

## DETERMINISTIC SEISMIC HAZARD ANALYSIS FOR WAH CANTT, PAKISTAN: A SITE-SPECIFIC ASSESSMENT

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**Abstract**

Seismic hazard assessment is essential for the safe design of strategic infrastructure in tectonically active regions. This paper presents a site-specific deterministic seismic hazard analysis (DSHA) for Wah Cantt, Pakistan (33.77° N, 72.75° E), with emphasis on the Main Boundary Thrust (MBT) as the controlling seismic source. The analysis considers active fault systems within approximately 100 km of the site. It estimates the median horizontal peak ground acceleration (PGA) using the Boore and Atkinson (2008) ground-motion prediction equation (GMPE) under reference-rock conditions ( $V_{s, 30} = 760$  m/s). The MBT is identified as the governing source due to its proximity and a maximum credible magnitude of Mw 8.1. The resulting median PGA of 0.267g exceeds the upper limit of Seismic Zone 2B in the Building Code of Pakistan (BCP 2007), indicating that generalized zoning may understate near-source hazard at strategic facilities. A 5%-damped site-specific response spectrum is also presented, with peak spectral acceleration of 0.452g at  $T = 0.15$ s.

**Keywords-** Deterministic Seismic Hazard Analysis, Main Boundary Thrust, Peak Ground Acceleration, Response Spectrum.

**1. INTRODUCTION**

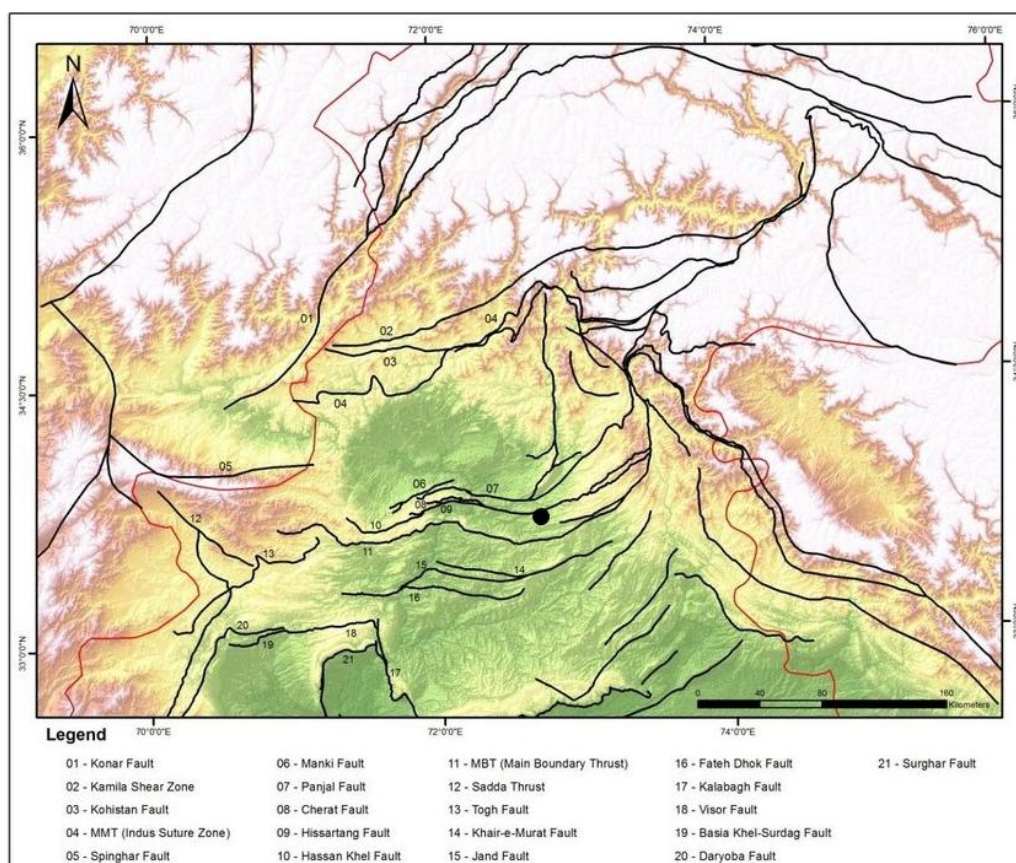
Pakistan is one of the most seismically active countries in South Asia, which lies along the converging plate boundary between the Indian plate and the Eurasian plate. The ongoing plate convergence is manifested in the northern part of Pakistan as a series of major active thrust faults, such as the Main Boundary Thrust (MBT), Panjal Thrust, Himalayan Frontal Thrust (HFT), and the Salt Range Thrust (SRT). Wah Cantt, which is in the Potwar Plateau region, about 35 km

north-west of Islamabad, is in the tectonically active zone where the seismic hazard is controlled by both the regional plate kinematics and the close proximity of the individual fault structures [1], [6]. While a code-based seismic zoning offers an important minimum exposure measure for design, it is a spatially averaged hazard as opposed to the shaking of a specific scenario involving a nearby active fault. A deterministic approach is more suitable for critical or strategic infrastructure, and it considers the maximum

credible earthquake (MCE) that is likely to occur on the most critical source and gives a physically-bounded ground motion parameter that can be used in structural design. This paper therefore follows the following 4-step DSHA procedure, with MBT as a governing source, and compares the resulting PGA with the zoning values provided by BCP 2007 for Wah Cantt [3], [4].

Wah Cantt is located in the front-end compressional zone of the Himalayan orogen, called the Potwar Fold-and-Thrust Belt. The belt is limited to the north by the MBT and to the south by the Salt Range Thrust, Panjal Thrust is at a similar distance to the north, while the HFT and SRT are further away but with

within which there are many subsidiary thrusts and related folds that continue to accommodate the ongoing north-south crustal shortening [6]. The most important of the existing structures within the area is the MBT. It is one of the major crustal-scale reverse faults along the boundary of the sub-Himalayan fold-thrust belt and the Lesser Himalayas, dipping steeply northward, and has produced large magnitude thrust earthquakes during the Quaternary. Jan and MonaLisa [2] record their activity and seismogenic potential in particular for the Islamabad-Wah segment. The faults in the region, and the circle marks the site.



high potential for large magnitudes. The Salt Range Thrust is the farthest of the four considered, at ~113 km to the south. All four faults are reverse or thrust faults, in keeping with the compressional tectonic regime [6], [7]. Figure 1 indicates the tectonic map of northern Pakistan and NE Afghanistan and major

Figure 1: Tectonic map of northern Pakistan and NE Afghanistan showing major regional faults [8]

#### METHODOLOGY

This investigation is based on the well-known four-step DSHA method by Reiter (1990), as adopted in later practice [8].

3.1. **Source Identification**

The published geological maps, fault databases, and regional seismicity catalogues were used to identify all active or potentially active seismic sources within about 100 km of Wah Cantt. Four major thrust faults were chosen, namely MBT, Panjal Thrust, HFT and SRT.

3.2. **Distance Estimation**

Site-to-source distances were measured as the shortest horizontal distance from the site to the surface projection of each fault rupture plane, expressed as the Joyner-Boore distance RJB. This metric is the appropriate distance measure for the Boore and Atkinson (2008) GMPE and characterizes the near-field ground-motion environment correctly for shallow thrust events.

3.3. **Controlling Earthquake Selection**

Site-to-source distances were calculated as the minimum horizontal distance between the site and the surface projection of the rupture plane of each fault (Joyner-Boore distance RJB). For shallow thrust events, this is the proper distance measure for the Boore and Atkinson (2008) GMPE and represents the near-field environment for ground motions properly.

4. **Ground-Motion Estimation**

Median horizontal PGA and 5%-damped spectral accelerations were determined with the aid of the GMPE for active shallow crust earthquakes proposed by Boore and Atkinson (2008). The reference-rock site conditions were assumed as  $V_{s, 30} = 760$  m/s (time-averaged shear-wave velocity to 30 m depth) [1],[11]. The GMPE form is:

$$\ln \text{PGA} = \text{MS} (M_w) + \text{DS} (\text{RJB}, M_w) + \text{SF}(V_{s30}) \tag{1}$$

where MS is referred as the magnitude-scaling term, DS is referred as the distance-scaling and attenuating term, and SF is referred as the site-amplification term. If the reference rock conditions are used, then FS = 0, and the calculation is simplified. The regression coefficients listed in Table 3 are used.

SOURCE INVENTORY

Table 1 details the four seismogenic sources that have been considered for Wah Cantt, which comprise their fault mechanism, their mapped length, site distance, and their maximum moment magnitude [8], [10].

TABLE 1. Seismogenic Sources Considered for Wah Cantt

Fault System	Mechanism	Mapped Length (km)	R <sub>JB</sub> (km)	Max Mw	Role in Hazard
Main Boundary Thrust (MBT)	Reverse/thrust	381	16	8.1	Controlling source
Panjal Thrust	Reverse/thrust	195	17	7.7	Secondary source
Himalayan Frontal Thrust (HFT)	Reverse/thrust	417	97	8.1	Regional source
Salt Range Thrust (SRT)	Reverse/thrust	245	113	7.8	Distant source

The maximum magnitude potential (M<sub>w</sub>) of the MBT Panjal Thrust is 8.1 and 7.7, respectively, but the two are at almost equal distances from Wah Cantt (16 km and 17 km, respectively). The HFT is also assigned M<sub>w</sub> 8.1, but it is also located at almost 6 times the distance, thus resulting in a much lower ground motion at the

site. The PGA generated by the SRT is quite small at a distance of 113 km from the site.

GROUND-MOTION MODEL

The Boore and Atkinson (2008) GMPE was chosen for this analysis under the criteria recommended by Cotton et al. (2006) [9] for deterministic seismic

hazard studies. Table 2 summarizes the important considerations for choosing this model which shows criterion and the reason for suitability.

TABLE 2. Criteria for Selecting the Boore and Atkinson (2008) GMPE

Criterion	Reason for Suitability
Tectonic environment	Developed for active shallow-crust faulting – appropriate for the Himalayan thrust environment
Magnitude range	Applicable to Mw 7.7–8.1 events; regression domain covers the MBT scenario
Distance range	Covers Joyner-Boore distances from a few km to several hundred km
Site characterization	Explicit $V_{s, 30}$ scaling term; reference-rock condition ( $V_{s, 30} = 760$ m/s) is the natural baseline
Strong-motion database	Grounded in the PEER NGA-West1 database of recorded strong-motion accelerograms
Fault mechanism	Includes a reverse-slip flag term; MBT is a pure reverse/thrust fault.

Note that for events with a magnitude  $M_w \geq M_h$  (the hinge magnitude), the  $e_7$  saturation coefficient is zero. This is the case in the MBT scenario at  $M_w 8.1$ , and  $e_7$  will not contribute to the magnitude-scaling sum. This is the normal behavior of this formulation of

BA2008 and does not signify a missing coefficient. Table 3 shows the coefficients and their values which are being used in BA 2008 GMPE for calculation of PGA.

TABLE 3 Boore and Atkinson (2008) Regression Coefficients Used for PGA

Parameter	Term	Coefficient ID	Value
Magnitude scaling	FM	$e_4$ (reverse-slip flag)	-0.50970
Magnitude saturation	FM	$e_7$ (saturation; = 0 for $M_w \geq M_h$ )	0.00000
Distance decay (intercept)	FD	$c_1$	-0.66050
Distance scaling (linear)	FD	$c_2$	+0.11970
Anelastic attenuation	FD	$c_3$	-0.01151
Pseudo-depth	FD	$h$ (km)	1.35

6. RESULTS

The deterministic hazard evaluation matrix for each of the 4 candidate sources is shown in Table 4. The

natural logarithm of the median PGA is then  $\ln(\text{PGA}) = -1.3203 \ln g$  for  $M_w = 8.1$  and  $RJB = 16$  km, the median horizontal PGA being 0.267g at the conditions at reference rock.

TABLE 4 Deterministic Hazard Evaluation Matrix

Fault Source	Mw	RJB (km)	ln (PGA) [ln g]	Median PGA (g)
MBT	8.1	16	-1.3203	0.267
Panjal Thrust	7.7	17	-1.4814	0.227
HFT	8.1	97	-2.6651	0.069
SRT	7.8	113	-3.0537	0.047

Figure 2 shows the curve of PGA vs Distance and the controlling source, which is MBT with a PGA value of 0.267g at a distance of 16km from the site.

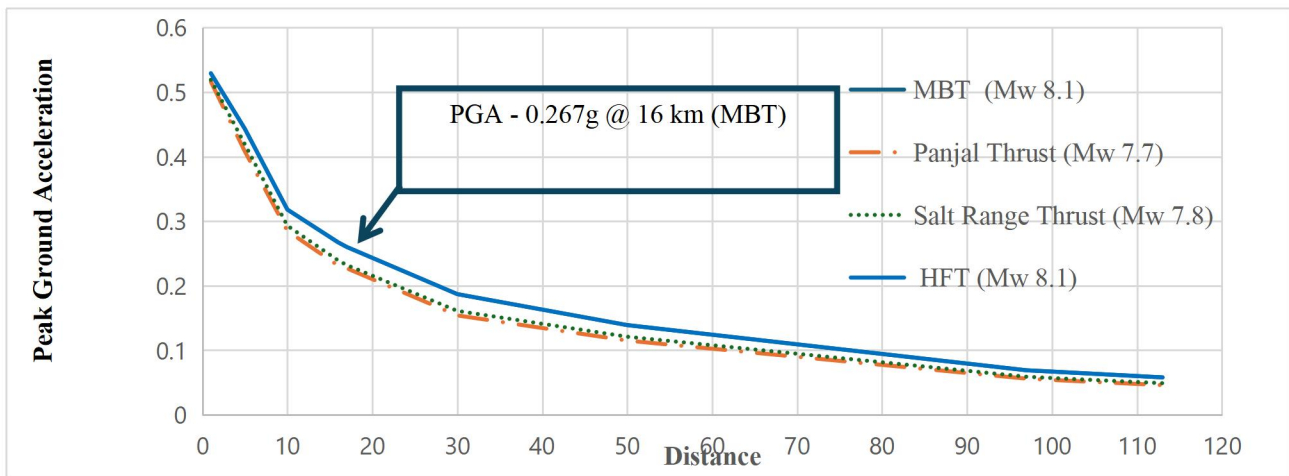


Figure 2: PGA vs Distance Curve showing controlling source

Although the HFT has an equal maximum magnitude, the MBT is confirmed as the controlling source due to the higher PGA at the site. The near-source distance of just 16 km is key: Under the influence of attenuation, the contribution of the HFT's is reduced to about 1/4 of MBT's value, or 0.069g. This is a result that suggests Wah Cantt is subject to a ground shaking that is greater than the top limits for BCP 2007 Zone 2B as

described in Section 8.

RESPONSE SPECTRUM

The spectrum of deterministic responses was evaluated for the controlling MBT scenario for the Boore and Atkinson (2008) GMPE at 0.0 s (PGA) to 1.0 s spectral period. Table 5 represents the 5 % damped response spectrum of MBT with Mw 8.1 and RJB 16 km, along with the corresponding period.

TABLE 5 5%-Damped Response Spectrum (MBT Scenario, Mw 8.1, RJB = 16 km)

Period T (s)	Sa (g), 5% damping
0.00	0.267
0.05	0.380
0.10	0.430

0.15	0.452 (peak)
0.20	0.420
0.25	0.380
0.30	0.340
0.40	0.270
0.50	0.220
0.75	0.150
1.00	0.110

The peak value of the spectrum is at  $T = 0.15$  s, with  $S_a = 0.452g$ , which is about 1.7 times the PGA value. For the short period range ( $T = 0.05$  s to 0.30 s), the fundamental periods of unreinforced masonry and reinforced concrete structures, typical of the low-rise structures of the Wah Cantt region and the rest of the Potwar area, have elevated spectral demand values. This is significant for two to five story buildings, which

are most sensitive to shaking during this period band. At longer time scales ( $T > 0.5$  s), demand drops off considerably, making taller and more flexible structures less hazardous than low-rise buildings. Deterministic response spectrum with 5% damping against Period plot is shown in Figure 3, which also presents a comparison between  $S_a$  and BCP 2007.

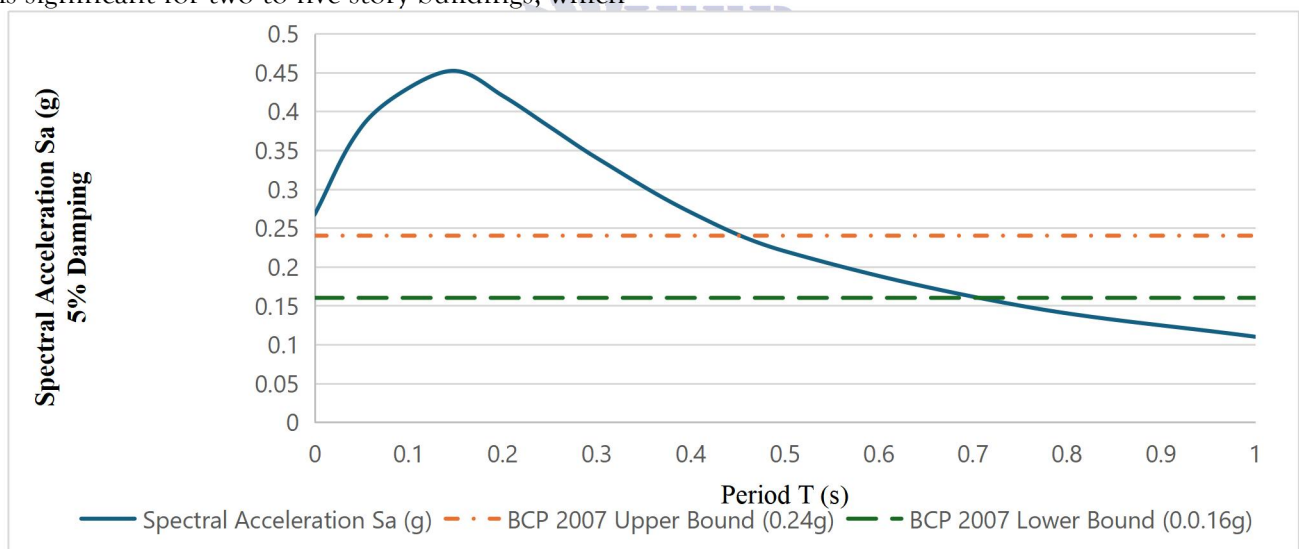


Figure 3: Deterministic response spectrum plotted against Period

8. COMPARISON WITH CODE ZONING

BCP 2007 adopted seismic zonation based on PGA values for the country, while BCP 2021 moved towards a parameter-based seismic design approach and did not keep the same seismic zone format as BCP 2007. Within the BCP 2021 seismic design framework

based on design parameters, the result of this study indicates that the seismic demand at near source is high enough to warrant site-specific seismic design input for Wah Cantt, rather than general regional seismic interpretation. The identified controlling fault and resulting response spectrum have shown that the local hazard is more intense at short periods, so the

proposed spectrum is applicable for seismic design of structures in the local area [12]. According to the BCP 2007, the Seismic Zone 2B falls within the EPA range of 0.16g to 0.24g and is for Wah Cantt [4], [5]. The

DSHA result (0.267g) was 0.027g above the upper bound of Zone 2B (0.240g) and 11.25% exceedance. This comparison is summarized in Table 6.

TABLE 6 Comparison of DSHA Result with BCP 2007 Code Zoning

Design Standard / Study	Seismic Zone	PGA Range (g)	Exceedance
Building Code of Pakistan (2007) – Wah Cantt	Zone 2B	0.16 - 0.24	–
This study (DSHA, MCE scenario)	Site-specific MCE	0.267	+11.25%

The exceedance is not very large in absolute value, but it is of great engineering significance. In critical or strategic facilities, designed to the code minimum, the actual MCE demand may be greater than the designed one by more than 10%, which may not meet the performance objectives. This is a reminder of the need to apply DSHA on a case-by-case basis to facilities in Zone 2B within proximity of the MBT. The DSHA value is 11.25% higher than the upper limit of the zone 2B range.

## 9. DISCUSSION

The results indicate that the MBT is predominant in seismic hazard at Wah Cantt. It is located in an area with relatively high ground motion (RJB = 16 km) and relatively high maximum magnitude ( $M_w = 8.1$ ), which means that it produces ground motion much greater than more distant sources of the same magnitude. The Panjal Thrust, despite being just 1 km further away and 0.4 magnitude units lower, is responsible for a PGA of 0.227g, which is 17% lower than the MBT, highlighting the combined effect of distance and magnitude on near-field hazard.

There are several caveats for this analysis. The calculation is based on reference rock conditions ( $V_{s, 30} = 760$  m/s). Wah Cantt is located in the Potwar plateau, underlain by thin to thick sequences of sediments. The values of ground motion above those presented here would be amplified by soft or intermediate soils, especially at short periods, where the demand for spectrum is already high. So, a site-

response analysis with a borehole or surface-wave survey should be conducted before the final design parameters. Second, the DSHA framework is by definition not designed to consider the probability of the MCE scenario occurring, so the hazard levels resulting from the DSHA would be compared with hazard levels from a complementary probabilistic seismic hazard analysis (PSHA) that would yield hazard levels consistent with the return period.

Although limited in these simplifications, the deterministic approach is the first-order right choice for near-fault sites with well-known MCE. The results offer a physically sensible upper-bound estimate for use in structural design and clearly demonstrate the need for site-specific investigation.

## 10. CONCLUSIONS

This paper is based on a deterministic seismic hazard assessment carried out for Wah Cantt, Pakistan, on the basis of the Main Boundary Thrust as a controlling source. The principal findings are as follows:

The MBT ( $M_w 8.1$ , RJB = 16 km) with  $M_w 8.1$  and RJB 16km is the controlling source at Wah Cantt. Using the Boore and Atkinson (2008) GMPE with reference-rock conditions gives a horizontal PGA value of 0.267g.

This value surpasses the upper limit of BCP 2007 Seismic Zone 2B (0.24g) by 11.25%, signifying that code-based zoning may underrate near-source hazard for important facilities in this area.

3. The deterministic response spectrum peaks at  $T = 0.15$  s with  $S_a = 0.452g$ , represents that most vulnerable structures are low-rise masonry and reinforced concrete structures.
4. Geotechnical investigation and site-response study are highly recommended before completing seismic design parameters for critical infrastructure at Wah Cantt.

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