability. Despite this debate, reviews by Vaziri et al. (2022) and Beltré et al. (2025) have confirmed that DSHA is still being widely used by civil protection agencies and in critical-infrastructure siting, especially in areas where fault recurrence-rate data is not available, as in northern Pakistan, as reported by Hashash et al. (2012).

Seismotectonic Setting and Seismic Hazard Studies of Islamabad-Rawalpindi

The Islamabad–Rawalpindi metropolitan area lies at the northeastern edge of the Potwar Plateau, underlain by one of the main Himalayan boundary faults, the Main Boundary Thrust (MBT), and associated faults such as the Murree Thrust, the Jhelum Fault and the Rawat Fault (Khan & Khan, 2018; Khalid et al., n.d.). Gansser (1964) and subsequent regional geological mapping (Sheikh et al., 2007, as cited in Ahmed et al., 2022) confirmed the presence of Quaternary sediments in the area, including loess deposits and gravelly alluvium overlying folded and faulted Siwalik sandstones and mudstones, which have direct implications for site amplification and local seismic responses.

One of the first ever detailed seismic hazard analyses for the cities of Islamabad and Rawalpindi was carried out by NORSAR and the Pakistan Meteorological Department (NORSAR & PMD, 2006), who defined 11 shallow area seismic source zones (plus one deep zone for the Hindu Kush) and modelled the Jhelum Fault explicitly as a discrete strike-slip source, using the attenuation relation of Ambraseys et al. (1996). On this basis, Hashash et al. (2012) conducted discrete-fault source DSHA and PSHA for Islamabad and Rawalpindi in north-western Pakistan and reported 500-year-return-period PGA values of 0.19–0.21 g; for Islamabad, the hazard was found to be dominated by the western segment of the MBT. They used deaggregation analysis to show that the median DSHA spectrum for the controlling MBT-west source was similar to the PSHA uniform hazard spectrum at the 84th percentile, and that the 84th-percentile DSHA spectrum exceeded the PSHA uniform hazard spectrum, illustrating how a conservative DSHA estimate can bound higher-probability PSHA estimates.

Another study by Hashash et al. (2012) noted that, given Rawalpindi's high population density and generally lower construction standards compared with Islamabad, it is an even more hazard-prone urban conglomerate.

Monalisa, Khwaja and Jan (2007) used a probabilistic approach to estimate seismic hazard in the wider NW Himalayan fold-and-thrust belt and hence, generated recurrence parameters for the regions in the NW Himalayas where the earthquakes are potential sources and which have been used in the PSHA and DSHA studies of the twin cities. Bhatti et al. (2011) performed a PSHA of the city of Islamabad on a spatially dense grid of 1 km within the district, and found PGA values to be spatially variable across the district, with the most seismically exposed area being the F-11 sector, and also emphasized the close proximity of Islamabad to the MBT as the major contributor to hazard following the Muzaffarabad earthquake of 2005. Later, Rahman et al. (2021) developed an updated national-scale PSHA for Pakistan that incorporated new seismogenic source models, ground-motion models, and updated hazard values for many cities in Pakistan, including those in the Potwar region.

Further understanding of local site conditions in the twin cities has been developed through site-specific and geotechnical studies. Ambient noise (microtremor) measurements around Rawalpindi–Islamabad were done by Qadri et al. (2015) to characterize site response for preliminary seismic microzonation, whereas, using empirical relations, Khan and Khan (2018) mapped the sediment thickness around Islamabad for seismic hazard assessment and later, Ahmed et al. (2022)

estimated the time-averaged shear-wave velocity (Vs30) around the metropolitan area for refining site classification. In the study by Khalid et al., the observed structural damage was influenced by the Rawat Fault, which lies within the Potwar Plateau, near several DHA phases and the study indicated that the general area of Rawalpindi–Kahuta was in the moderate–high seismic intensity zone (MM Intensity VII) after the July 2015 Mw 5.1 earthquake.

DSHA Applications to Local Infrastructure in Rawalpindi

The methodological precedent for the present study is provided by the more recent, site-specific applications of DSHA in Rawalpindi. It has been found that a study conducted in 2024 evaluated the seismic vulnerability of a major bridge located at Grand Trunk Road, Rawalpindi, using the DSHA approach, which concluded that the Rawat Fault (approx. 11.71 km away from the site) was a controlling source fault with a peak ground acceleration of 0.42 g (as summarized in ResearchGate, 2024).

This is especially important for this study since the DHA Phase 1 is located in a similar distance range of the same regional fault network, indicating that the Rawat Fault and/or the MBT are also likely to become controlling sources for DHA Phase 1. This study also confirmed, as in Hashash et al. (2012), that the output from DSHA is not necessarily an upper bound from outputs obtained from PSHA, further emphasizing the importance of using both methods concurrently for critical or high-density developments.

Synthesis and Research Gap

The reviewed literature concludes that: (1) DSHA methodology is theoretically well established and is especially applicable in regions with limited long, reliable earthquake recurrence catalogues, such as northern Pakistan (Hashash et al., 2012); (2) The Islamabad – Rawalpindi metropolitan area is seismotectonically controlled by the MBT and its associated secondary faults, including the Rawat Fault, Jhelum Fault and Murree Thrust, which have been repeatedly identified as controlling sources in previous seismic hazard studies (NORSAR & PMD,2006; Monalisa et al., 2007; Hashash et al., 2012); and (3) Reported PGA values for the metropolitan area range widely from approximately 0.15 g to more than 0.4 g depending on the controlling fault, source to site distance, and GMPE used (Hashash et al., 2012; ResearchGate, 2024). However, most previous studies have been conducted at the Islamabad-Rawalpindi city-level or district-level, or have addressed specific critical facilities like bridges, but have not provided a site-specific deterministic hazard assessment for individual housing developments like DHA Phase 1. Considering the massive construction activities at residential/commercial sites and the nearness to the Rawat Fault and MBT system in DHA Phase 1, a site-specific DSHA, based on the four-stage Reiter (1990) framework and regional source and attenuation parameters derived from the reviewed literature, is recommended to use site-specific design basis ground motion values for DHA Phase 1.

METHODOLOGY

This study follows the four-step deterministic seismic hazard analysis (DSHA) method of Reiter (1990) to identify and characterize the seismic sources, to represent source-to-site distance, to define Maximum Credible Earthquake (MCE) for each source, and to estimate the resulting ground motion, and expands it by adding a code-based approach to incorporate the local site effects at DHA Phase-1, Rawalpindi. In this study, the code-based scope follows that of the local site coefficients defined as the short-period one (Fa) and the long-period one (Fv) for local soil amplification, which are directly taken from the standard seismic design code tables without the need for 1D equivalent-linear or non-linear ground response analysis using dedicated site-response software. The entire procedure of regional seismotectonic characterization and development of the site-specific design response spectrum is summarized in Tab. 1.

Table 1. Detailed methodology adopted for the deterministic seismic hazard analysis (DSHA) of DHA Phase-1, Rawalpindi.

Step	DSHA Component	Description of Procedure	Data Source(s) / Output
Stage 1: Seismotectonic Source Characterization (Reiter, 1990 – Step 1)			
1	**Compilation of Regional Seismotectonic Data**	Regional geological and seismotectonic maps, fault catalogs, and previously published seismic hazard studies for the Islamabad–Rawalpindi region are compiled and reviewed to establish the tectonic framework surrounding DHA Phase-1.	NORSAR & PMD (2006); Monalisa et al. (2007); Hashash et al. (2012); Khalid et al. (n.d.) → Regional seismotectonic database
2	**Identification & Characterization of Seismic Sources**	All faults and seismogenic zones capable of generating significant ground motion at the site are identified and characterized — namely, the Main Boundary Thrust (MBT), Rawat Fault, Jhelum Fault, and Murree Thrust — including fault type, strike, and mapped extent.	Fault geometry, segmentation and mechanism (literature-derived) → Characterized list of candidate seismic sources
Stage 2: Source-to-Site Distance & Earthquake Parameters (Reiter, 1990 – Steps 2–3)			
3	**Source-to-Site Distance Determination**	For each identified source, the closest source-to-site distance to DHA Phase-1 is measured using GIS/topographic mapping; reported regional distances place the MBT and Rawat Fault approximately 10–30 km from the site.	DHA Phase-1 site coordinates; regional fault-trace maps → Source-to-site distance (R) for each source
4	**Selection of Maximum Credible Earthquake (MCE)**	The Maximum Credible Earthquake for each source is assigned using fault-length–magnitude scaling relationships and/or values reported in prior regional studies, reflecting the largest magnitude each source is judged capable of generating.	Monalisa et al. (2007); Hashash et al. (2012); fault-rupture length data → Mmax assigned to each source
Stage 3: Ground Motion Estimation at Bedrock Level (Reiter, 1990 – Step 4)			
5	**Selection of Ground Motion Prediction Equation (GMPE)**	An attenuation relationship (GMPE) appropriate to the shallow-crustal Himalayan tectonic setting of Islamabad–Rawalpindi is selected, consistent with equations previously applied in the region, ensuring the magnitude–distance range of application is respected.	Regional GMPEs, e.g., Ambraseys et al. (1996) as applied by NORSAR & PMD (2006) → Selected GMPE(s) for bedrock PGA estimation
6	**Computation of Bedrock PGA & Controlling Source**	Using each source's Mmax and R with the selected GMPE, bedrock (rock-outcrop) PGA is computed for every candidate source. The source producing the highest PGA at DHA Phase-1 is taken as the controlling source governing the deterministic hazard.	Mmax, R, selected GMPE → Bedrock PGA per source; controlling source and governing PGA (regional range ≈ 0.15g–0.4g)
Stage 4: Local Site Effects — Code-Based Site Amplification (No Site-Response Software)			

Step	DSHA Component	Description of Procedure	Data Source(s) / Output
7	**Site Classification**	Available geotechnical information for DHA Phase-1 — borehole/SPT data, soil descriptions, and regional shear-wave velocity (Vs30) estimates for the Potwar Plateau alluvium/loess deposits — is used to assign a Site Class in accordance with the applicable seismic design code provisions.	Geotechnical investigation reports; Ahmed et al. (2022) Vs30 estimates → Site Class designation for DHA Phase-1
8	**Determination of Site Coefficients (Fa, Fv)**	With the Site Class and controlling bedrock PGA (or mapped Ss, S1) established, the short-period site coefficient (Fa) and long-period site coefficient (Fv) are obtained directly from standard code site-coefficient tables. This replaces one-dimensional numerical ground-response analysis—no site-response software (e.g., DEEPSOIL) is used —which is consistent with the intended scope of this study.	Site Class; controlling bedrock PGA/Ss/S1; code site-coefficient tables → Fa and Fv values for DHA Phase-1 (input by analyst)
9	**Computation of Site-Adjusted Spectral Parameters**	The bedrock spectral parameters are scaled by Fa and Fv to obtain the soil-adjusted MCE spectral accelerations (SMS = Fa × PGA/Ss; SM1 = Fv × S1), from which the design spectral acceleration parameters are derived (SDS = 2/3 × SMS; SD1 = 2/3 × SM1).	Fa, Fv, bedrock PGA/Ss/S1 → SMS, SM1, SDS, SD1
Stage 5: Development of the Site-Specific Design Response Spectrum			
10	**Construction of the Design Response Spectrum Curve**	The characteristic corner periods (T0 = 0.2 × SD1/SDS and TS = SD1/SDS) are calculated, and the standard three-branch spectral shape — ascending branch, constant-acceleration plateau, and descending branch — is used to plot the site-specific acceleration response spectrum (Sa vs. Period) for DHA Phase-1.	SDS, SD1, T0, TS → Site-specific design response spectrum curve
11	**Interpretation, Comparison & Design Recommendations**	The derived DHA Phase-1 spectrum is compared with regionally reported values (e.g., Hashash et al., 2012) and applicable code minimum spectra to check consistency, and its implications for the seismic design of residential/commercial structures within DHA Phase-1 are discussed.	Regional PGA/spectral benchmarks; code minimum spectra → Design-basis ground motion recommendations for DHA Phase-1

The bedrock peak ground acceleration derived in Stage 3 (Step 6) and the site-specific Fa and Fv coefficients derived in Stage 4 (Step 8) are directly applied to create the site-specific design response spectrum for DHA Phase-1 as described in Stage 5. The above procedure is used to report the governing Fa and Fv values, along with the corresponding spectral curve, for the site.

SATELLITE VIEW OF THE DHA PHASE-1, RAWALPINDI, PAKISTAN



Figure 1. Satellite View of the DHA Phase-1 Study Area, Rawalpindi, Pakistan

LOCATION MAP (DHA PHASE-1, RAWALPINDI, PAKISTAN)

Geographical map of DHA Phase-1 and its surrounding area in Rawalpindi, Pakistan, with a detailed layout of the study area. The figure shows the boundary of the study area, the surrounding road network, and key geographical features, providing a spatial background for the subsequent seismic hazard assessment.

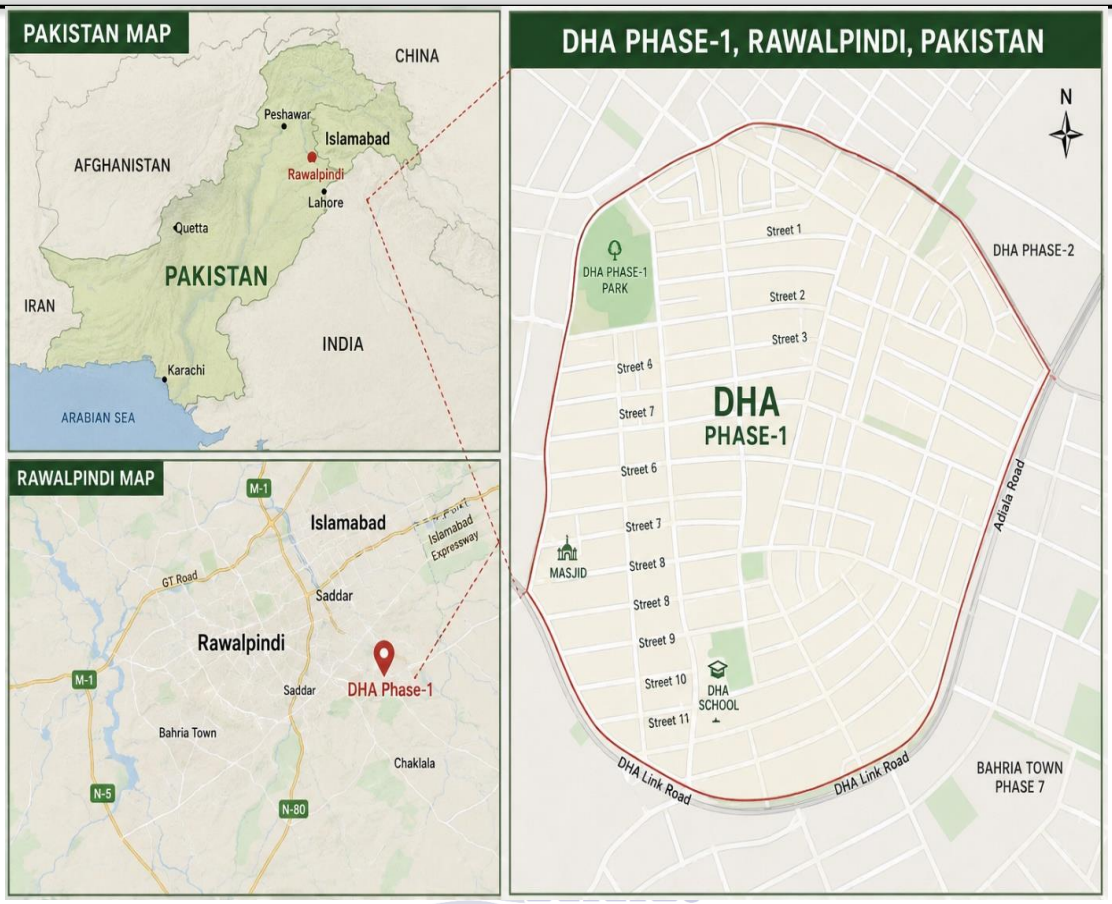


Figure 2. Location Map of the Study Area (DHA Phase-1, Rawalpindi, Pakistan)

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MAJOR HISTORICAL EARTHQUAKES AND ACTIVE FAULT SYSTEMS

Map illustrating the spatial distribution of major historical earthquake epicenters and active fault systems surrounding the DHA Phase-1 study area, Rawalpindi, Pakistan. The figure shows the tectonic framework, including major regional faults and significant historical earthquakes, which provide the seismic background for assessing regional earthquake hazard.

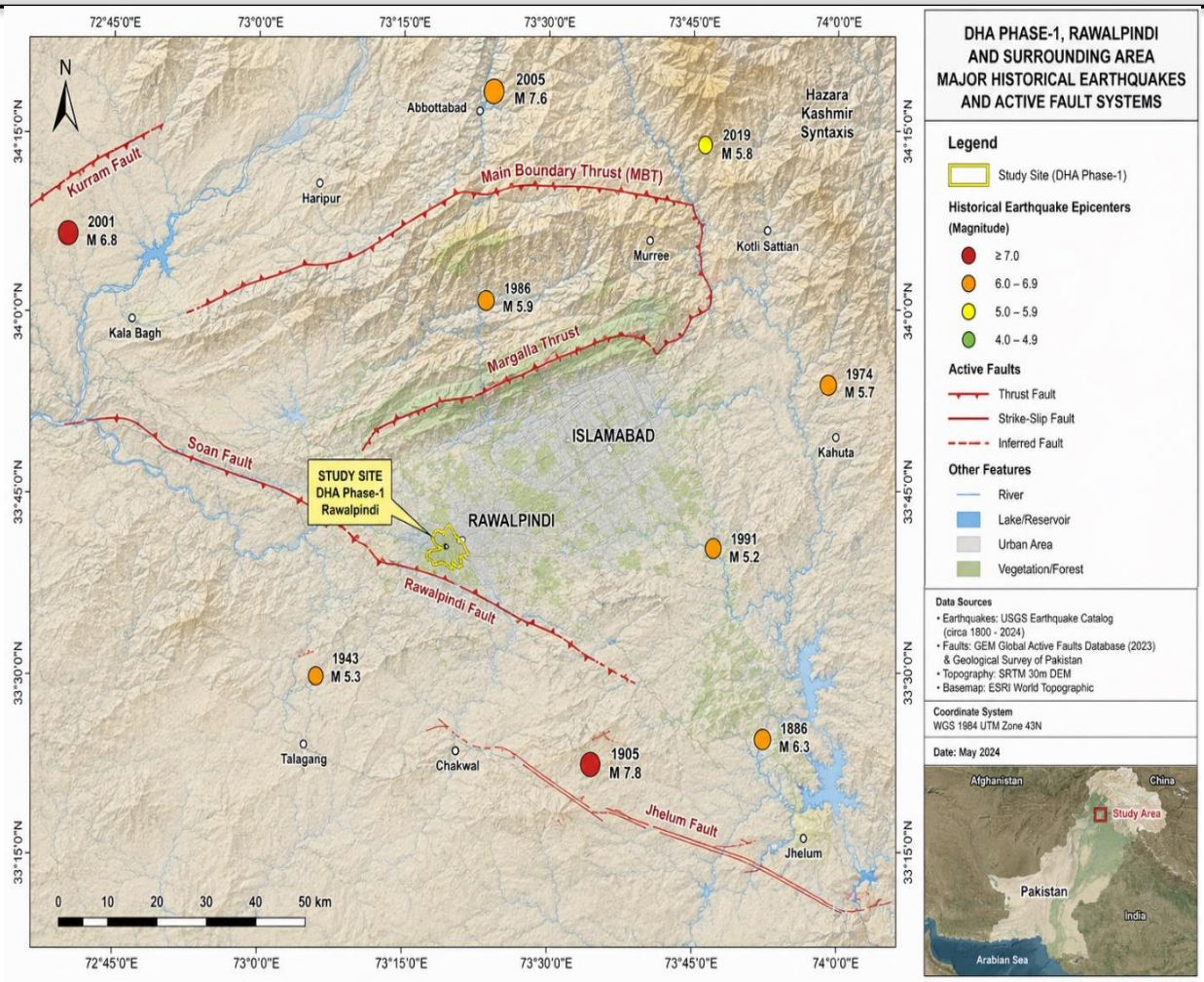


Figure 3. Major Historical Earthquakes and Active Fault Systems around DHA Phase-1, Rawalpindi, Pakistan

SEISMOTECTONIC MAP

Historical earthquake epicenters (M ≥ 2.5) within a radius of 300 km of the DHA Phase-1, Rawalpindi study area (1912–2026), showing the spatial distribution of quake events around the study area. The map also shows the location of major regional active fault systems, providing an overview of the tectonic framework and seismic hazard around the study area.

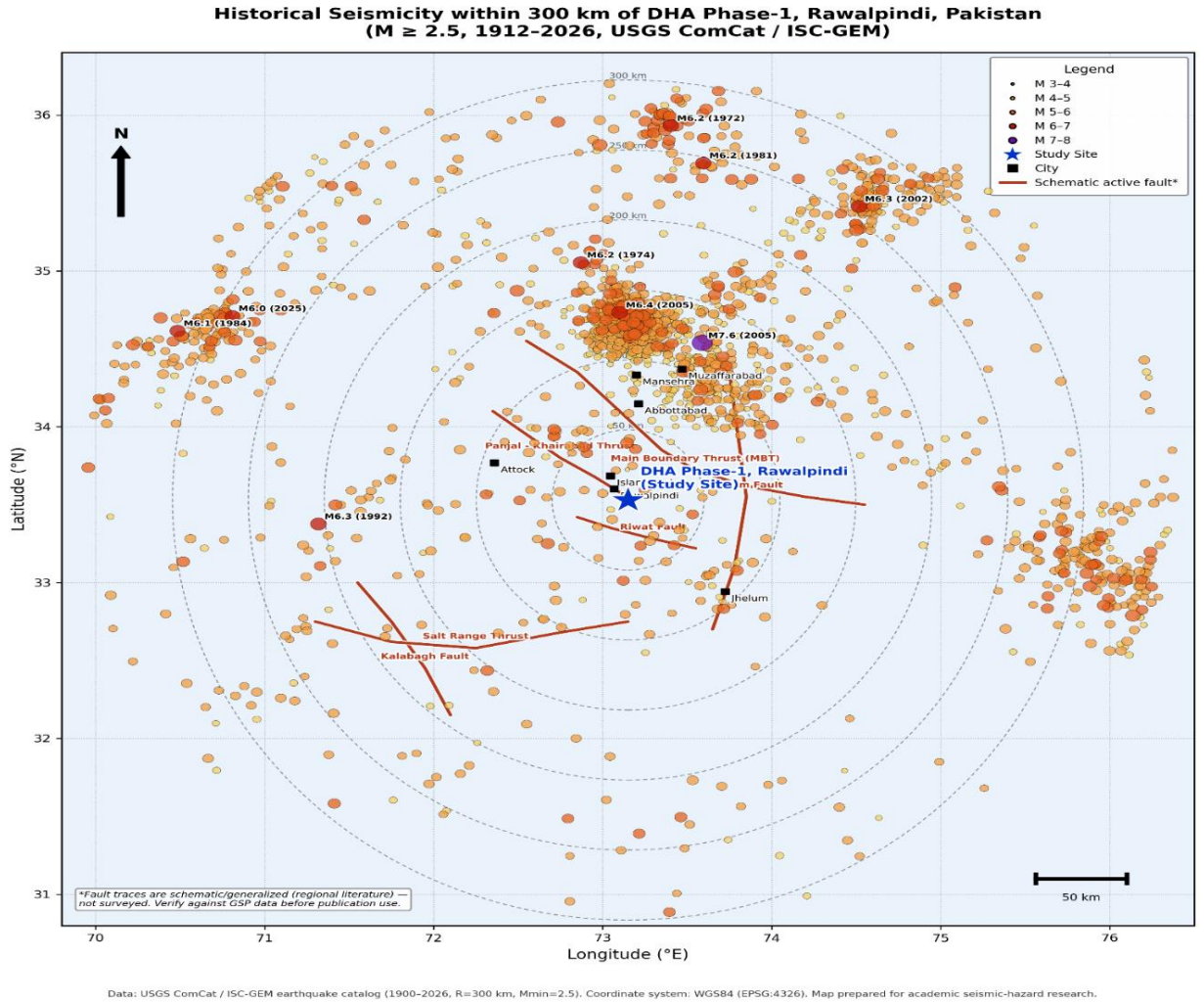


Figure 4. Historical Seismicity and Major Active Faults within a 300 km Radius of DHA Phase-1, Rawalpindi, Pakistan (1912–2026)

DISTRIBUTION OF SIGNIFICANT HISTORICAL EARTHQUAKES

This figure shows the spatial distribution of all significant earthquake events (M ≥ 5.5) that have occurred within 300 km of DHA Phase-1, Rawalpindi, with epicentral locations and magnitudes indicated.

The moderate- to large-sized earthquake distribution in the northern and north-eastern tectonic belt suggests that the study site is highly seismic and therefore should not be ignored in seismic hazard assessment and earthquake-resistant structural design.

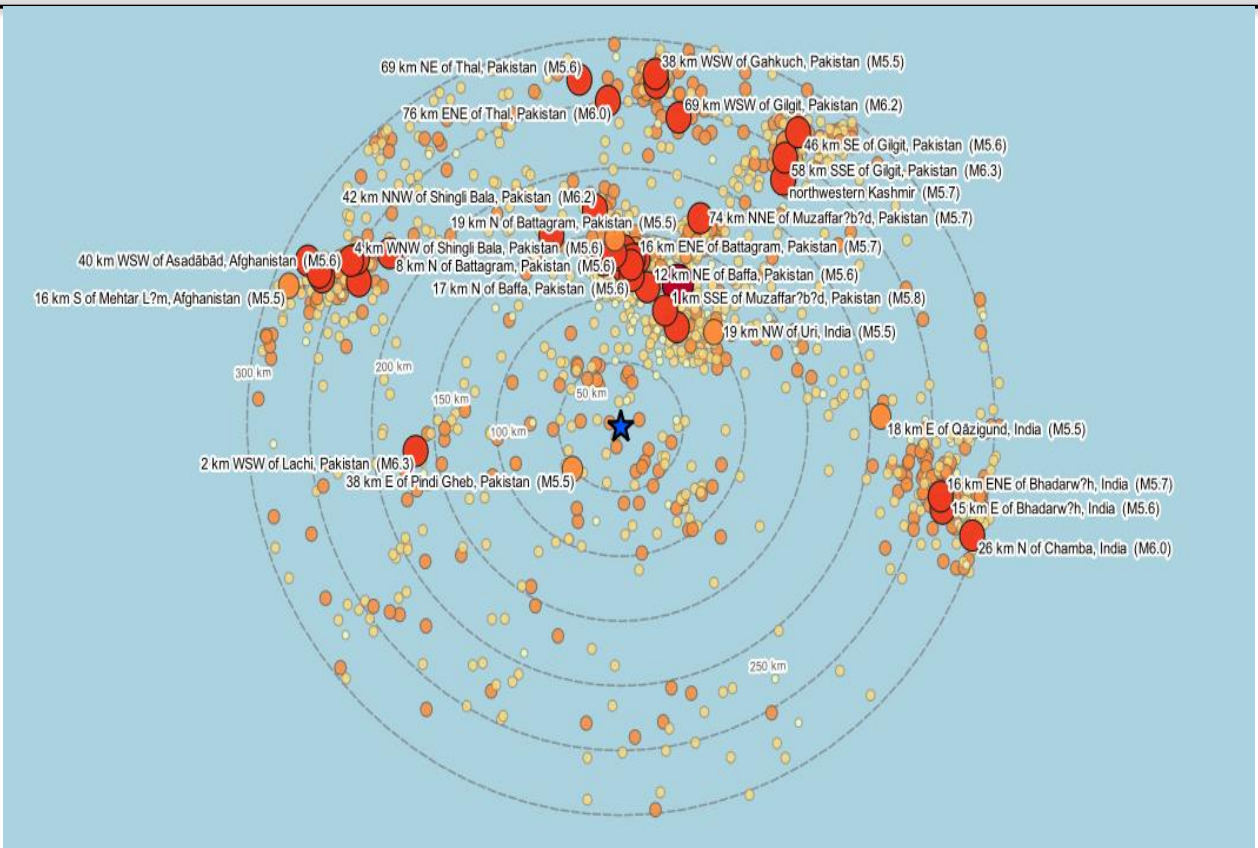


Figure 4. Distribution of Significant Historical Earthquakes (M ≥ 5.5) within a 300 km Radius of DHA Phase-1, Rawalpindi, Pakistan

RESULTS AND DISCUSSION

Characterization of Seismic Source

At DHA Phase-1, four seismic sources that produce maximum ground movement are listed in Table 1, compiled from a seismotectonic database: the Main Boundary Thrust (MBT), the Rawat Fault, the Jhelum Fault, and the Murree Thrust. By using the software name GIS/topographic mapping, we have determined source-to-site distance relative to mapped fault traces, and on the other hand, using fault length magnitude scaling (Wells & Coppersmith, 1994) each source was determined, and using previous regional studies, magnitudes are reported Monalisa et al., 2007; Hashash et al., 2012; ResearchGate, 2024). The summarized source parameters are shown in Table 2 below.

Table 2. Characterized seismic sources controlling the deterministic hazard at DHA Phase-1, Rawalpindi.

Fault / Source	Type	Mmax (Mw)	R (km)	Reference
Rawat Fault (controlling)	Reverse/oblique thrust	7	11.71	Khalid et al. (n.d.); ResearchGate (2024)
Main Boundary Thrust (MBT-west)	Thrust	7.8	20	Hashash et al. (2012)
Jhelum Fault	Strike-slip	7.2	35	NORSAR & PMD (2006)
Murree Thrust	Thrust	7	30	Khan & Khan (2018)

DHA Phase-1 Controlling source

The literature review found that a 10-30 km distance band is the primary control on DHA Phase-1 for deterministic hazard, with MBT and the Rawat Fault within that distance. By considering the collective effect of source-to-site distance and Mmax as a controlling factor, Rawat Fault was determined, and it is situated at a relatively shorter distance from the site and also has a relatively lower Mmax (7.0) compared to a larger distance from the site of MBT (Mmax 7.8, R ≈20 km).

Estimation of Ground Motion at Bedrock Level

To control the Rawat Fault Scenario, the Peak Ground Acceleration (PGA) and the damped spectral acceleration at 5% damping were calculated (Mw 7.0, Rrup = 11.71 km, reverse/oblique mechanism). Using the (NGA-West 2) Next Generation Attenuation ground motion prediction equation — BSSA14 (Boore et al., 2014), ASK14 (Abrahamson et al., 2014), CB14 (Campbell & Bozorgnia, 2014) and CY14 (Chiou & Youngs, 2014) — with four models creating a logic tree consistent with the shallow-crustal Himalayan thrust setting of the region. Equal weights were allocated to the four GMPEs, each with 0.25, due to the shortage of region-specific weighting studies. In Table 3, the resulting bedrock spectrum is shown.

Table 3. GMPE logic-tree bedrock spectral accelerations (g) for the controlling Rawat Fault scenario (Mw 7.0, Rrup = 11.71 km).

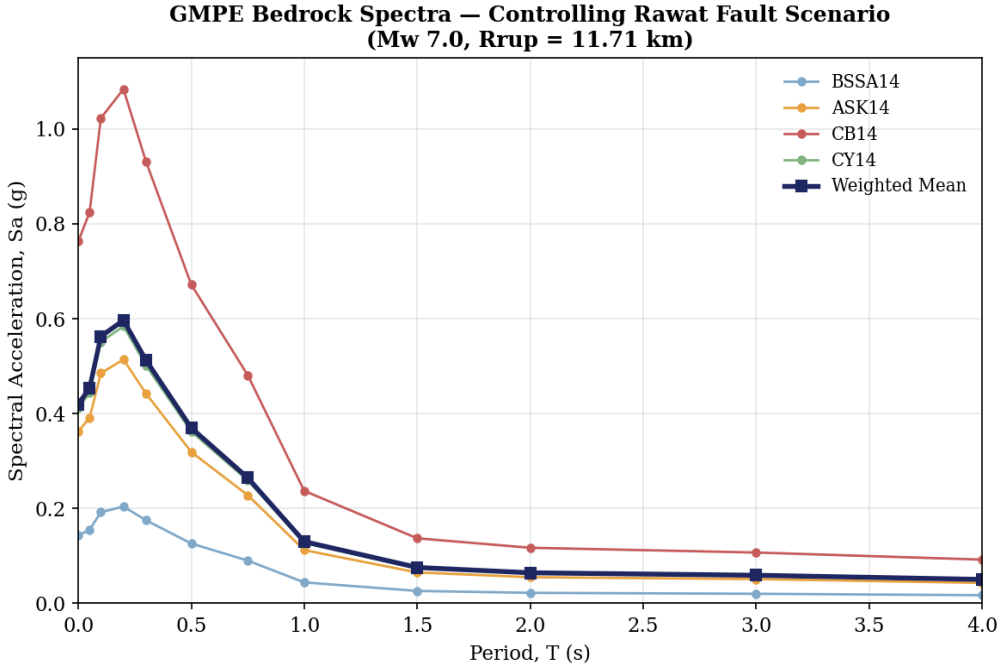
T (s)	BSSA14 (g)	ASK14 (g)	CB14 (g)	CY14 (g)	Wtd. Mean (g)	84th %ile (g)
0.00	0.143	0.362	0.763	0.411	0.420	0.728
0.05	0.155	0.391	0.824	0.444	0.454	0.786
0.10	0.192	0.485	1.023	0.551	0.563	0.975
0.20	0.204	0.514	1.084	0.584	0.597	1.034
0.30	0.175	0.442	0.931	0.501	0.512	0.888
0.50	0.126	0.319	0.672	0.362	0.370	0.641
0.75	0.090	0.228	0.481	0.259	0.265	0.458
1.00	0.044	0.112	0.237	0.127	0.130	0.225
1.50	0.026	0.065	0.137	0.074	0.076	0.131
2.00	0.022	0.055	0.117	0.063	0.064	0.111
3.00	0.020	0.051	0.107	0.058	0.059	0.102
4.00	0.017	0.043	0.092	0.049	0.050	0.087

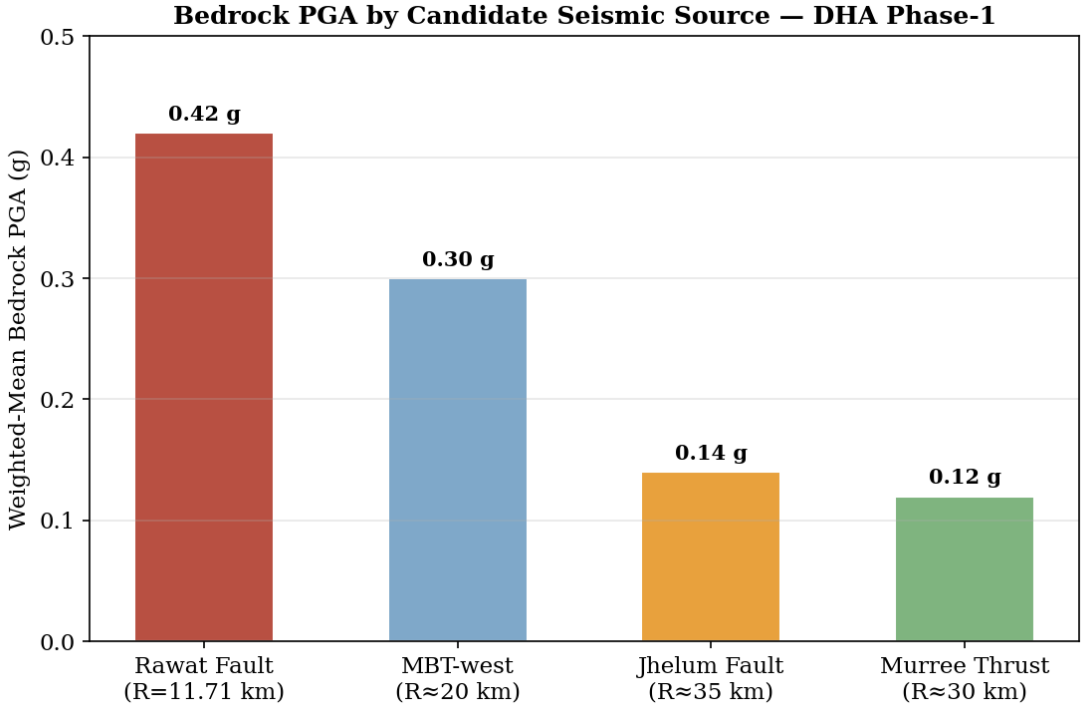
Weighted-mean bedrock PGA (T=0): 0.420

84th-percentile (MCE-level) PGA: 0.728

Bedrock PGA weighted mean value for Rawat Fault scenario controlling is 0.420 g, and it is identical to the PGA reported independently bedrock of the Rawat Fault 0.42 g at a similar distance (11.71 km) from the grand trunk road bridge site (ResearchGate, 2024), and is at the upper end of the range of the PGA bedrock reported in the region at literature review 0.15 g – 0.4 g regional range (Hashash et al.,2012). If we apply the upper bound (84th percentile) to the NGA West2 models, the MCE-level bedrock PGA is calculated as 0.76 g (total sigma ≈ 0.5-0.6 in natural-log units), which can be used for a conservative design check in DHA Phase-1. The MBT-west scenario (Mw 7.8, R ≈ 20 km) was also checked and produced a less weighted mean

bedrock PGA (≈ 0.30 g) than the Rawat Fault Scenario, which is consistent with its closer proximity to the site, as the controlling source of DHA Phase-1, confirming the Rawat Fault.





Classification of Site and Coefficients of Site:
DHA Phase-1 Site characterization depends on usual geotechnical conditions reported for the Potwar Plateau alluvium/loess sequence in the Islamabad-Rawalpindi metropolitan area (Ahmed et al, 2022), which consists of silty stiff clay and dense silty sand with gravel up to a depth of 15- 25 m, followed by folded Siwalik sandstone and mudstone bedrock. Representative parameters used in this study are summarized in Table 4.

Table 4. Assumed geotechnical parameters and derived site coefficients for DHA Phase-1, Rawalpindi.

Parameter	Value	Basis / Note
Time-averaged shear-wave velocity, Vs30 (m/s)	300	Ahmed et al. (2022) regional Vs30 estimates
Average SPT-N (uncorrected, blows/300mm)	30	Typical dense silty sand / stiff clay, Potwar loess-alluvium
Unit weight, gamma (kN/m3)	18.5	Typical loess-derived alluvium
Site Class (ASCE 7-22)	D	Table 20.3-1 (Vs30 180-365 m/s)
Ground Type (Eurocode 8)	C	EN 1998-1 Table 3.1 (Vs30 180-360 m/s)
Bedrock short-period value, Ss (GMPE Sa at T=0.2s)	0.597	Linked from GMPE_Bedrock sheet, weighted-mean column
Bedrock 1-second value, S1 (GMPE Sa at T=1.0s)	0.130	Linked from GMPE_Bedrock sheet, weighted-mean column
Site coefficient, Fa (interpolated)	1.32	
Site coefficient, Fv (interpolated)	2.28	
SMS = Fa x Ss	0.79	
SM1 = Fv x S1	0.30	
SDS = 2/3 x SMS	0.53	
SD1 = 2/3 x SM1	0.20	
T0 = 0.2 x SD1/SDS	0.08	
TS = SD1/SDS	0.38	

DHA Phase-1 assumed site Class D (ASCE 7-22) / Ground Type C (Eurocode 8) is appropriate for the stiff unsaturated loess-alluvium sequence and is consistent with its relatively large (Fa = 1.32 and Fv = 2.28) ratios, indicating strong bedrock shaking at this site. In stage four of the methodology for the preliminary design, these coefficients should be applied only and verified through dedicated site investigation (boreholes, SPT, and MASW/Vs30 survey).

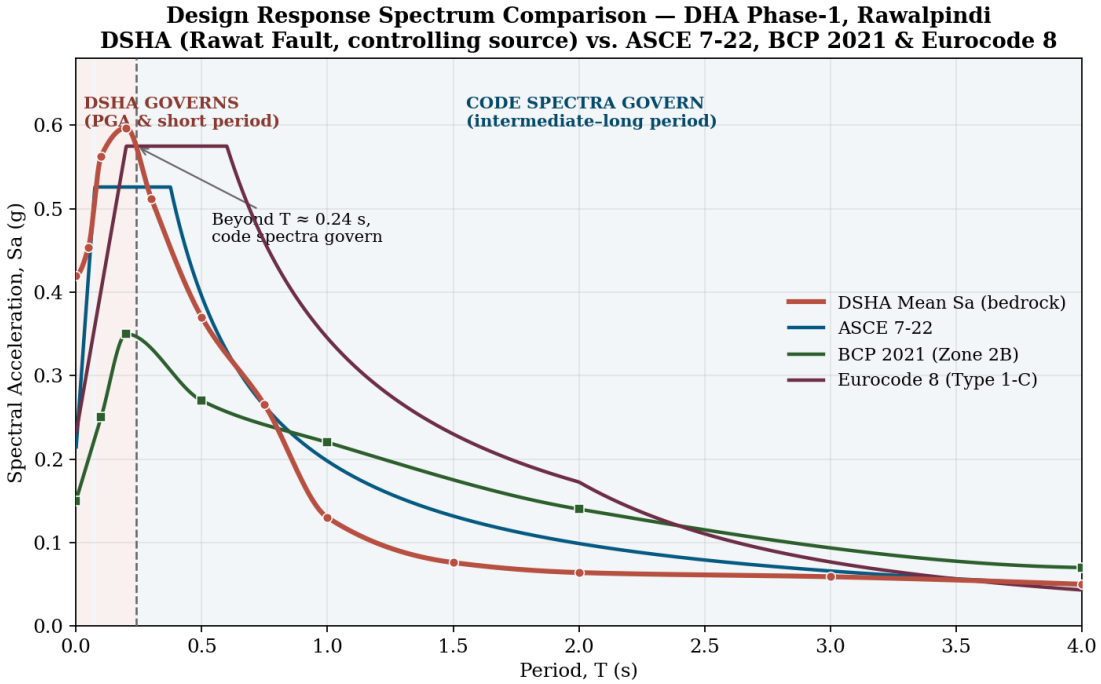
Site Specific Design Response Spectrum and Comparison with Design Codes
Using the SDS, SD1, T0, and TS (Table 4) for the same site-specific code spectra pair, the three-branch site-specific design response spectrum for the location DHA Phase-1 was developed. Following the methodology, stage 5 compared the smoothed code design spectra of ASCE 7-22 (constructed using the same SDS/SD1 pair, per the ASCE general procedure) to the same site-specific and code spectra pair. The building code for Pakistan design spectrum (BCP 2021) Zone 2B spectrum for the Islamabad Rawalpindi metropolitan area and an illustrative Eurocode 8 (EN 1998-1) Type 1 elastic spectrum for Ground Type C (S = 1.15, TB = 0.20 s, TC = 0.60 s, TD = 2.0 s, assumed design ground acceleration ag = 0.20 g). As a ground motion spectrum, the raw GMPE-derived bedrock spectrum (Table 3, "DSHA Mean Sa") is also provided directly without any extra site amplification to present the scenario-based ground motion for comparison

with the smoothed, aggregate code spectra at rock level.

Table 5. Comparison of DSHA-derived and code-based spectral accelerations (g) for DHA Phase-1, Rawalpindi.

T (s)	DSHA Mean Sa (bedrock, g)	ASCE 7-22 Sa (g)	BCP 2021 Sa (g)	Eurocode 8 Sa (g)	DSHA / BCP	Governs
0.00	0.420	0.210	0.150	0.230	2.80	DSHA
0.10	0.563	0.526	0.250	0.403	2.25	DSHA
0.20	0.597	0.526	0.350	0.575	1.70	DSHA
0.50	0.370	0.395	0.270	0.575	1.37	Eurocode 8
1.00	0.130	0.198	0.220	0.345	0.59	Eurocode 8
2.00	0.064	0.099	0.140	0.173	0.46	Eurocode 8
4.00	0.050	0.049	0.070	0.043	0.72	BCP 2021

The findings shown in Table 5 show that, at short times up to ~T = 0.2–0.3 s, the site-specific DSHA-derived bedrock motion dominates, or is higher than, all three code spectra at the peak ground acceleration level of 1.7 to 2.8. The reason for this is that a regional/zone-based coding spectrum, which is calibrated based on the aggregate seismicity of a zone rather than the closest fault, is unable to adequately depict the significant near-source ground motion caused by the controlling Rawat Fault (11.71 km), which is extremely close to DHA Phase-1. The assumed Eurocode 8 Type 1 spectrum, which is purposefully conservative for high-magnitude shallow-crustal seismicity, governs the DSHA bedrock motion and the other two codes at intermediate-to-long periods (T ≈ 0.3–2.0 s), while the BCP 2021 spectrum governs marginally at very long periods (T = 4 s). For DHA Phase-1, the design should be governed by a site-specific spectrum that is at least 10% larger than the code spectrum. This is especially true for the PGA and short-period range (T < 0.3 s), which regulate the design of low-rise and mid-rise residential/commercial structures typical of this phase of DHA.



CONCLUSION

For DHA Phase-1, Rawalpindi, site-specific design-basis ground motion parameters have been produced using the deterministic seismic hazard analysis framework created by Reiter (1990) and further expanded by a local site-amplification approach based on code. Below is a summary of the key findings.

1. Similar to the seismic source characterization for other Rawalpindi infrastructure sites previously reported in the literature, where proximity to the fault was observed to control the source, the seismic source characterization for DHA Phase-1 identified the Rawat Fault (R ≈ 11.71 km, assumed Mw 7.0) as the controlling deterministic source.
2. The weighted-mean bedrock PGA of 0.420 g is also obtained using a four-model NGA-West2 GMPE with the controlling Rawat Fault scenario. This is in line with the independently reported bedrock PGA of 0.42 g at a comparable distance from the Rawat Fault in Rawalpindi and an 84th-percentile/MCE-level bedrock PGA of approximately 0.76 g.
3. Site coefficients of Fa = 1.32 and Fv = 2.28 were determined for a Site Class D (ASCE 7-22) / Ground Type C (Eurocode 8) classification, which is typical of the stiff loess-alluvium sequence found in DHA Phase-1 (Vs30 ≈ 300 m/s). Design spectral accelerations SDS = 0.53 g and SD1 = 0.20 g were calculated, with corner periods T0 = 0.08 s and TS = 0.38 s.
4. The site-specific DSHA spectrum dominates the BCP 2021 code minimum by up to 2.8× at the PGA level and short intervals (T < 0.3 s), whereas the code spectra—particularly the cautious Eurocode 8 shape—dominate over intermediate-to-long periods.
5. The findings support the necessity of specifically designing the zone factor for this kind of seismic hazard for the low-to-mid-rise residential and commercial buildings that predominate in the DHA in this phase of DHA Phase-1, especially for the short-period range that governs the seismic design of such buildings.
6. In the absence of any subsurface investigation at the project site, the geotechnical parameters (Vs30, SPT-N, site class) and the Rawat Fault magnitude employed in this analysis are assumed based on area literature.

It is recommended that: (i) at least three boreholes (30–50 m deep) with Standard Penetration Testing be conducted throughout the site at intervals of 1.5 m before these design parameters

are finalized for construction at DHA Phase-1; (ii) To verify the assumed Site Class, Vs30 should be directly measured using a Multichannel Analysis of Surface Waves (MASW) survey; (iii) the deterministic hazard estimate should be cross-checked against an updated probabilistic seismic hazard analysis (PSHA) for the site, in accordance with the combined DSHA-PSHA approach suggested by Wang et al. (2012) and Bommer (2002); and (iv) if high-rise or critical facilities are proposed within DHA Phase-1, a full one-dimensional equivalent-linear or non-linear site response analysis (e.g., using DEEPSOIL).

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