Estimation of Deterministic Seismic Hazard for Saharsa and Adjoining Region

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Abstract

This study presents a comprehensive estimation of the bedrock level deterministic seismic hazard for Saharsa and its adjoining region in Bihar, India, a seismically active area situated near the Himalayan seismic belt. The analysis incorporates a deterministic seismic hazard assessment approach, identifying potential seismic sources within about 300 km radius and evaluating their maximum credible earthquake potential based on historical and instrumental seismicity data, regional geology and tectonic features. Ground motion parameters including peak ground acceleration, are computed using regionally appropriate ground motion prediction equations.

The results reveal spatial variability in seismic hazard levels, with higher hazard concentrations near active fault zones and tectonic lineaments. The estimated peak ground acceleration values at bedrock level provide critical inputs for earthquake-resistant design and urban planning in the region. This study aims to aid policymakers, engineers and urban planners in implementing effective seismic risk mitigation strategies, enhancing regional resilience to future seismic events.

Keywords: Deterministic Seismic Hazard Assessment (DSHA), Peak Ground Acceleration (PGA), Ground Motion Prediction Equations (GMPEs), Seismotectonic.

Introduction

As per BSDMA[9], among the 38 districts in Bihar, approximately 15.2% fall within seismic zone V, 63.7% in zone IV and the remaining 21.1% are classified under zone III. Over the last 250 years, the State has experienced around ten significant earthquakes with magnitudes ranging from 5.5 to 8.5 based on the database of International Seismological Centre[21]. The Bihar–Nepal border area is located in a highly seismically active region along the Himalayan tectonic boundary[9]. According to the Geological Survey of India[15], this region is characterized by six major subsurface faults with strike-slip mechanisms that extend across the Gangetic plains in multiple directions. In particular, about 44% of the Saharsa district lies within zone V, while the rest falls under zone IV, as shown in fig. 1. Past occurrence of earthquakes of magnitude about 8.0 originating from Himalayan region has badly affected Nepal-Bihar (Munger, Muzaffarpur, Saharsa etc.) resulting in large number of human losses and homeless people[16]. Situated in the eastern region of Bihar, India, Saharsa is regularly undergoing significant urban growth. Located on the eastern side of the Kosi River, the city serves as the administrative headquarters for both Saharsa District and the Kosi Division according to portal of Saharsa District[43]. Covering an area of nearly 27 square kilometers, it lies at approximately 25.88°N latitude and 86.6°E longitude, with an average elevation of around 41 meters[43].

The region around Saharsa lies within a broad alluvial plain which is also under the extensive basin of Kosi River. The city itself is positioned on the Kosi alluvial mega fan, one of the largest of its kind globally. While the soil in the area is notably fertile, the Kosi River, an important Ganges tributary, frequently shifts its course, leading to severe soil erosion issues. Seasonal flooding significantly hampers connectivity in the region, often damaging infrastructure like bridges. These floods, which affect around 21,000 square kilometers of productive farmland, occur nearly every year and result in major economic losses and threats to life and property. Due to its destructive nature, the Kosi River is often referred to as the "Sorrow of Bihar". The Bagmati River often overflows its embankments and shifts its course frequently due to natural meandering. It deposits alluvium at a high annual rate.

Additionally, the Gandak River passes through the southern region of Saharsa[50]. The location of Saharsa places it near a seismically active segment of the Himalayan arc, which spans from the Pamir-Hindukush region in the west to the Burma arc in the east[19]. The proposed study region is highly susceptible to seismic hazards due to almost all favorable conditions such as falling under higher seismic zone having higher PGA values[22] containing soft soil deposits of loose fine saturated sand. With ongoing urbanization, rising population and heightened seismic activity in India, it has become essential to assess region-specific seismic hazard indicators such as site classification, ground motion (PGA), site effects, potential for liquefaction and landslide susceptibility for effective microzonation of cities situated close to tectonically active Himalayan areas[2].

Numerous researchers have developed attenuation relationships to estimate PGA for different regions, leading to a wealth of empirical models. Several comprehensive reviews summarize these efforts, including those by Boore et al[8], Campbell[11], Abrahamson and Litehiser1, Fukushima and Tanaka[14] and Sharma[45] giving attenuation relation for Himalayan region.

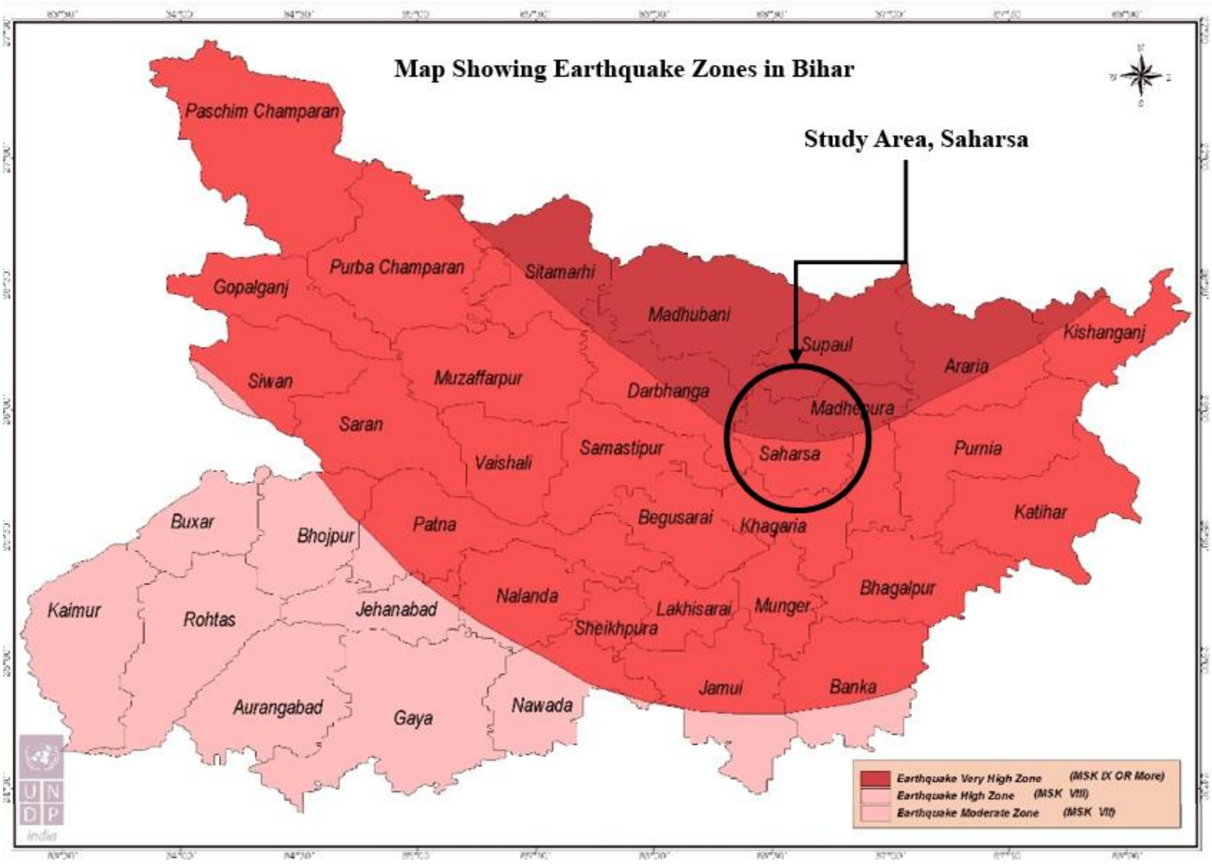

Figure 1: Study area marked under Seismic Zone map of Bihar (Modified after Bihar State Disaster Management Authority)

Review of Literature

The estimation of seismic hazard at bedrock level is a critical component of earthquake engineering, urban planning and disaster risk mitigation, particularly in regions vulnerable to tectonic activity. In the Indian context, seismic hazard assessment has gained prominence due to the country's location at the convergence of the Indian and Eurasian plates, making many regions including parts of Bihar susceptible to significant seismic events. DSHA is pivotal for evaluating seismic risks, especially in regions with sparse historical seismic data. In India, DSHA has been applied across various regions to understand and mitigate potential earthquake impacts.

Tandon[48] was among the first to discuss earthquake hazard in India, focusing on intensity-based assessments. Khattri et al[25] later introduced probabilistic seismic hazard analysis for the Himalayan region, utilizing ground motion prediction equations originally developed for the eastern United States. Subsequently, Bhatia et al[6] conducted seismic hazard evaluations across India and neighboring areas within the latitude-longitude range of 0°N–40°N and 65°E–100°E, applying a grid resolution of 0.5° × 0.5° using the attenuation model proposed by Joyner and Boore[24].

Gupta[18] described seismic hazard concerned with estimate of the strong motion parameters with a lot of examples. Mahajan et al[32] computed the latest PSHA estimates for the Garhwal region. Rajaram et al[38] analyzed approximately 110 major faults to determine the PGA at the bedrock level by applying the attenuation model developed by Atkinson and Boore[4]. The peninsular region examined in the study was divided into 1˚ x 1˚ grids, with around 280 specific locations assessed for a detailed analysis. Kumar et al[30] conducted a DSHA for Dehradun city, located at the Himalayan foothills, utilizing data from the India Meteorological Department (IMD) and the Geological Survey of India (GSI).

Anbazhagan et al[2] carried out seismic hazard estimation for Patna, Bihar, compiling key region-specific parameters such as the seismic study area (SSA), maximum moment magnitude (M_w) and appropriate GMPEs within a 500 km radius of the city. Burnwal et al[10] estimated the PGA for the Sitamarhi region near the India-Nepal border, while Ramkrishnan et al[40] evaluated seismic risk in Mangalore by integrating hazard data with land use characteristics. Anbazhagan et al[3] explained PSHA of Patna district through a logic tree framework. Several other studies have also explored deterministic and probabilistic approaches for seismic hazard assessment within India and vicinity.

Parvez et al[36] utilized deterministic methods to estimate PGA in various Indian cities, demonstrating that GMPEs tailored to regional seismicity provide more reliable hazard estimates. They noted that using regionally calibrated GMPEs significantly reduces uncertainties in ground motion estimation. Iyengar and Ghosh[23] conducted extensive research on seismic zoning in India, highlighting that the northeastern region, the Himalayan belt and parts of Bihar are seismically active due to the complex fault systems and crustal deformations. Their work underpins the necessity of region-specific seismic hazard assessments rather than relying solely on national zoning maps. Bansal and Rao[5] emphasized the importance of DSHA for areas with sparse historical data, as it considers the worst-case credible seismic scenario.

This method, though conservative, is particularly valuable for critical infrastructure and safety assessments in regions with limited seismic records. Gupta[17] and Rajendran et al[39] have further underscored the importance of integrating geological, seismological and geotechnical data for comprehensive hazard assessment. Their works demonstrate that a combination of historical earthquake catalogues, fault characterization and site response studies forms the backbone of reliable DSHA. In Bihar, particularly in northern districts like Saharsa, studies are comparatively sparse. However, Kumar et al[16] have contributed to the understanding of the area's seismic vulnerability by mapping active faults and lineaments, emphasizing the role of near-surface geological features in amplifying ground motion.

Moreover, recent advancements in geospatial tools and GIS-based modeling have allowed for more detailed spatial analysis of seismic hazards. Chopra et al[13] used GIS to overlay seismic sources, fault lines and soil profiles, thereby improving the spatial resolution of hazard maps. Several studies have employed DSHA to assess seismic hazards in different parts of India. Shukla and Choudhury[46] estimated ground motion parameters through DSHA for various important cities in Gujarat. They evaluated faults across the region and applied empirical relations to estimate maximum earthquake magnitudes, providing deterministic spectra for cities like Ahmedabad, Surat and Bhuj. Mehta and Thaker[34] applied both deterministic and probabilistic approaches to assess seismic hazards in Vadodara. They utilized four ground motion prediction relationships to evaluate PGA at the rock level, contributing to a comprehensive understanding of the region's seismic risk.

Rao and Choudhury[42] conducted a DSHA for the north-western region of Haryana, assuming different levels of seismicity. Their study provided insights into PGA and response spectra, essential for planning of infrastructure in the region. Rao and Satyam[41] conducted a detailed DSHA and Probabilistic Seismic Hazard Analysis (PSHA) for Tindharia, emphasizing the region's vulnerability due to its proximity to the Himalayan seismic belt. They developed seismo-tectonic maps within a 300 km radius and generated hazard maps indicating PGA and spectral acceleration values.

Kiruthika et al[27] performed a DSHA for Chennai, identifying fault 26 as having the maximum magnitude potential. Their assessment revealed a PGA of 0.011g and a spectral acceleration of 0.8 g, highlighting the city's seismic vulnerability.

While comprehensive DSHA studies in Bihar are limited, Anbazhagan et al[2,3] presented an SHA study on Patna; Burnwal et al[10] and Paul et al[37] performed a SHA for Sitamarhi, near the Central Himalayan region. Their research contributes to understanding the seismic risks in Bihar, emphasizing the need for further DSHA studies in areas like Saharsa. The reviewed literature underscores the importance of DSHA in assessing seismic hazards across various Indian regions. However, there is a noticeable gap in DSHA studies specifically focusing on Saharsa and its adjoining areas in Bihar. Addressing this gap is essential for informed infrastructure development and disaster preparedness in the region.

In summary, the literature reveals a growing body of research on DSHA in India, but also a clear gap in detailed site-specific studies for regions like Saharsa. This study aims to address this gap by integrating geological, seismotectonic and geophysical data to develop a robust bedrock level DSHA model for Saharsa and its adjoining areas, thus contributing to the regional seismic risk reduction framework. Hence the Saharsa region has been focused for DSHA in present study.

Material and Methods

The DSHA at bedrock for Saharsa entails a structured approach to evaluating potential earthquake hazards by analyzing known seismic faults and historical earthquake data in the area. This process focuses on identifying the most impactful earthquake scenarios based on regional geological structures like the Himalayan Frontal Thrust and nearby strike-slip faults extending across the Gangetic plains (Fig. 4). The steps include:

Selection of Study Area (SA) and Seismic Study Area (SSA): For the DSHA, Saharsa and adjoining regions have been identified because Saharsa lies in seismic zone in V and it is near the Himalayan region which is the main cause of occurrence of earthquakes. During the past, there have been several earthquake occurrences resulting in large number of human losses and homelessness. The district is situated around latitude 25.8774° N and longitude 86.5928° E (Figures 1 and 3). The Bihar-Nepal border region lies within a high seismic risk zone, positioned along the tectonic boundary where the Indian plate interacts with the Himalayan tectonic system. Almost entire area of Saharsa and adjoining region is equally shared as each of zone IV and zone V. Occurrence of earthquakes of magnitude about 8 and above around adjacent Himalayan region has affected the territory of Nepal-Bihar (Munger, Muzaffarpur, Saharsa etc.).

To demarcate the details of study area Saharsa, the seismotectonic map was sourced from the Bhukosh Portal of

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the GSI (Fig. 3). The Bhukosh portal serves as a comprehensive geospatial platform that provides access to authoritative geological and tectonic datasets across India. The selected map for Saharsa includes critical geological features such as fault lines, thrust systems such as main central thrust (MCT), main frontal thrust (MFT), main boundary thrust (MBT), basement ridges and other tectonic structures relevant to seismic hazard characterization. The map was chosen for its high spatial fidelity, Government-authenticated content and inclusion of regionally significant fault systems such as the Munger–Saharsa Ridge (MSR) fault, West and East Patna faults and the Katihar–Nilphamari fault, which are essential for modeling potential seismic sources in the area (Fig. 3).

To facilitate detailed analysis the Bhukosh map was digitized using AutoCAD (Fig. 4). The digitization process involved tracing fault geometries, tectonic boundaries and regional features from the raster map, converting them into vector layers for use in seismic source modeling. This vector data was later exported into compatible formats (e.g. DXF, DWG) for incorporation into hazard analysis workflows. This digitization approach ensures higher accuracy, scalability and customization of seismic source zones and enables integration with site-specific data, such as ground motion models and local geology, thereby improving the precision of the seismic hazard assessment.

The delineation of the seismic study area for Saharsa is guided by both geological relevance and empirical seismic influence. A radial distance of approximately 300 kilometers from the epicentral location of study area is considered as SSA in general as per the recent practices by several authors and guidelines covered under the National Disaster Management Authority report[35]. This radius is consistent with standard practices in DSHA, as it captures the potential impact of both proximal and distal seismic sources capable of producing ground motions affecting the region.

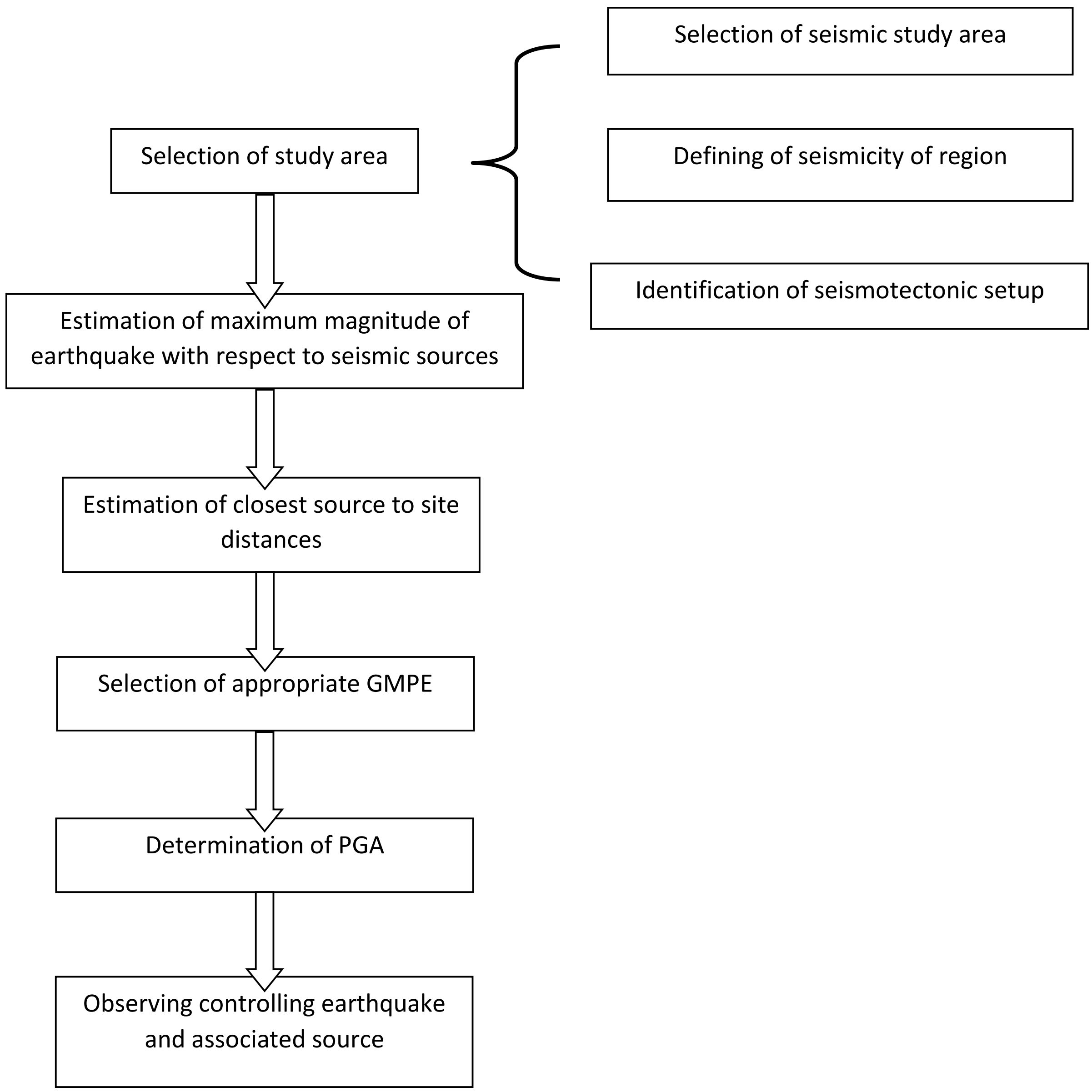

Figure 2: Flow Chart of Methodology for DSHA

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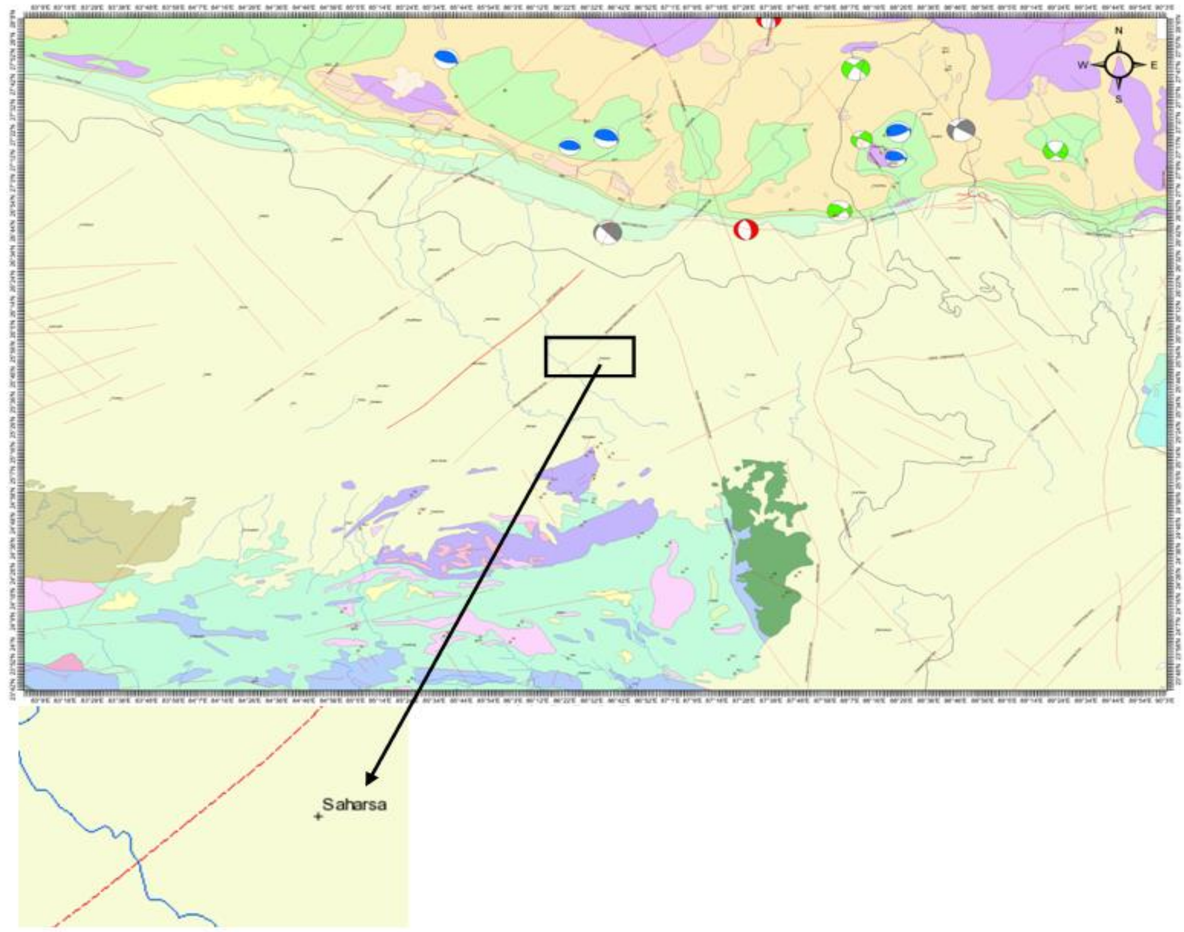

Figure 3: Seiesmotectonic Map of study area and associated seismic study area(GSI-Bhukosh Map)

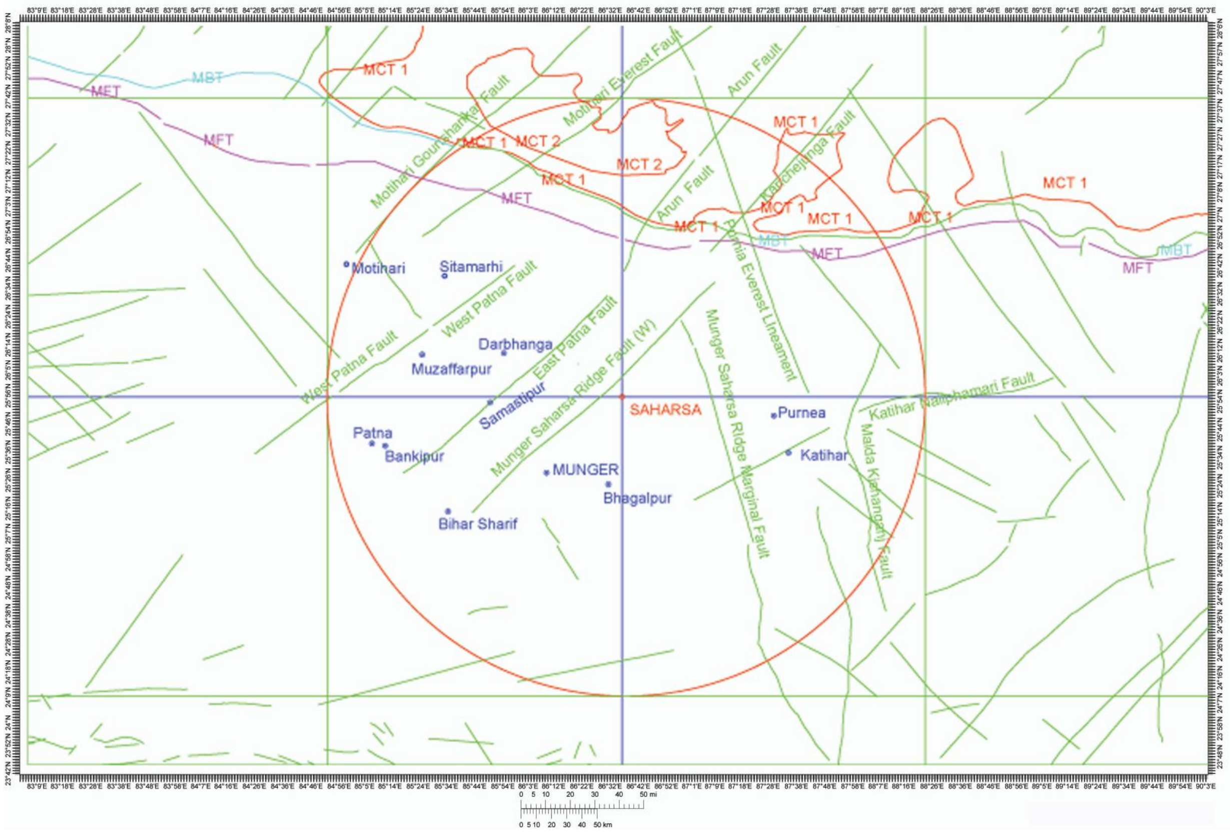

Figure 4: Digitized Seismotectonic map of Saharsa and Adjoining Region (Edited with AutoCAD)

Under the present study a rectangular seismic study area approximately around 500 km has been considered for the analysis of earthquake hazard. The geographical spread of the seismic study region has been considered from 23° 42'N, 83° 09' E to 28° 06'N, 90° 03' E. The selected area encompasses key regional tectonic features including the MCT, MFT, MBT and other associated active fault systems of Himalayan region extending across the Indo-Gangetic plain (Fig. 3). These structures are known to be seismically active due to ongoing convergence between the Indian and Eurasian tectonic plates. Additionally, the inclusion of this broader region ensures coverage of significant historical seismicity, such as the 1934 Bihar–Nepal earthquake, which had substantial effects on Saharsa and surrounding districts. By integrating regional tectonics, historical earthquake data and potential fault rupture characteristics, this spatial extent facilitates a comprehensive evaluation of seismic hazards pertinent to Saharsa's geological and socio-economic context.

Seismicity of the Region

The seismic catalogue pertaining to the considered SSA with respect to study area around latitude 25.8774° N and longitude 86.5928° E has been collected from the portal of the International Seismological Centre[21] Bulletin through event catalogue search option. The tectonic sources present within the Himalayan region are the main cause of seismicity in the study area. The seismicity of the study area has been examined over a significant temporal span from the year 1900 to 2024, encompassing 871 earthquake events including the details of date, time, geographical co-ordinate location, depth of focus and having magnitude greater than 4. These events are geographically confined within latitudes ranging from 23° 42'N to 28° 06'N and longitudes from 83° 09' E to 90° 03' E, clearly reflecting a more focused regional dataset.

Analysis of seismic catalogue: The vast majority (~90%) of the earthquakes have magnitudes ≤ 4.9, signifying frequent low-magnitude seismic activity. Moderate earthquakes (5.0–5.9) account for approximately 9% of the total events. Only 10 events exceeded a magnitude of 6.0, with the maximum magnitude recorded at 8.2, one of the greatest earthquakes in India (1934 Bihar–Nepal Earthquake) alongwith 1988 Nepal earthquake (Mw- 6.8) highlighting the rare but significant potential for high-intensity seismic events (Figures 5 and 6). Overall, the region exhibits predominantly low to moderate seismicity. However, the historical occurrence of a major earthquake (magnitude 8.2) underscores the importance of continuous seismic monitoring and proactive hazard mitigation measures in the area.

Seismotectonic Setup: The seismic study area surrounding Saharsa, located in the central part of the Indo-Gangetic Plain, is characterized by a complex and active seismotectonic framework influenced by Himalayan orogenic processes. The region lies in proximity to several significant tectonic structures that contribute to its seismic potential.

Figures 3 and 4 recognise notably that the area is bound to the north by major Himalayan thrust systems, including the MBT, MFT and MCT, which appears in multiple segments (MCT 1 and MCT 2) and trends NW–SE across the northern edge of the study area. These thrusts run parallel to strike length of Himalayas and are manifestations of ongoing crustal shortening due to the convergence between the Indian and Eurasian plates.

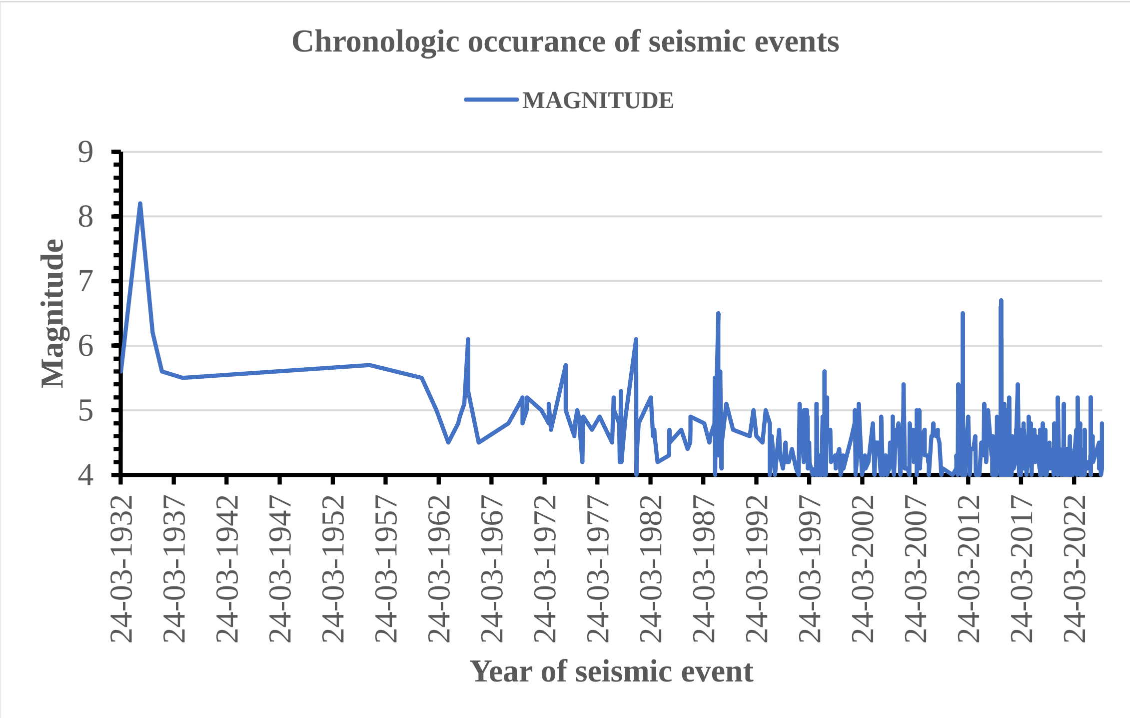

Figure 5: Seismicity of the study area based on past recorded Earthquake events (ISC).

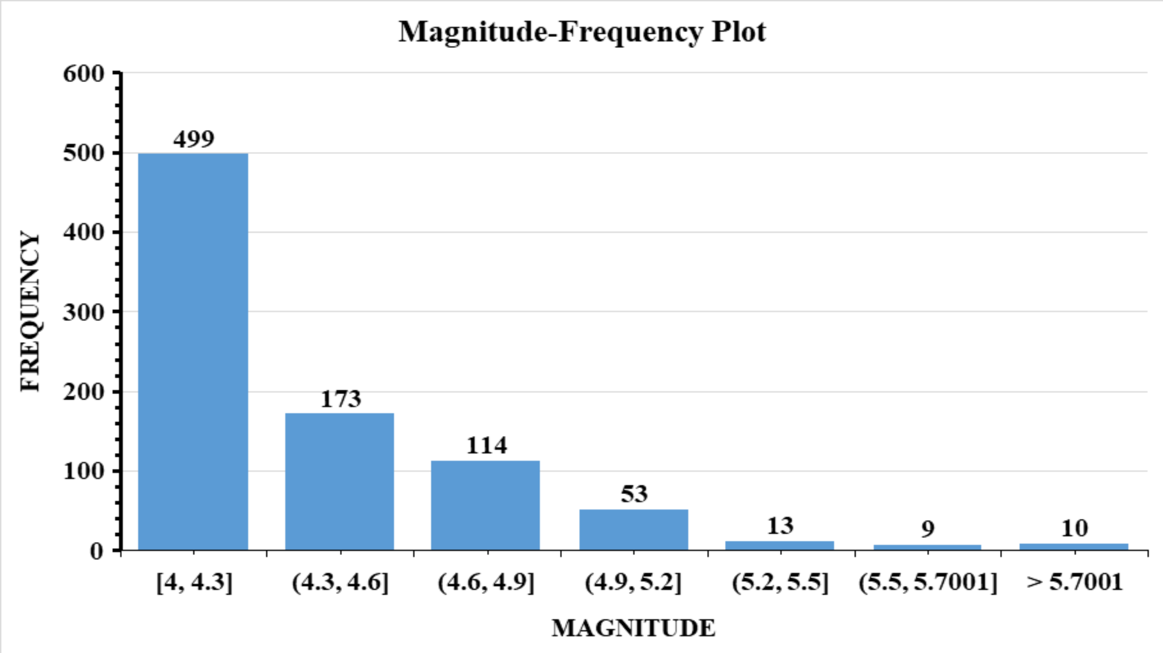

Figure 6: Magnitude Frequency distribution relevant with the study area

Table 1
Details of seismotectonic sources in and around the study area

S.N.	Fault	L_0 (km)	1/3 L_0 (km)	Type	R (km)
1	MSR Fault(W)	224.94	74.98	Reverse Fault (RF)	9.4423
2	MSR Marginal Fault	152.23	50.74	RF	56.34
3	Katihar Nilphamari Fault	234.12	78.04	RF	85.11
4	East Patna Fault	180.65	60.21	RF	53.73
5	Arun Fault	207.19	69.06	RF	79.90
6	Purnia Everest Lineament	263.80	87.93	RF	83.33
7	Kanchejunga Fault	164.29	54.65	RF	89.90
8	West Patna Fault	203.14	67.71	RF	112.08
9	Malda Kishanganj Fault	290.29	96.76	RF	150.20
10	Sainthia Bahmani Fault	158.75	52.91	RF	128.88
11	Motihari Everest Fault	249.70	83.23	RF	162.24
12	Motihari Gourishankar Fault	227.51	75.83	RF	195.71
13	MFT	585.40	195.13	RF	101.68
14	MBT	842.17	280.72	RF	114.17
15	MCT 1	1099.50	366.50	RF	116.44
16	MCT 2	447.50	149.16	RF	146.54

Further south, the region is transected by several regional-scale faults, such as the MSR fault, the West Patna fault, the East Patna fault and the Katihar– Nilphamari fault. These faults are aligned in NE–SW and NW–SE directions and are potentially active, contributing to the intraplate deformation within the Ganga basin.

Additionally, the presence of transverse faults and basement ridges like the MSR highlights the reactivation of pre-existing structural fabrics under current stress regimes. The interaction between Himalayan tectonics and basement structures leads to strain accumulation and release in the form of seismic events. Slow movement results in the elastic strain buildup and sudden release of tectonic strain energy along any of these tectonic features cause earthquake activity. Given the regional tectonic setup and fault density, the Saharsa region is considered moderately to highly seismically active, with potential for both shallow and moderate-depth earthquakes. This underscores the need for continued geophysical monitoring and detailed seismotectonic investigations to better assess seismic hazards in the region.

Estimation of Maximum Magnitude of Sources: In this study, the estimation of the maximum expected magnitude of earthquake (M_{max}) has been carried out with the help of the simplified empirical relations proposed by Wells and Coppersmith[49] based on rupture dimension method. These relations are widely used in seismic hazard analysis due to their ease of application and their empirical derivation from a global dataset of historical earthquakes, correlating fault parameters (e.g. rupture length, rupture area, displacement) with earthquake magnitude. Estimating maximum magnitude solely from past seismicity has limitations, as some faults may not show significant historical earthquakes in the observed catalog but could still contribute to future ground motion. However, it may provide the idea of occurrence of earthquake in future.

However, it is important to note that while the Wells and Coppersmith[49] approach provides a convenient first-order estimate, it does not account for the inherent uncertainties in the earthquake generation process and historical catalogue incompleteness. In contrast, Kumar et al[29], Anbazhagan et al[3], Sinha and Sarkar[47] etc. have used an approach proposed by Kijko and Sellevoll[26] which is a statistically robust method that integrates both instrumental and historical earthquake data, allowing for the incorporation of incomplete and uncertain records and providing confidence intervals for M_{max}. This probabilistic approach is better suited for regions with limited or uncertain seismic history such as intraplate or low-to-moderate seismicity zones.

Despite these advancements, Wells and Coppersmith[49] method remains a practical and widely accepted tool, particularly in preliminary hazard studies, due to its simplicity and global applicability. It serves as a useful benchmark, especially when detailed fault geometry or sufficient seismicity data are unavailable. Extensive earthquake studies have revealed that faults typically do not rupture along their entire length or area during a single event; instead, only a portion of the fault ruptures, which is sufficient to generate a significant earthquake[28].

The worldwide data suggests that fault rupture length lies between half to one third of the total fault length and the rupture length of a fault provides the information of maximum magnitude of earthquake[33]. The rupture length of approximately 3/4 to the total length of fault is taken in general for the faults having length less than 50 km[7]. Wells and Coppersmith[49] suggested the following relationship of moment magnitude (M_w) of earthquake with respect to given surface rupture length (L) separately for Strike slip Faults (SSFs), RFs and Normal faults (NFs). Additionally, another relationship among Rupture Width (R_w) and moment magnitude (M_w) has also been used in this study.

$$Mw = 5.16 + 1.12 \text{ Log } L \text{ (SSF)} \quad (1)$$
$$Mw = 5.00 + 1.22 \text{ Log } L \text{ (RF)} \quad (2)$$
$$Mw = 4.86 + 1.32 \text{ Log } L \text{ (NF)} \quad (3)$$
$$\text{Log } (R_w) = -1.01 + 0.32M_w \quad (4)$$

Depth of Energy Release: For the calculation of depth of energy release (D_z), general focal depth (GFD) was assumed to be 20 km because moderate earthquake occurrence in the region falls in the range of 10 km to 40 km depth and non seismogenic depth (NSD) was taken as 3 km[11,12]. The value of dip angle α was considered as 15° for thrust fault and 90° for the NF and SSF. The given equation is used for the calculation of value of D_z:

$$D_z = NSD + GFD – (R_w/2) \sin\alpha \quad (\text{if } R_w \leq GFD) \quad (5)$$
$$D_z = NSD + (R_w/2) \sin\alpha \quad (\text{if } R_w \leq GFD) \quad (6)$$

Table 2
Estimation of Maximum Magnitude, Rupture Width and Depth of Energy Release with respect to Seismotectonic Sources

S.N.	Fault	M_{max}	R_w (km)	D_z (km)	D_e (km)
1	MSR Fault(W)	7.86	32.229	19.114	21.319
2	MSR Marginal Fault	7.66	27.672	16.836	58.807
3	Katihar Nilphamari Fault	7.89	32.736	19.368	87.290
4	East Patna Fault	7.75	29.585	17.792	56.604
5	Arun Fault	7.82	31.211	18.605	82.045
6	Purnia Everest Lineament	8.05	36.976	21.488	86.055
7	Kanchejunga Fault	7.7	28.509	17.254	91.548
8	West Patna Fault	7.81	30.971	18.485	113.596
9	Malda Kishanganj Fault	7.93	33.868	19.934	151.521
10	Sainthia Bahmani Fault	7.68	28.129	17.064	130.013
11	Motihari Everest Fault	7.92	33.570	19.785	163.447
12	Motihari Gourishankar Fault	7.87	32.372	19.186	196.648
13	MFT	8.37	46.818	26.409	105.058
14	MBT	8.56	53.960	29.980	118.044
15	MCT 1	8.71	59.880	32.940	121.012
16	MCT 2	8.23	42.156	24.078	148.507

The distance to the energy release D_e is estimated using the depth to the zone of energy release (D_z) and the epicentral distance (E_p) between source to site as:

$$D_e = (E_p^2 + D_z^2)^{0.5} \quad (7)$$

The estimated values as per the eqs. (1-7) are presented in table 2.

GMPEs: The selection of appropriate GMPEs is crucial for accurate seismic hazard assessment. Selvan and Sinha[44] evaluated the performance of 16 GMPEs against recorded ground motion data in the Western and Central Himalayas and the Indo-Gangetic Plains. Their analysis aids in selecting suitable GMPEs for specific regions, enhancing the reliability of DSHA outcomes.

Recent advances such as those highlighted in Selvan and Sinha[44], evaluate a suite of 16 global and regional GMPEs under varying tectonic regimes to identify models that provide optimal performance across different magnitude and distance bins. These modern GMPEs incorporate more extensive datasets, better site classification schemes and refined formulations that account for both shallow crustal earthquakes and subduction interface events. Current best practices, including those adopted by the Global Earthquake Model (GEM) and United States Geological Survey (USGS) National Seismic Hazard Model (NSHM) methodologies, recommend using a logic-tree approach that includes multiple GMPEs to accommodate model uncertainty. This allows for a more robust hazard characterization, especially in data-sparse regions like eastern India.

In this study, PGA values have been estimated using GMPEs developed by Abrahamson and Litehiser[1] and Sharma[45]. These GMPEs, although developed for specific tectonic environments, have been widely used in Indian seismic hazard studies due to their early availability and regional relevance. Abrahamson and Litehiser's[1] model accounts for distance attenuation in stable continental regions, while Sharma's[45] GMPE is tailored to Indian seismicity and reflects empirical ground motion characteristics observed during Himalayan and intra-plate events.

However, these models are considered simplified in comparison to recent probabilistic frameworks and they may not comprehensively account for site conditions, stress drop variations and depth-dependent attenuation effects. Furthermore, the regional bias and the limited dataset used in developing these models can introduce epistemic uncertainty when applied to diverse tectonic settings like the Indo-Gangetic Plain. The equations for horizontal and vertical PGA as per Abrahamson and Litehiser[1] are given as:

$$\log_{10}A_h\ (g) = -0.62+0.177M-0.982\log_{10}(r + e^{0.284M}) + 0.132F - 0.0008E.r \quad (8)$$

$$\log_{10}A_v\ (g) = -1.15+0.245M-1.096\log_{10}(r + e^{0.256M})+0.096F-0.0011E.r \quad (9)$$

where A_h (g) and A_v (g) are horizontal PGA and vertical PGA respectively, r is the distance in kilometers to the closest approach of the zone of energy release, M is the moment magnitude, F is the dummy variable that is 1 for reverse or oblique faults and 0 otherwise, E is a dummy variable that is 1 for interplate region and 0 for intraplate regions.

Another set of equations for horizontal and vertical PGA as per Sharma[45] is given as:

$$\log_{10}A_h\ (g) = -1.072+0.3903M-1.21\log_{10}(X + e^{0.5873M}) \quad (10)$$

$$\log_{10}A_v\ (g) = -2.87+0.634M-1.16\log_{10}(X + e^{0.62M}) \quad (11)$$

where M is the magnitude and X is the hypocentral distance of point of consideration from the source. The values of parameter 'X'[45] and 'r'[1] have been considered equivalent and considered same as the value of 'R' from table 1.

Results and Discussion

Seismicity and Seismotectonics: Analysis of the magnitude-frequency distribution reveals that the majority of recorded events lie within the 4.0–4.3 magnitude range, with the frequency dropping sharply for higher magnitudes. This reflects moderate but consistent seismic activity alongwith rare or low probability of major seismic events. A histogram representation of this distribution clearly illustrates the dominance of low-magnitude events, indicative of strain accumulation along minor and major fault lines.

The Saharsa region lies adjacent to some of the most prominent tectonic structures of the Himalayan seismic belt including the MBT, MCT and MFT. The digitized seismotectonic map, extracted from the Bhukosh portal of the GSI and prepared using AutoCAD for spatial accuracy, reveals the presence of 16 seismic sources around Saharsa, each capable of generating significant ground motion. One of the most critical sources is the Munger–Saharsa Ridge Fault (W), which is considered capable of generating moderate-to-large magnitude earthquakes due to its proximity to Himalayan deformation zones and its tectonic alignment with NE-SW trending faults in the region. Other significant faults include the West Patna Fault, North Patna Fault and Samastipur Fault, all contributing to the regional strain accumulation and seismic risk.

Maximum Magnitude: The maximum credible earthquake (MCE) magnitudes were estimated using the empirical relationships (equation 1-3) by Wells and Coppersmith[49], based on fault rupture length and slip-type classifications. Though alternative statistical approaches like Kijko and Sellevoll[26] exist and are particularly useful in sparse seismicity regions, the deterministic approach ensures a conservative basis for hazard definition of worst-case scenario ground motions for structural safety. The assigned maximum magnitude across the existing 16 seismic sources has been represented in table 2, considering its mapped length and strike-slip character.

PGA: To quantify bedrock level ground motion, two widely recognized GMPEs were selected and were applied based on their suitability for the tectonic setting of the region covering both intraplate and Himalayan characteristics:

- Abrahamson and Litehiser[1] GMPE yielded a PGA of 0.27g.
- Sharma[45] GMPE gave a PGA of 0.33g.
- The mean value of both PGA was estimated as 0.30g.

The PGA values obtained from these GMPEs were compiled and presented in table 3 and fig. 7, offering clear visualization of fault-specific hazard levels at the latitude 25.8774° N and longitude 86.5928° E of the Saharsa. The highest among the estimated PGA was controlled by the presence of Munger Saharsa ridge Fault(W).

Comparison of PGA Results with IS 1893 Zone Map: According to IS 1893[22] seismic zoning, Saharsa lies within seismic Zone IV and V, with a basic zone factor of 0.24g and 0.36g respectively. The deterministic PGA values obtained (0.27g–0.33g) were found comparable with this value, indicating that local site effects and proximity to specific faults such as the Munger–Saharsa Ridge fault may produce expected ground motion of the zone average. This supports the need for microzonation studies and customized seismic design for infrastructure.

Conclusion

This DSHA study for the Saharsa region integrates seismological, geological and geotechnical inputs to evaluate seismic hazard in a deterministic framework. The analysis of 871 earthquakes and identification of 16 nearby active faults reveal that the region faces moderate to high seismic hazard potential. The use of Wells and Coppersmith[49] for maximum magnitude estimation and two validated GMPEs for ground motion calculations underline the need for stringent earthquake-resistant design practices in the region, consistent with provisions of IS 1893[22]. The conclusions are:

1. Being situated in the foothills of Himalayas, Saharsa region is exposed to moderately high level of seismicity.
2. Besides various seismotectonic sources, the maximum PGA at bedrock level is contributed from Munger Saharsa ridge fault (W) and has a mean value of 0.30g obtained from PGAs of Abrahamson and Litehiser[1] and Sharma[45] for Saharsa and adjoining region.
3. The study provides essential input for earthquake-resistant infrastructure design, site-specific seismic safety assessments and regional development planning and is very useful in microzonation studies.
4. The nearby sources such as MSR Marginal Fault, East Patna Fault, Katihar Nilphamari Fault, MBT, MCT and MFT are having major contributions towards PGA.
5. In terms of future aspects, steps for reducing vulnerability and earthquake losses must be taken and earthquake resistance design should be focused.

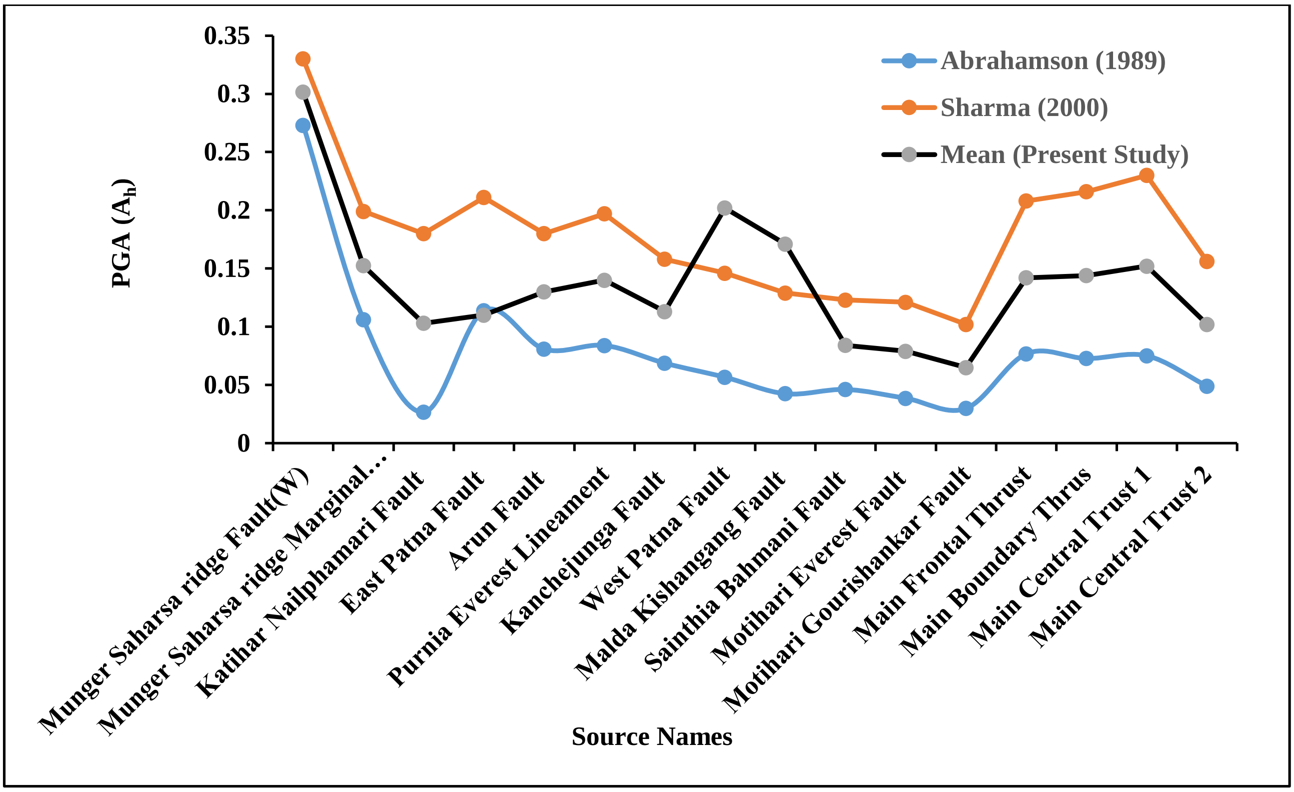

Figure 7: Graphical representation of PGA (A_h) (g) with respect to controlling seismotectonic sources

Table 3
Calculated Peak Horizontal Acceleration A_h (g).

S.N.	Fault	E	F	Abrahamson Ah	Sharma Ah	Mean value
1	MSR Fault(W)	1	1	0.27302	0.33	0.3015
2	MSR Marginal Fault	1	1	0.10606	0.199	0.1525
3	Katihar Nilphamari Fault	1	1	0.0267	0.18	0.103
4	East Patna Fault	1	1	0.11386	0.211	0.11
5	Arun Fault	1	1	0.08077	0.18	0.13
6	Purnia Everest Lineament	1	1	0.08396	0.197	0.14
7	Kanchejunga Fault	1	1	0.06872	0.158	0.113
8	West Patna Fault	1	1	0.05665	0.146	0.202
9	Malda Kishanganj Fault	1	1	0.04249	0.129	0.171
10	Sainthia Bahmani Fault	1	1	0.04616	0.123	0.084
11	Motihari Everest Fault	1	1	0.03858	0.121	0.079
12	Motihari Gourishankar Fault	1	1	0.02993	0.102	0.065
13	MFT	1	1	0.07682	0.208	0.142
14	MBT	1	1	0.07274	0.216	0.144
15	MCT 1	1	1	0.07504	0.23	0.152
16	MCT 2	1	1	0.04898	0.156	0.102
		Max		**0.27302**	**0.33**	**0.3015**

6. The digitization of seismotectonic features using AutoCAD and the integration of Bhukosh GSI data, further strengthen the spatial accuracy of the fault-source model.
7. This approach may be used for another similar seismic region as well.

While Abrahamson & Litehiser[1] and Sharma[45] remain useful for comparative and preliminary analyses, incorporation of recent GMPEs (as evaluated by Selvan and Sinha[44] is recommended for enhanced reliability and defence of seismic hazard assessments. Overall, this study employs a simplified deterministic approach, the results align well with regional geological understanding and highlight the importance of local fault geometry in hazard evaluation. Future work may extend this analysis through probabilistic seismic hazard assessment and incorporation of local site studies for better design and planning.

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