

FAULT-BASED DETERMINISTIC SEISMIC HAZARD ASSESSMENT FOR KHALABAT
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Abstract

The present study was carried out based on the identification and characterization of major active faults within 200 km radius of Khalabat Township Haripur, for preparation of a Deterministic Seismic Hazard Analysis (DSHA). Estimates of seismic demand were made based on evaluation of the source parameters: fault mechanism, maximum moment magnitude (M_w) and closest source-to-site distance. Peak Ground Acceleration (PGA) was chosen as the governing ground motion parameter, and was computed from two Ground Motion Prediction Equations (GMPEs), the attenuation relationship from Cornell-Banon et al. (1977) and the Boore and Atkinson (2008) model. The results show that the Panjal Fault has been controlling the seismic hazard at the study site as it is located at a close distance of 40 km and has a seismic capacity of M_w 7.5 and results in a maximum PGA of 0.295 g using Cornell model and 0.155 g using the Boore and Atkinson model. The deterministic estimate was compared with Building Code of Pakistan (BCP 2007) which has set the area under Seismic Zone 2B where the PGA values are 0.18–0.24 g, finding the values to be around 23% above the upper limit of the code. Results were clearly highlighting the advantage of local seismic hazard assessment over generalized seismic zoning to ensure safer and more reliable seismic design of the rapidly developing northern Pakistan, and show the importance of incorporating site-specific hazard evaluation in such seismic design.

Introduction:

Earthquakes are one of the most important natural hazards and their effect on environment is quite significant. In the tectonically active regions the stresses accumulate over the time, when these stresses are released, it generates strong ground motion capable of producing extensive loss of infrastructure and lives [1]. The assessment of seismic hazard is a fundamental component in earthquake engineering, disaster reduction, urban planning and in order to develop a resilient infrastructure [2]. Pakistan resides at the northwestern margin of the Indian plate. The convergence of the Indian plate and Eurasian plate is mostly responsible for the active tectonic deformation

throughout the regions like, Himalayan, Karakoram, and Hindu Kush. The Northward movement of the Indian plate has resulted to develop major thrust systems and fault lines that gather the crustal shortening with in the Himalayan fold and trust belt [3]. The tectonic structures include the Main Boundary Thrust (MBT), Main Mantle Thrust (MMT), Panjal Thrust, and several faults that contribute to the overall seismicity of northern Pakistan. The interaction between these major structures has generated huge amount of the large to moderate earthquake making the northern Pakistan one the most seismically vulnerable area in South Asia [1].

Table 1: Some Major Earthquake Events and Number of fatalities occurred in Pakistan and adjoining regions [4].

Date	Magnitude (M_w)	Locations	Deaths
24/09/2019	5.6	Mirpur, Azad Kashmir	38
25/12/2015	6.3	Gilgit-Baltistan	4
26/10/2015	7.5	Badakhshan, Afghanistan	399
28/09/2013	6.8	Awaran, Balochistan	400
24/09/2013	7.4	Awaran, Balochistan	825
18/01/2011	7.2	Dalbandin, Balochistan	3
29/10/2008	6.4	Ziarat, Balochistan	215
08/09/2005	7.6	Balakot, Azad Kashmir	73000
27/02/1997	7	Balochistan region	57
28/12/1974	6.2	Khyber Pukhtunkhwa	5300
28/11/1945	8.2	Makran, Balochistan	300-600
31/05/1935	7.7	Ali jaan, Balochistan	30000-60000
21/10/1909	7	Sibi, Balochistan	100
24/09/1827	7.8	Lahore, Punjab	1000
02/05/1668	7.6	Sindh region	50000

The seismic hazard is another important aspect to consider for the safety of structures and urban planning in Pakistan, which is located in a seismically active tectonic environment that demands attention.

In these areas, deterministic seismic hazard analysis at a site is a critical tool for determining the realistic ground-motion demand, and must explicitly account for nearby active faults, their maximum magnitude

potential, and source-to-site distance. This is considered better than the approach of simply using zoning on a broad regional basis, especially in the case of critical structures and in the growing urban areas of northern Pakistan [5].

One of the seismic hazard analysis techniques which focuses on the maximum credible earthquake is Deterministic Seismic hazard analysis (DSHA). For critical infrastructure where conservative hazard estimates are needed, deterministic approach is very useful in assessing the impact of the nearby active faults, and is widely used in the design of such

infrastructure. The first step in identification of the sources of seismic hazard in DSHA is to identify those that could pose a significant hazard and then to characterize them according to the characteristics of the source (tectonic properties, fault mechanisms and maximum expected amplitudes). Ground Motion Prediction equations (GMPEs) which are suitable for site are then used calculate the estimated seismic intensity parameter such as peak ground acceleration (PGA). The hazard values then provide the realistic representation of maximum credible earthquake scenario [1]

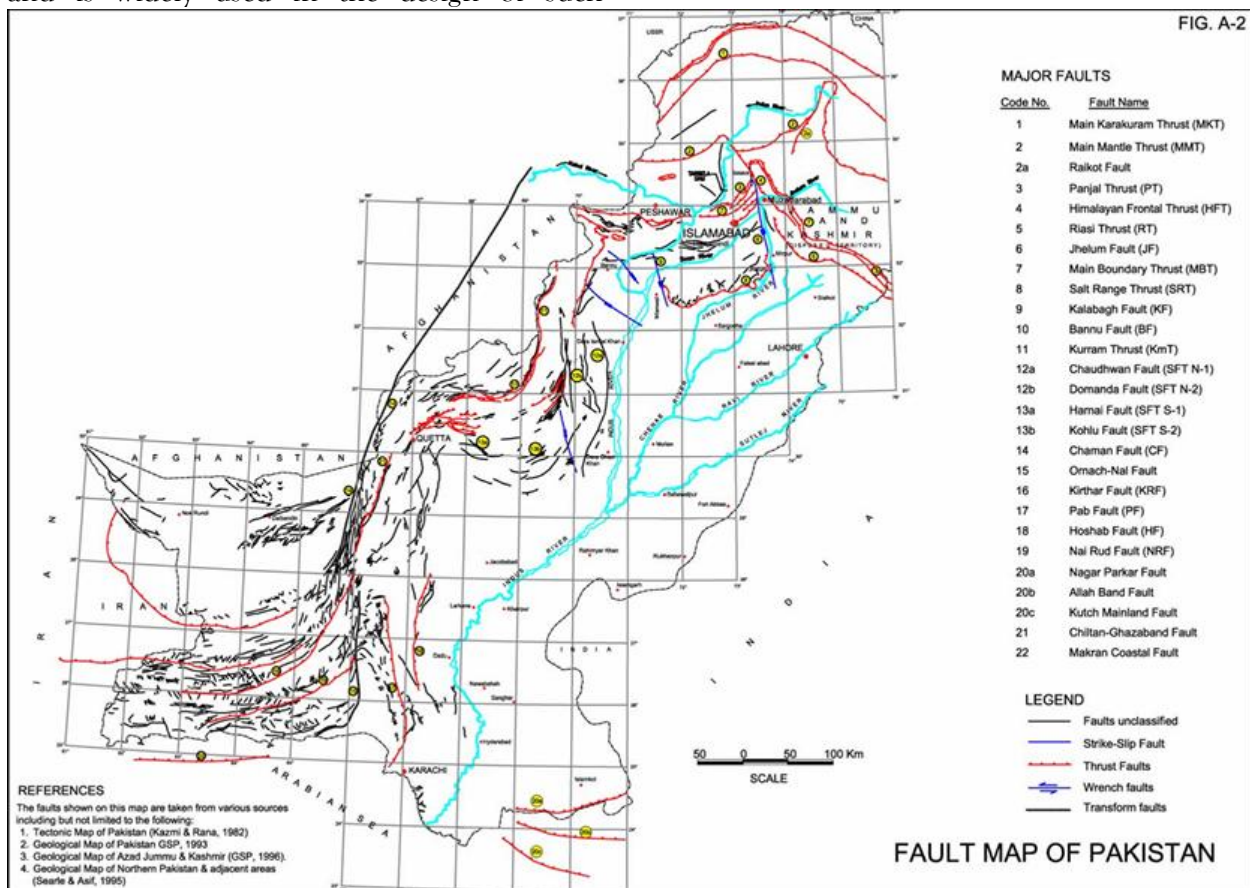


Figure 1: Fault Map of Pakistan (Building code of Pakistan)

Objectives:

This study aims to conduct a Deterministic Seismic Hazard Analysis for Khalabat Township, Haripur,

Pakistan. Active seismic sources within the proximity or the one which have significant effect on the study area will be used from the available databases. The

maximum considered earthquakes from these sources will be utilized and the appropriate attenuation relationships will be used to determine Peak Ground Acceleration (PGA) values at the site. These values will be later compared to the seismic design parameters given in the Building Code of Pakistan. This will help make a good comparison and emphasize the significance of performing a local/site specific seismic hazard analysis to obtain safer and more economical designs for structures.

Geology of the Study Area:

The Hazara-Kashmir Syntaxis (HKS) is one of the most prominent tectonic culminations of the northwestern Himalayas, which resulted from the ongoing convergence between the Indian and Eurasian plates. Geometrically, the HKS is defined as a well-defined hairpin which is like a bend in the Himalayan fold and thrust belt, with the regional structure trend changing from NW-SE to NE-SW. The syntaxis formed due to the crustal shortening and localized rotational deformation during the Himalayan orogeny. Studies show that the HKS is an antiformal pile built from Precambrian to Cenozoic sedimentary sequences which have been highly folded, faulted and uplifted during the Cenozoic collisional stage [6]. It is a transfer zone between the western and central Himalayan end-segments and so has very complex structural relationships such as imbricate thrust sheets, overturned folds, duplexes and strike-slip faulting. The progressive indentation of the Indian Plate and rotation of thrust sheets around the apex of the syntaxis have been suggested to be responsible for the arcuate geometry of the syntaxis and significant distortion of regional tectonic boundaries [7;8]. In addition, the HKS is one of the most seismically active regions in the Himalayan mountain belt due to its

rapid uplift, and the intense erosion present in the region [9].

Several major regional faults and thrust systems controlling the tectonic architecture of Hazara-Kashmir Syntaxis. The Main Mantle Thrust (MMT) in the north is a major crustal scale tectonic structure that separates the Kohistan Island Arc from the Indian Plate and reflects a major suturing event that occurred during the closure of the Neo-Tethys Ocean [10]. The Balakot Bagh Fault (BBF) is an out of sequence reverse fault along the western limb of the syntaxis, which was the source of the much-feared devastating Kashmir earthquake on 8th October, 2005 (Mw 7.6) in the vicinity of the syntaxis, thus indicating the activity of deformation in the syntaxis region. The lateral movement has been accommodated by the Jhelum Fault, which is a major lateral fault, and the Hazara Thrust System and imbricate faults have absorbed the shortening of the crust in the fold-and-thrust belt. These tectonic structures together exhibit that the Hazara-Kashmir Syntaxis is a region where the interaction of thrusting, folding, strike-slip faulting, and seismicity are occurring to account for ongoing convergence between India and Eurasia [7].

Haripur District along with Khalabat Town ship is well within the boarder of Hazara region and is in proximity of the many active tectonic structures particularly Main Boundary Thrust (MBT), Main Karakorum Thrust, Northern Fault and Many other major faults. Many previous studies have confirmed the Hazara Kashmir region as an area which is under active deformation which is characterized by its shallow seismicity and accumulation of the stresses along major thrust systems [11]. The earthquake of Kashmir (8 October 2005) highlighted the seismic hazards of this region and pointed out to the need for

local and detailed seismic hazard assessment in the neighboring urban areas [12].

Khalabat Township lies in Haripur District within the Hazara Tectonic influence zone in Khyber Pakhtunkhwa Province (Elevation 495.3m) ($34^{\circ} 01'9.65''N$, $72^{\circ} 54'36.61''S$). With the region having experienced rapid development and population

growth and continuing to see an uplift in the number of residential and public infrastructure, the importance of understanding the seismic hazard characteristics of the region is growing. Although important, almost no studies have been undertaken to quantify the site specific seismic hazard at Khalabat Township through deterministic methods based on faults

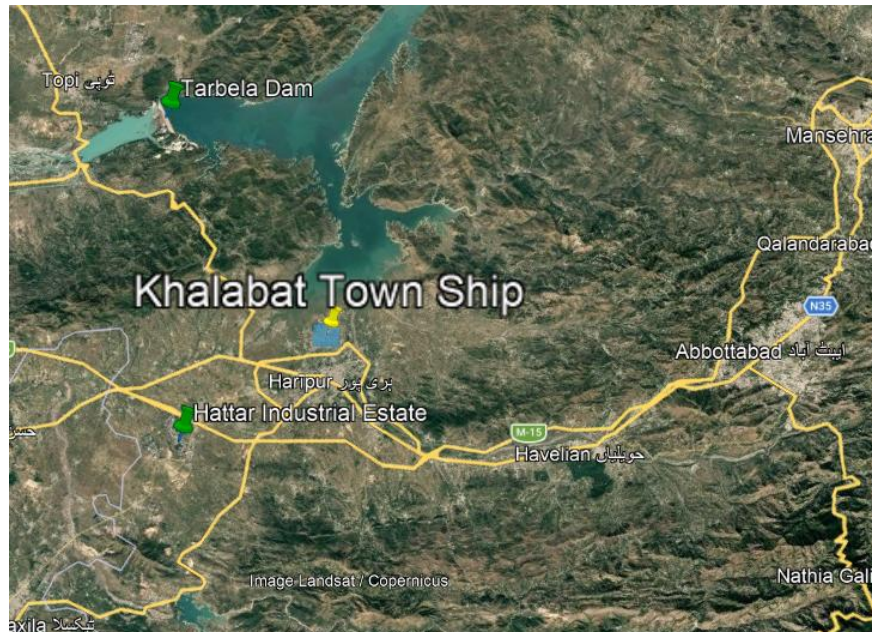


Figure 2: Khalabat Township Location

Methodology:

Identification and Distance of Seismic Sources to the site:

Identification and characterization of the seismic sources is one of the most essential steps in the Deterministic Seismic Hazard Analysis (DSHA) process, the accuracy of the resulting hazard estimates will depend greatly on the correct selection and representation of the active faults capable of producing significant ground motions at the site of interest. Within this framework sources are often characterized

using mapped active faults and tectonic structures that have geometric, rupture, fault mechanism and maximum probable magnitude data. The characterization process includes fault length, fault type, depth, maximum credible earthquake (MCE) and shortest distance from fault to the study site, all of which have direct influence on the ground shaking expected at the study site. Thus, it is necessary to have a thorough knowledge of the geotectonic context of the study area to have realistic and reliable seismic hazard estimates [1].

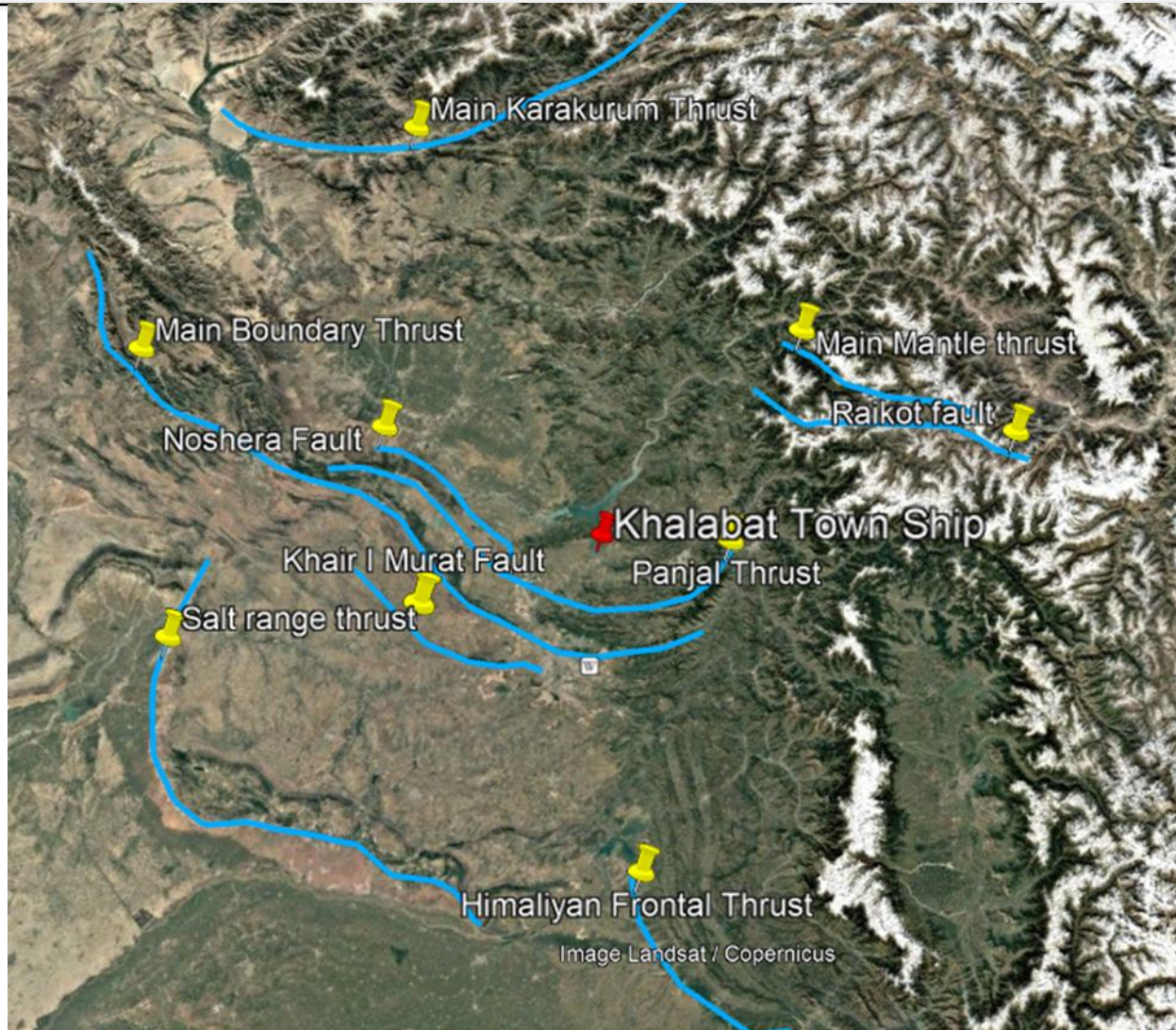


Figure 3: Faults around Khalabat Township within 200km radius

Main Karakoram Thrust (MKT):

One of the important crustal-scale tectonic structures in the northern Pakistan is the Main Karakoram Thrust (MKT) also known as Main Karakoram Fault Zone or Karakoram tectonic boundary. The fault represents an important zone between the Karakoram Block and the Kohistan-Ladakh Arc, and documents the complex evolution and convergence of the Indian and the Eurasian plates. The MKT is known to have a broad zone of deformation, comprising of thrusting, faulting and tectonic imbrication, during the closure

of the Neo-Tethys Ocean and during the emplacement of arc-related terranes against the edge of the Indian Plate [13]. Despite being north of the Hazara division, the evolution of this fault in terms of its large scale tectonic significance and its ability to generate moderate to large earthquakes it must be included in regional deterministic seismic hazard assessments of northern Pakistan.

On the seismic hazard side, the Main Karakoram Thrust is part of the whole framework of the western Himalayas and Karakoram region where the processes

of crustal shortening and accumulation of strain are still in progress because of continuing convergence of the plates. Structural analyses reveal the presence of a long history of tectonic activity, as the fault is several hundred kilometers in length and shows signs of many deformation phases [14].

MKT is considered as one the potential seismic source which may influence our site. The analysis pointed out the minimum (closest) source to site distance to be 181km. Although being at the greater distance it is still considered because it lies well within the 200 km radius. The fault is capable of generating maximum magnitude earthquake of Mw 7.6 [1].

Main Mantle Thrust:

The Main Mantle Thrust (MMT) is a major tectonic boundary in the northern Pakistan which defines the suture between the Kohistan-Ladakh island arc terrane and the Indian Plate in the northwestern Himalayas. It is the region of the Indian continental margin which has been underthrust beneath the Kohistan arc during Himalayan collision, experiencing significant crustal shortening, metamorphism and juxtaposition of contrasting lithologic units. Regionally, the MMT separates Indian plate sedimentary and metamorphic rocks to the south from arc rocks mafic, ultramafic and plutonic rocks to the north. The MMT is considered as a significant tectonic feature, as it is a first order plate boundary and also a long-lived deformation zone, and should be taken into consideration for deterministic seismic hazard assessment of northern Pakistan and its adjacent Himalayan regions [15].

Based on the source characterization, the distance between the source and the site distance is 68 km, resulting in close proximity of the fault to the site and thus the necessity to include it in the deterministic seismic hazard analysis. Beyond its relatively low

distance, the MMT has also substantial seismic observables as it is a major tectonic boundary at the regional scale, and can produce up to a maximum moment magnitude (Mw) of 8.3 [16].

Noshera Fault:

The Noshera Fault is known as an active tectonic fault and is part of the overall deformational zone of the ongoing shortening of the northern crustal region of Pakistan. It is generally associated with 'strike-slip to oblique-slip' kinematics and has been suggested as being a trigger for moderate and strong earthquakes that could have affects on the nearby urban and infrastructural developments in the Peshawar-Noshera area. It is also located in an actively deforming sedimentary basin, and therefore is listed as a possible seismic source in regional hazard assessments. The Noshera Fault is considered as a potential seismic source with a source-to-site distance of 35 km. The fault has the potential to produce a maximum Mw 7.3 earthquake, and is modelled as part of deterministic seismic hazard analysis due to its locality and seismic potential [17].

Panjal Fault:

The Panjal Fault is one of the important and active tectonic structure in northwestern Himalayas and is a part of the fold-and-thrust belt related to the ongoing convergence of India and the Eurasian plate along the northward boundary of the Indian plate. Expansive and can host moderate to strong seismic events because it continues to undergo tectonic stress build up in the region. Due to its seismic activity and structural connections in the Himalayan thrust system, it is considered to be a relevant seismic source for the regional hazard assessments. The Panjal fault is located at 40 km distance and It has potential to output a maximum earthquake of Mw 7.5, it is one of the

closest sources to the our concerned region and hence is part of the deterministic seismic hazard analysis [1].

Salt Range Thrust:

Led by the Salt Range Thrust (SRT), the hinge front of deformation in an active section of the Himalayan fold and thrust belt in northern Pakistan, is the Salt Range Thrust. It features thin-skinned tectonic style with a weak evaporite or salt detachment layer which allows for large scale thrusting and separation of sedimentary cover from underlying basement. Evidence for seismic and structural shortening within the SRT confirms that it has accommodated significant amounts of crustal shortening and a major contribution to propagating the Himalayan deformation front to the south. Ductile Salt has had significant impact on thrust geometry and surface expressions of deformation within the region. The SRT is an active tectonic boundary and is known to be an important seismic source for regional tectonic and hazard studies [18]. The source is located at a moderate distance of 141km from the study area. Although at a greater distance this fault is one of the major active faults and lies well within the 200km radius. The source has a potential of producing earthquake of 8 (Mw) and is considered for analysis.

Khair-I-Murat Fault:

The Khair-i-Murat Fault (KMF) is a prominent structural feature of the Himalayan foreland fold and thrust belt of northern Pakistan, which is still active and is linked to the continuing Indo-Eurasian plate convergence. It is included in the Potwar Plateau structural system, which conveys compressional strain to its sedimentary layers by means of the thrust related deformations and folding. Based on structural interpretation, the fault system is related with the shortening of the region and deformation of

subsurface rocks of the Potwar basin. It is an active tectonic feature and is near populated areas, so should be considered as a relevant seismic source in regional hazard evaluation studies. For this reason it is deemed to be important for seismic hazard assessment of northwestern Himalayan foreland [19]. The Khair-I-Murat fault is located at a distance of 80km from our concerned region being fairly close to our site. This source is reported to produce earthquake of 7.6(Mw) and is also considered for the analysis

Himalayan Frontal Thrust:

This is the youngest and most active tectonic boundary of the Himalayan fold and thrust belt, the Himalayan Frontal Thrust/Himalayan Main Thrust (HFT), is the boundary between the Sub-Himalaya and the Indo-Gangetic foreland basin. It is a region in which the convergence of the Indian and Eurasian plates continues and it is believed that it is the most prominent surface manifestation of the ongoing deformation of the Himalayas. Geodetic and geomorphic data suggest that the HFT are capable of producing large magnitude earthquakes and major surface rupture events. It is known as the main seismic source governing current seismicity of the Himalaya, in virtue of its active kinematics and regional continuity [20]. The Seismic Source is reported to have the potential to generate an earthquake with a magnitude of 8(Mw) and is situated at 128km from the site therefore is included in the DSH analysis.

Raikot Fault:

The Raikot Fault is a major north-south trending active formational feature along the west of Nanga Parbat syntaxis in northern Pakistan that accommodates high levels of crustal deformation and rapidity's associated with uplift of the massif. The features that mark it are thrust and transgressional

features, and it is an important segment of active deformation zone in the western Himalayas. There is geological and seismological evidence that brittle deformation in the fault zone continues, giving rise to high seismic activity. The fault is an important factor in regulating uplift, and seismic hazard in the Nanga Parbat region [21].

This fault has been reported to have the potential to produce an earthquake of magnitude 7.1(Mw). The closest site to fault distance is found to be 91.7km.

Main Mantle thrust:

Indus suture zone is broken into blocks, of which the exposed part is Main Mantle Thrust (MMT) featuring a major tectonic boundary in the northern part of Pakistan between the Indian plate and the Kohistan

Table 2: Identified Faults and details within 200km radius of Khalabat Town Ship.

S.no	Fault Name	Fault type	Maximum Magnitude Mw
1	Main Karakorum Thrust fault	Reverse	7.6
2	Main Boundary Thrust	Reverse	8.3
3	Noshera fault	Normal	7.3
4	Panjaj Fault	Reverse	7.5
5	Salt range Thrust	Reverse	8
6	Khair I Murat Fault	Normal	7.6
7	Himalayan Frontal Thrust	Reverse	8
8	Raikot Fault	Reverse	7.1
9	Main Mantle Thrust	Reverse	8.3

Use of Ground Motion Prediction Equations (GMPEs):

Following the identification of active seismic sources around the Khalabat Township and calculation of the shortest distances from the source to the study site, the next step in deterministic seismic hazard analysis (DSHA) is the estimation of the expected ground motion at the study site. For the present study Peak Ground Acceleration (PGA) has been chosen as the main ground-motion parameter as it reflects the intensity of shaking during an earthquake directly, and

and Ladakh island arc complex. It is associated with a complex zone of ductile- to brittle-shear associated with mylonitic, ultramafic rocks, imbricated thrusts that represent strong shear during continental collision. The MMT features substantial crustal scale shortening and has been the area over which long-term tectonic convergence between India and Asia has occurred. It continues along its course as a zone of multiple shear surfaces with different ages and kinematics. It is a key element of the tectonic framework and seismicity of the western Himalayas [10]. The fault is capable of producing an earthquake of magnitude 8.3(Mw) and is located at the distance of 114km from the area under consideration. Although at a greater distance it resides well within the 200km radius and is then considered for the analysis.

it is one of the main design parameters in earthquake resistant structural design, for each seismic source the PGA is estimated using an empirical relationship between earthquake magnitude and distance from source to site, called an attenuation relationship or Ground Motion Prediction Equation (GMPE). This study aims to assess the seismic hazard of the individual faults affecting the Khalabat township, and this requires the seismic source parameters to be linked with the expected PGA at the site by a suitable

analytical relation, which is provided by the attenuation relationships.

Two attenuation relationships are used in this study for estimation of PGA, one of Cornell attenuation relationship following Banon et al. (1977) and another of Boore and Atkinson (2008) GMPE. One of the earlier empirical relationships presented by Banon et al. (1977) for seismic hazard estimation is the attenuation relationship, which relates the intensity of ground motion to magnitude and distance from the seismic source. This connection is based on the deterministic hazard framework of Cornell and has been extensively employed in the initial engineering seismology investigations to estimate strong ground motion for scenario earthquakes. It is also useful for deterministic seismic hazard studies where, due to its relative simplicity, the main input parameters that can be used are the maximum moment magnitude and closest source-to-site distance. For the present study, the Banon et al. (1977) equation was employed to calculate a first order estimate of PGA at Khalabat Township for each fault source identified.

$$\ln(\text{PGA}_{\text{gal}}) = 6.74 + 0.859M - 1.80 \ln(R + 25)$$

(Cornell, Banon et al. 1977)

M = Earthquake magnitude (Mw).

R = Source-to-site distance (km).

PGA = Peak Ground Acceleration.

The more recent Boore and Atkinson (2008) ground-motion prediction equation was also used, in addition to the classical Cornell-Banon attenuation relationship. The NGA-West strong-motion database is a large collection of recorded earthquake ground motions in active shallow crustal regions, where the authors of the NG database, Boore and Atkinson

(2008), were able to derive empirical equations for the PGA, peak ground velocity (PGV), and 5%-damped response spectra. They incorporate the effects of earthquake magnitude, source-to-site distance, local site conditions, and fault mechanism in their model to describe ground-motion attenuation more completely than the previous empirical models. One aspect of the present analysis that is notable is the use of the Boore and Atkinson (2008) equation, which reflects the current state of strong-motion seismology and lets the PGA estimates from the classical attenuation relationship be compared to those from a more modern and well accepted GMPE. The comparison enhances the reliability of the deterministic seismic hazard assessment and provides insights into the sensitivity of estimated PGA values to the selection of an attenuation model.

$$\ln(\text{PGA}_g) = -1.715 + 0.5M - \ln(R + 0.0055e^{(0.4M)}) + 0.3 \ln(V_{s30}/760)$$

(Boore & Atkinson, 2008)

M = Earthquake magnitude (Mw).

R = Source-to-site distance (km).

V_{s30} = Average shear-wave velocity in the upper 30 m of soil profile. (350m/s)

PGA = Peak Ground Acceleration.

The maximum moment magnitude and closest distance between the source and site were chosen as the main input parameters for the attenuation relations used for each fault, in this study. The PGA values calculated using the Banon et al. (1977) and Boore and Atkinson (2008) equations have then been compared to assess the seismic contributions of the two equations, as well as to identify the controlling fault generating the highest ground-motion intensity at Khalabat Township.

Table 3: Results for Ground Motion Prediction Equations

S.no	Fault Name	Closest Source to site Distance (km)	Fault type	Maximum Magnitude (Mw)	Cornell, Banon et al. (1977)	Boore & Atkinson (2008)
1.	Main Karakorum Thrust fault	181	Reverse	7.6	0.0403	0.0352
2.	Main Boundary Thrust	68	Reverse	8.3	0.2541	0.115
3.	Noshera fault	35	Normal	7.3	0.2872	0.1563
4.	Panjaj Fault	40	Reverse	7.5	0.2952	0.1512
5.	Salt range Thrust	146	Reverse	8	0.0795	0.0533
6.	Khair I Murat Fault	80	Normal	7.6	0.1357	0.0796
7.	Himalayan Frontal Thrust	128	Reverse	8	0.0972	0.0608
8.	Raikot Fault	91.7	Reverse	7.1	0.073	0.0541
9.	Main Mantle Thrust	114	Reverse	8.3	0.1494	0.0793

From table 3 it is clear that The highest PGA value of 0.295 g was calculated at 40 km distance from Panjal Fault using the Cornell et al. attenuation relationship which is identified as the controlling seismic source for

Khalabat Township. The Boore and Atkinson (2008) model, by contrast, has a lower PGA prediction for the same fault distances for all, suggesting less conservative seismic demand than the Cornell model.

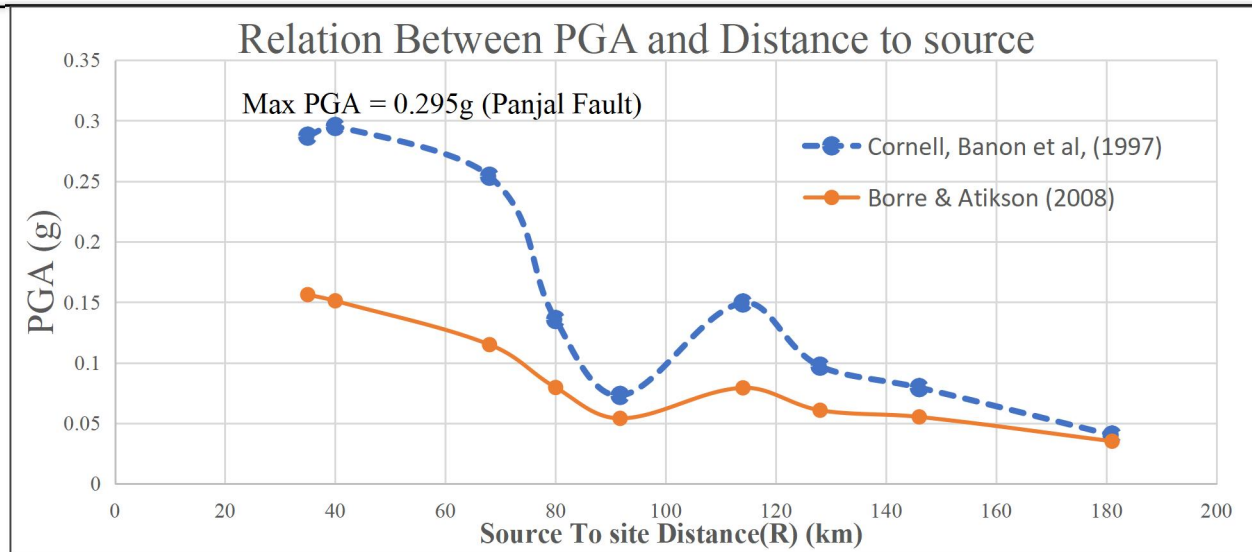


Figure 4: Relation Between PGA and Distance to source

From figure 4 As expected, the PGA generally decreases with increasing distance from the source, as is seen on this graph, which is consistent with the decrease in attenuation of seismic waves with distance from the fault source. The trend also reveals that at a distance greater than around 100 km, faults make a relatively smaller contribution to the PGA, although the contribution of these faults cannot be neglected in the hazard assessment overall.

Results and Discussion:

Among the various faults analyzed, the Panjal Fault was found to be the controlling one for the seismic hazard of Khalabat Township, Haripur in the deterministic seismic hazard assessment. The source characterization yielded a maximum moment magnitude of Mw 7.5 for the Panjal Fault, and a shortest source-to-site distance of 40 km between the fault and Khalabat Township. These parameters suggest that the Panjal Fault is a great seismic hazard to the study area due to its relatively high earthquake generating potential and its proximity to the area. Both of these factors are important in the

deterministic seismic hazard analysis because, in a deterministic analysis, larger magnitudes of earthquakes tend to produce larger ground motions and shorter distances between the earthquake source and the site tend to mean that seismic waves will not decay as much before they reach the site. Thus, the Panjal Fault was considered as the dominant fault in the study area given that it caused maximum ground shaking at Khalabat Township.

The calculated Peak Ground Acceleration (PGA) values for the controlling fault with different attenuation relationships also indicate the importance of the fault in the seismic hazard assessment of Khalabat Township. The PGAs is calculated using the Cornell et al., (1977) attenuation relationship and Boore and Atkinson, (2008) Based on this relationship, the more conservative estimate for the PGA for deterministic seismic demand is obtained, and in this case, the value of 0.2952 g is used as the governing PGA for the study area.

Comparison with building Code of Pakistan:

To assess the level of representation of seismic hazard through code provisions, the PGA values derived from the deterministic seismic hazard analysis for Khalabat Township were compared with the seismic hazard provisions of the Building Code of Pakistan (BCP 2007). From BCP 2007, the Seismic Zone of Khalabat Township is 2B, where the range of the PGA prescribed is 0.18 g – 0.24 g. The deterministic seismic hazard analysis carried out in the present study on the other hand, resulted in a governing PGA of 0.2952g from the Cornell et al. (1977) attenuation relation, where the Panjal Fault was found to be the controlling seismic source. This value is greater than the maximum value of the zoning range of BCP and shows a 23 % difference in comparison to the codal seismic hazard representation. Based on the comparison made here, it can be deduced that the deterministic ground-motion demand at Khalabat Township could be greater than the implication presented by the generalized seismic zoning map of the Building Code of Pakistan.

Conclusion:

This study has conducted the site-specific seismic demand assessment of Khalabat township, Haripur, Pakistan using the surrounding active tectonic structures through the in-depth application of the Deterministic Seismic Hazard Analysis (DSHA) approach. The analysis combined seismic source characterization with Ground Motion Prediction Equations (GMPEs), and determined that the Panjal Fault was the controlling seismic source because of the relatively short source-to-site distance and potential for significant earthquakes. The maximum estimated Peak Ground Acceleration (PGA) obtained from the Cornell-Banon et al., (1977) attenuation model was found to be in excess of the upper seismic design limit specified by the Building Code of Pakistan (BCP 2007)

for the study area by about 23%, suggesting that the generalized code-based zoning may not adequately account for the local seismic effects. The sensitivity of seismic hazard estimates to the choice of attenuation model was further confirmed by comparing with results from the Boore and Atkinson (2008) model and the need to adopt multiple predictive approaches when performing a seismic hazard evaluation. The results highlight the importance of local and fault-based seismic hazard assessments in fast-growing areas for safer design of structures, urban planning and increased seismic resiliency. The use of probabilistic approaches, comprehensive geotechnical site characterization and local soil amplification effects should be considered in future studies to enhance the seismic demand estimation for Khalabat Township and the surrounding region.

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