Evaluation of seismic hazard for Cuttack District, Odisha using regional attenuation models

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Abstract

This research conducts a comprehensive seismic hazard analysis for Cuttack District, Odisha, India, utilizing both deterministic and probabilistic approaches within a 300 km radius of Cuttack city. An earthquake catalog, spanning from 1837 to 2022 AD, has been compiled and homogenized using local empirical relationships. The completeness of this catalog is assessed via the Cumulative Visual Inspection (CUVI) method. Seismicity parameters and maximum magnitudes for various sources are meticulously evaluated. Ground motion estimates are derived from faults within the study area using region-specific Ground Motion Prediction Models (GMPMs), with normalized weight factors assigned to each model through the Log-Likelihood (LLH) method.

The seismic hazard is quantified by peak ground acceleration (PGA) and hazard curves are generated to evaluate PGA values at 2%, 5% and 10% probabilities of exceedance over 50 and 100 years. Uniform Hazard Spectra (UHS) are developed for spectral periods ranging from 0.0 to 2.5 seconds. The results show excellent agreement with previous studies. Additionally, a spatial variation map of PGA values for the district indicates that PGA values range from 0.0392g to 0.102g.

Keywords: Cuttack District, DSHA, PSHA, LLH, PGA, Hazard Curve, Uniform Hazard Spectra.

Introduction

Earthquakes, as natural catastrophes, result in substantial casualties and damage to infrastructure and assets globally. These seismic events manifest across a spectrum of magnitudes, from minor tremors barely discernible to the human senses but detectable by advanced seismographic equipment, to major quakes that can precipitate extensive destruction including ground shaking, landslides, flooding and tsunamis. The accurate prediction of seismic activity is hindered by the complex interplay of geological conditions, soil characteristics and other site-specific variables. According to the IS 1893:2016 standards, the seismic risk in India is stratified into four distinct zones, reflecting varying levels of seismic hazard[11].

Although peninsular India is typically regarded as tectonically stable, certain regions have experienced significant seismic activity resulting in severe damage. Prominent seismic events include the Latur earthquake in Maharashtra, the Bhuj earthquake in Gujarat and the Jabalpur earthquake in Madhya Pradesh. Recent destructive earthquakes underscore the urgent need for enhanced risk reduction strategies. Comprehensive seismic hazard assessments are vital for mitigating the impacts of major seismic events on both human lives and infrastructure. These evaluations are integral to the development of earthquake-resistant design within the infrastructure sector. In India, researchers have undertaken localized seismic risk assessments to effectively understand and address the potential earthquake hazards.

Recent studies on seismic activity have been undertaken for key cities including Silchar[18], Guwahati[20], Warangal[25], Kolkata[7], Dhanbad[27], Amaravati[23], Bangalore[2] and Chennai[19]. This study focuses on assessing deterministic and probabilistic seismic hazards within a 300km radius from the district headquarter. Situated in the eastern part of peninsular India, the study region includes active seismic sources such as faults and lineaments. Some important seismic sources in the region are Brahmani fault, Vamsadhara fault and Singhbhum lineament. According to IS: 1893-1 2016[11], the area is classified as zone III with a zone factor of 0.16g.

Despite being less seismically active in comparison to northeastern India, the district faces high seismic risk due to inadequate earthquake-resistant design of buildings, the presence of dilapidated structures, archaeological sites and dense population. Any seismic activity in such densely populated regions would adversely impact the region's economic development. These factors highlight the importance of conducting seismic hazard studies for Cuttack.

Geology and Location

Cuttack, a historic and economically significant city in Odisha, is strategically positioned at the confluence of two principal rivers, the Mahanadi and Kathajodi, approximately 30 kilometers from Bhubaneswar, the State capital. As depicted in fig. 1, the district's geographical location is notable. According to the Indian Standard (IS) 1893:2016[11] guidelines, Cuttack is classified within seismic zone-III, indicating a moderate seismic hazard.

The region has a history of experiencing low to moderate seismic events which historically have not resulted in substantial structural damage. Notably, on May 21, 2014, an earthquake measuring 6 on the Richter scale occurred in the Bay of Bengal, resulting in tremors felt in various parts of Cuttack and neighboring cities. However, due to localized

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soil amplification effects, no significant damage was reported in the city.

Cuttack district comprises rocks from Archaean to Late Holocene age, distributed more or less from west to east. Eastern Ghat supergroup forms the oldest suit of rocks in this area. It occupies the western high land and can be classified into Khondalite and Charnockite group. Khondalite group contains quartz-feldspar-garnet-sillimanite graphite schist gneiss and granetiferous quartzite. Charnockite group comprises acid to intermediate charnockite, basic charnockite and pyroxene granulite. The geological map of the study area is shown in fig. 2.

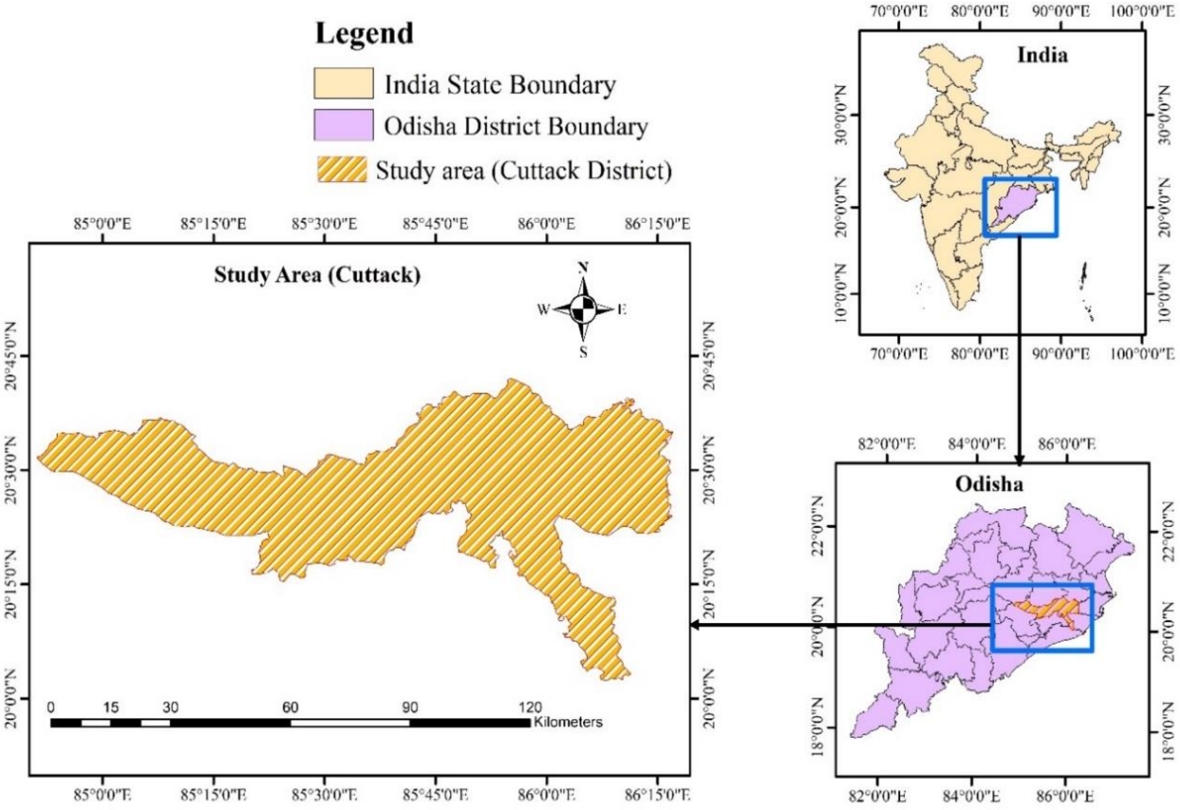

Figure 1: Study area location map

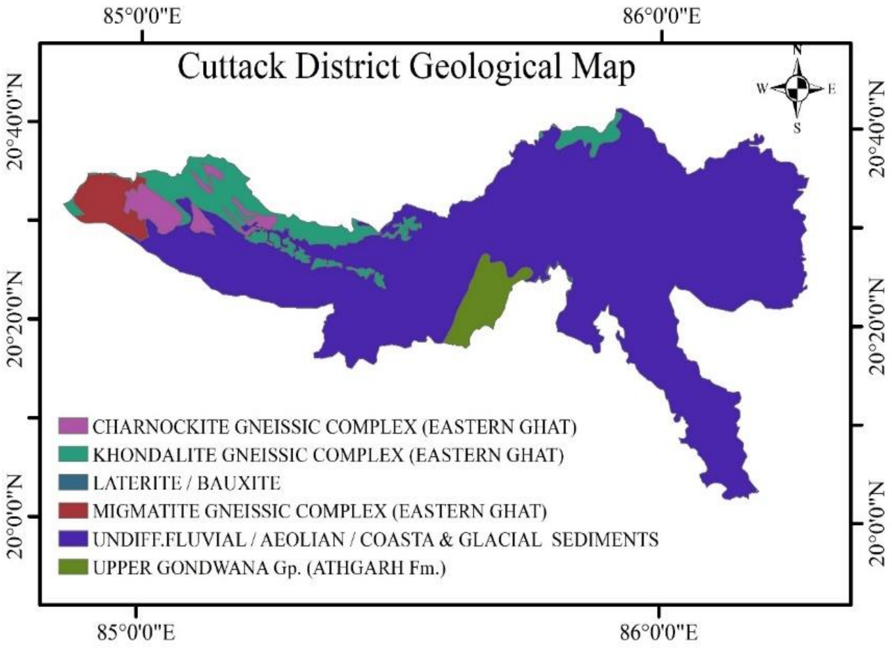

Figure 2: Geological map of Cuttack

Material and Methods

A seismic catalog for a specific area gives detailed insights into past earthquakes including their location, depth and magnitude, facilitating the identification of seismic activity in that region. For our research, we compiled a seismic event catalog covering both pre-instrumental and instrumental seismic events within a circular area with a 300 km radius, centered around the district headquarters of Cuttack. The geographical coordinates of Cuttack are 20.46N latitude and 85.88E longitude. Data for past events within this 300 km radius were compiled from various agencies such as the National Centre for Seismology (NCS), International Seismological Centre (ISC) and some relevant literature[12,16,21].

A total of 321 events were collected providing information such as coordinates of the epicenter, depth of the hypocenter, date, month, year and magnitude, measured in different scales such as body wave magnitude (mb), local magnitude (ML) and surface wave magnitude (Ms). To ensure consistency in the catalog, all collected events were converted to moment magnitude (Mw) using region-specific conversion relations proposed by Trianni et al[28].

To distinguish main seismic events from foreshocks and aftershocks, earthquake data must undergo de-clustering. Earthquake occurrences follow a Poisson distribution, indicating random and independent events with no consideration for time, size, or location. Therefore, it is necessary to eliminate all foreshocks and aftershocks before conducting seismic hazard analysis. In this study, a total of 321 events were de-clustered using the static window method[22]. This method groups the events into different clusters and the event with the maximum magnitude in each category is identified as the main shock while the other events are classified as foreshocks or aftershocks. This method was applied to the entire dataset to isolate independent events, resulting in a total of 116 main events identified after de-clustering.

Numerous faults have been identified in the vicinity of Cuttack, with some displaying movement during the Holocene epoch according to SEISAT[5]. One notable fault is the Brahmani fault near Bonaigarh. Additionally, the Mahanadi river flows through a graben structure and the Seismotectonic atlas[5] indicates the presence of several deep-seated faults beneath the Mahanadi delta. The Mahanadi and Brahmani grabens, the Mahanadi delta and sections of Balasore and Mayurbhanj districts are classified as earthquake risk zone-III. Other significant seismic sources in the area include the Vamsadhara fault, Malayagiri lineament, F1 (part of the Mahanadi graben), Singhbhum shear zone and Eocene hinge zone. Fig. 3 depicts the seismotectonic map showcasing de-clustered events and seismic sources.

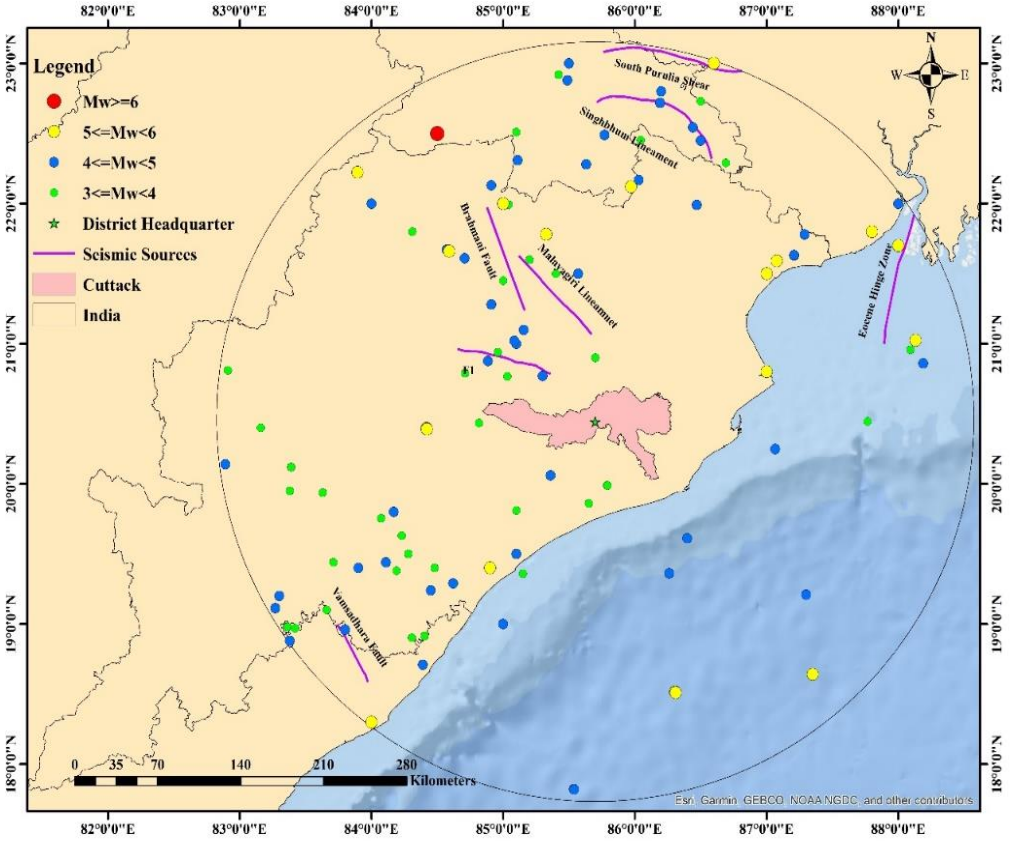

Figure 3: Seismotectonic map of the study region

Data completeness and seismicity of the region: Seismic hazard assessment for any area relies mostly on its historical seismic activity. Therefore, to predict ground motion from future earthquakes accurately, it is essential to understand the region's seismicity pattern based on past data. The accuracy of estimating seismic recurrence rates depends on having a complete dataset. To assess catalog completeness, the cumulative visual inspection (*CUVI*) method is utilized. This method involves plotting a graph of the cumulative number of earthquakes against time duration. The catalog is deemed complete for periods where the earthquake occurrence rate remains constant.

In our study, completeness analysis was conducted by dividing the earthquake catalog into magnitude intervals, starting from magnitude 3.0 with a 1.0 increment. Once the recurrence relationship for the region is determined, it becomes possible to estimate the maximum magnitude and frequency of various magnitude events.

The Gutenberg-Richter relationship[8] is commonly used for this purpose, providing a means to predict the annual earthquake occurrence rate as expressed in eq. 1:

$$(\lambda_M) = a - bM \tag{1}$$

where λ_m is the mean annual rate of exceedance of magnitude *M*, '*a*' and '*b*' are positive real constants in which '*a*' denotes the seismic activity (log number of events with *M* = 0) and '*b*' describes the relative abundance of large to small shocks. The *a* and *b* values of each seismic source were evaluated individually and the seismicity of the region is calculated by taking the whole region where *a* and *b* values are 3.77 and 0.94 respectively.

Maximum magnitude estimation: The earthquake catalog for any region only captures a fraction of its total seismic activity, making it challenging to fully grasp the region's seismic potential. The maximum magnitude (M_{max}) represents the highest possible magnitude earthquake the study area may face or the seismic sources in the region can produce.

However, the maximum observed magnitudes of each seismic source may not reflect the source's full potential, as the catalog only caters to total events for the past 185 years. Therefore, in the present work, we estimate M_{max} for each seismic source using two methods:

- **Incremental method**: This method is a simple method, proposed by Jaiswal et al.[13] In this method, the largest earthquake magnitude observed in a particular region was increased by 0.5 magnitude. It is a simple method that has been adopted by many researchrs[17,18,20.]
- **Kijko Method[15]:** In this method, maximum magnitude is estimated by considering doubly truncated Gutenberg-Richter relation as given below. This method is only valid when b for the region is known.

$$M_{max} = M_{max}^{obj} + \frac{E_1(n_2)+E_1(n_1)}{\beta e^{-n_2}} + M_{min} e^{-n} \tag{2}$$

In this equation, M_{max} represents the largest potential earthquake magnitude, M_{max}^{obj} signifies the highest observed magnitude on each fault and n represents the total number of earthquakes above a minimum magnitude threshold (in this study, the minimum magnitude considered for the region of interest is 3). E_1 denotes an exponential integration function which can be calculated as follows:

$$E_1 = \left(\frac{n^2+a_1 n+a_2}{n(n^2+b_1 n+b_2)}\right) e^{-n} \tag{3}$$

$$n_1 = \frac{n}{\left\{1-e^{-\beta(M_{max}-M_{min})}\right\}} \tag{4}$$

$$n_2 = n_1 e^{-\beta(M_{max}-M_{min})} \tag{5}$$

where a_1, a_2, b_1 and b_2 are constants[1]. The plot of bounded *G-R* recurrence of magnitude is shown in fig. 4. Table 1 enlists the values of estimated magnitude (M_{max}) for each source obtained from the two different methods. The highest magnitude value of M_{max} obtained from either method for each fault is considered to estimate hazard values.

Ground motion model selection: In the seismic hazard assessment, selecting the appropriate ground motion prediction equation (*GMPE*) is a critical step. For this study, three GMPEs i.e. RGTY-07[14], BAJAJ-19[3] and NDMA-11[12] suitable for peninsular India were chosen. *GMPEs* vary in complexity with simple ones relying on magnitude and distance parameters while more complex ones require additional fault rupture parameters, fault types and site characteristics to estimate peak ground motion.

Table 1
Maximum Magnitude Estimation by different Methods

Name of the Source	M_{max}^{obj}	M_{max}	M_{max}	$M_{max}^{Estimated}$
Brahmani Fault	6.26	6.8	7.14	7.14
Singhbhum Shear	5.87	6.4	6.73	6.73
Eocene Hinge Zone	5.7	6.2	6.26	6.26
Malayagiri Lineament	5.2	5.7	6.1	6.1
F1	5.02	5.5	5.56	5.56
Vamsadhara Fault	5.96	6.5	6.88	6.88

To determine the most suitable GMPE, the Log-likelihood (LLH) method proposed by Scherbaum et al[24] was utilized to assign data support index (DSI) values to different models. Subsequently, the logic tree method proposed by Delavaud et al[6] was employed to assign weightage factors and rankings to the selected GMPEs. The LLH for each model was calculated using a specific equation, with lower LLH values indicating higher rankings for the GMPEs.

$$LLH\ (g,x) = \frac{1}{N}\sum_{i=1}^{N} \log_2\left(g(x_i)\right) \tag{6}$$

where $x_1, x_2, \ldots, x_N$ are the number of ground motion samples computed using the GMPE model (g) and g(xi) represents the likelihood function for a single GMPE. Utilizing the LLH value, the weight (w_i) of the GMPE model g_j (j = 1, 2, …, M) can be estimated with the following equations:

$$w_i = \frac{2^{-LLH(g_i,x)}}{\sum_{i=1}^{N} 2^{-LLH(g_i,x)}} \tag{7}$$

$$DSI_i = 100\,\frac{w_i - w_{unif}}{w_{unif}} \tag{8}$$

Here DSI is the data support index and $w_{unif} = \frac{1}{M}$, M is the number of GMPEs considered. Fig. 5 shows the suitability of the chosen ground motion prediction models (GMPEs) for the study area by comparing them with recorded strong-ground motion data from the 2000 Jabalpur earthquake, which had a magnitude of M_w=4.7[26]. After the analysis, BAJAJ-19[3] and RGTY-07[14] models were used with weightage factors of 0.51 and 0.49 respectively. The NDMA-11[12] was not considered further because of the negative *DSI* value. The LLH values, *DSI* rank and weightage assigned to different GMPEs are presented in table 2.

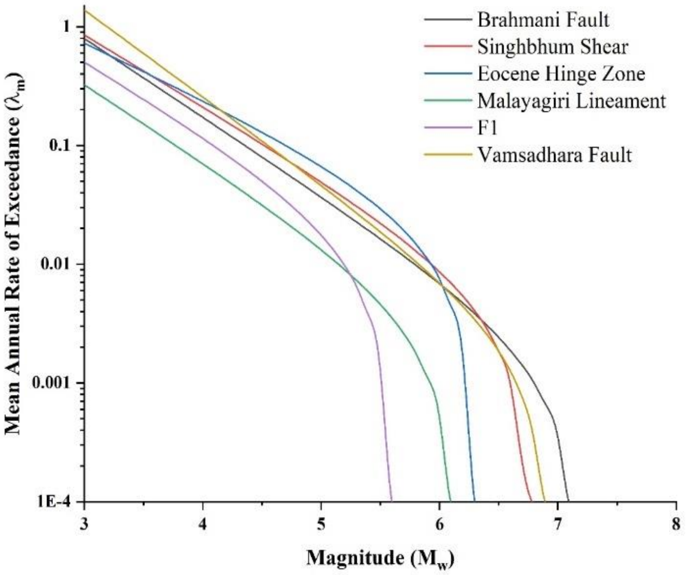

Figure 4: Bounded G-R recurrence plot of Mmax values for different sources

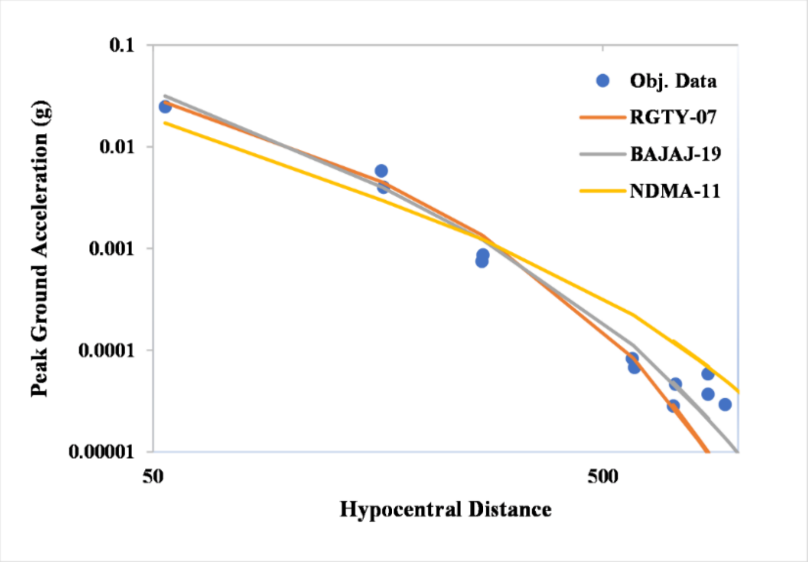

Figure 5: Comparison of GMPEs with Station observed data of Jabalpur earthquake (Mw=4.7)

Table 2
Comparison of selected GMPEs

GMPE	LLH	w_i	DSI_i	Rank	Weightage
RGTY-07	0.510409	0.337725	1.297246	2	0.49
BAJAJ-19	0.443867	0.353667	6.078812	1	0.51
NDMA-11	0.640481	0.308608	-7.43605	N/C	N/C

Seismic hazard analysis

Deterministic seismic hazard analysis (DSHA) and probabilistic seismic hazard analysis (PSHA) are commonly employed methodologies to assess the seismic risk of a region. Both approaches aim to predict the level of ground shaking, typically measured in terms of ground motion parameters such as peak ground velocity, peak ground acceleration (PGA), and/or spectral acceleration (SA), based on past seismic activity and estimated future earthquake magnitudes. DSHA focuses on determining the worst-case scenario earthquake without considering its likelihood during the structure's design life, leading to conservative results that may not be cost-effective. Nonetheless, such analyses are valuable in the preliminary stages of seismic hazard assessment and for critical structures like nuclear power plants, telecommunication towers, dams and bridges.

In this study, DSHA is conducted for Cuttack district using earthquake catalogs, identifying six earthquake sources with magnitudes exceeding 3 within a 300 km radius. Linear tectonic features provided by SEISAT[5] are utilized and aerial sources are excluded. Selecting appropriate ground motion prediction models is crucial, with two GMPEs chosen for this study: one by Bajan and Angbazgan[3], deemed best suited for the region and another by Kanth and Iyengar[14] for the peninsular India (PI) region. Weightage factors of 0.51 for BAJAJ-19 and 0.49 for RGTY-07 are assigned based on comparison using the LLH method, slightly favoring BAJAJ-19. From the DSHA, the PGA value at the district headquarter is determined to be 0.065g, with the Brahmani fault identified as the dominant seismic source in the region.

Estimating potential ground motions at a specific site for a given probability of occurrence over a defined period relies on understanding the cumulative probabilities associated with earthquake size, locations and ground shaking levels.

Cornell[4] developed the probabilistic seismic hazard method to address the uncertainties inherent in this process. This method, known as probabilistic seismic hazard analysis (PSHA), considers the probabilities of different earthquake magnitudes, hypo-central distances and ground motion levels.

By combining these probabilities, PSHA provides a way to determine the expected ground motions at a site within a specified probability of occurrence over a given exposure period. The main output of PSHA is a hazard curve which illustrates ground motion parameters such as PGA or SA as a function of the frequency of exceeding a certain level of ground motion. Each seismic source contributes to the hazard curve, considering all potential combinations of magnitudes, hypo-central distances and resulting ground shaking levels.

Fig. 6 presents the spatial variation of PGA values for a 2475-year return period (2% probability of exceedance in 50 years) for the Cuttack district. PGA values in the district range from 0.0392g to 0.102g, indicating variability in ground motion intensity across the region. The hazard curve illustrates the frequency of ground motion exceeding various levels. Fig. 7 depicts a plot showcasing the contributions of six seismic sources to ground motions for the Cuttack district headquarters.

Notably, the Brahmani fault emerges as the most significant source of vulnerability, located at a hypo-central distance of 88.12 km with a maximum magnitude of 7.14 (M_w). Additional vulnerable sources for Cuttack including F1, Malayagiri lineament, Singh him shear zone, Eocene hinge zone and Vamsadhara fault, are also depicted in fig. 7.

To further analyze hazard contributions from different combinations of magnitude and hypo-central distance, a disaggregation plot serves as a valuable tool. By summing the hazard curves obtained from all sources, the cumulative hazard curve for the district headquarters can be derived as shown in fig. 7. The ground motion levels were assessed using hazard curves for probabilities of exceedance at 2%, 5% and 10% over 50 and 100 years.

Fig. 8 illustrates a comparison of peak ground acceleration (PGA) values for Cuttack district headquarters for these probabilities. It is evident from the figure that PGA values obtained from the probabilistic seismic hazard analysis (PSHA) method for the district headquarters at 2% and 10% probabilities of exceedance over 50 years are 0.06g and 0.04g respectively. Notably, the Brahmani fault emerges as the vulnerable source producing the highest ground motion levels in both deterministic seismic hazard analysis (DSHA) and PSHA methods.

In this study, uniform hazard spectra (UHS) are utilized which represents spectral curves derived from probabilistic seismic hazard analysis (PSHA). These curves illustrate how spectral acceleration varies across different periods for the same probabilities of exceedance. Specifically, UHS curves for Cuttack city center are plotted for probabilities of exceedance of 2%, 5% and 10% over 50 and 100 years, as depicted in fig. 9. Notably, the spectral acceleration at 0 seconds is referred to as "zero spectral acceleration" or PGA.

Results and Discussion

The results of the deterministic analysis (DSHA) conducted for the Cuttack district headquarter indicate that the Brahmani fault is the primary contributor to the seismic hazard in the area. The highest PGA estimated through DSHA of Cuttack was 0.065 g. Huded and Dash[10] performed the DSHA for the entire State of Odisha and determined PGA of 0.12g for Cuttack. According to the NDMA[12] report from 2011, the PGA for Bhubaneswar city, located 30km from the Cuttack district headquarters, was measured at 0.02g for a 10% probability of exceedance (PE) over 50 years and 0.04g for a 2% PE over the same period. However, in our current study, the PGA for the Cuttack district headquarters at a 10% PE is recorded as 0.04g.

Huded and Dash[10] conducted a probabilistic analysis (PSHA) for the entire Odisha State using the RCRISIS computer program. Their predicted PGA values for Cuttack, considering a 10% and 2% PE over 50 years, are 0.009g and 0.023g respectively. These findings align closely with our study's results. A comparison of PGA values from our study with previously published data is provided in table 3.

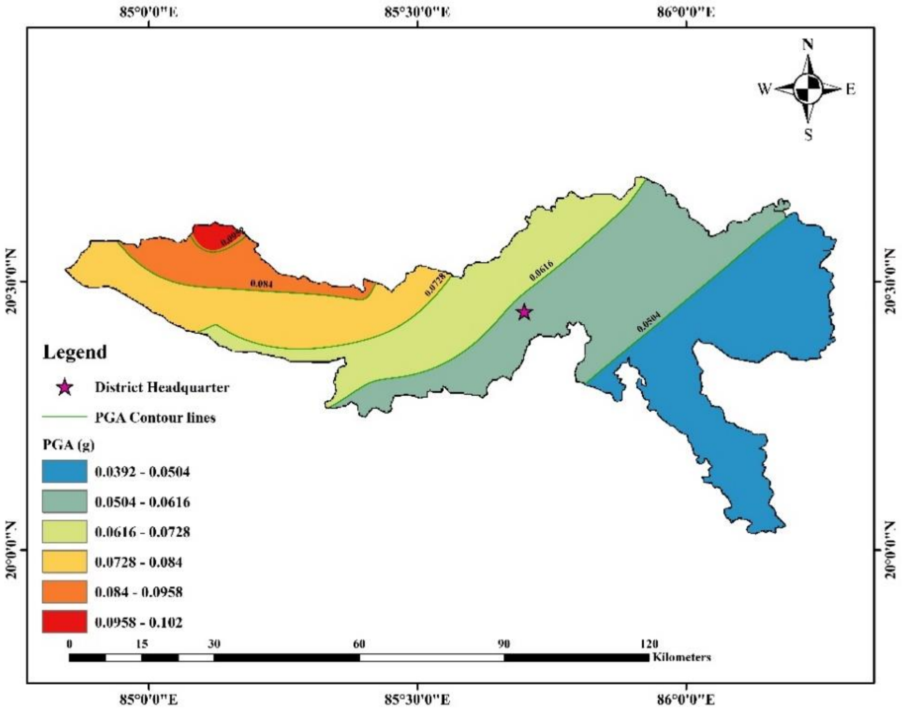

Figure 6: Spatial variation map of PGA(g) value for 2475-year return period

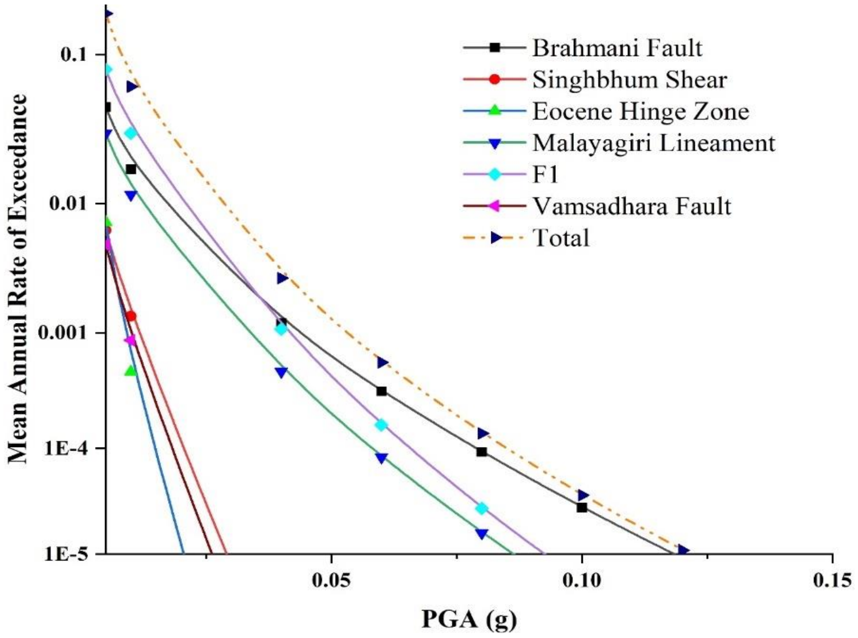

Figure 7: Hazard curves for different contributing sources at Cuttack district headquarter

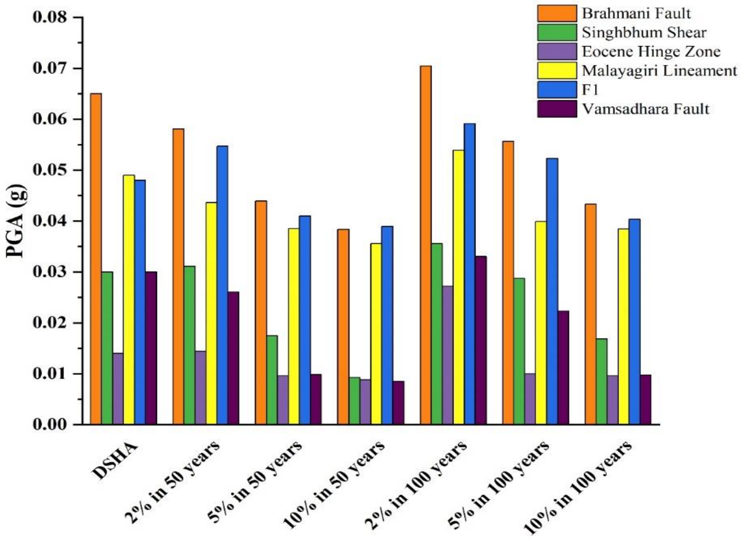

Figure 8: Comparison of results from DSHA and PSHA

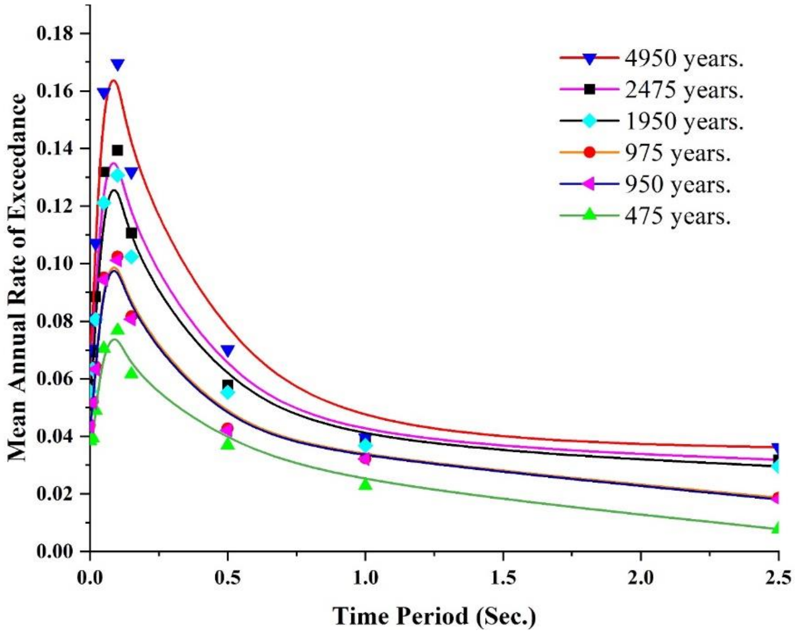

Figure 9: Plot of UHS curves at Cuttack city center for different return periods

Table 3
Result in comparison with literature

S.N.	Author	Method	Region	PGA (g)
1	Present Study	DSHA	Cuttack	0.065g
2	Present Study	PSHA (2% in 50 years)	Cuttack	0.06g
3	Present Study	PSHA (10 % in 50 years)	Cuttack	0.04g
4	Kolathayar et al.[16]	DSHA	Bhubaneswar	0.04g
5	Huded and Dash[9]	DHSA	Cuttack	0.12g
6	Huded and Dash[10]	PSHA (2% in 50 years)	Cuttack	0.023g
7	NDMA[12]	PSHA (10% in 50 years)	Bhubaneswar	0.02g
8	NDMA[12]	PSHA (2% in 50 years)	Bhubaneswar	0.04g
9	Sinha and Sarkar[28]	PSHA (2% in 50 years)	Dhanbad	0.12-0.23g

Our estimated PGA values are generally comparable to and slightly higher than those from previous studies, likely due to the use of updated seismicity data and GMPEs in our analysis.

Conclusion

In this investigation, we conducted a comprehensive assessment of the seismic hazard for the district headquarters of Cuttack by analyzing the seismotectonic characteristics within a 300 km radius. We systematically collected and scrutinized historical seismic data from this region, applying de-clustering techniques to mitigate spatial and temporal clustering, thereby ensuring a robust and consistent dataset. Utilizing this refined data, we developed a detailed seismotectonic map for Cuttack, incorporating all identified linear seismic sources within the specified radius. This map serves as a critical tool for understanding the seismic potential and informing mitigation strategies in the region. The findings from this investigation are outlined below:

- The earthquake catalog spanning the past 185 years for the study area has been prepared.
- The 'b' parameter, determined through G-R recurrence relations, is calculated as 0.94 for the study area.
- According to deterministic analysis, the PGA value at the district headquarter is 0.065g and the Brahmani fault is identified as the controlling seismic source for Cuttack district.
- To address uncertainties regarding earthquake magnitude, location and size, this study also conducted probabilistic seismic hazard analysis of the study area.
- Hazard curves of different seismic sources at the Cuttack district headquarter are generated.
- The PGA ranges from 0.0391 to 0.102g for the probabilistic analysis with a 2% PE over 50 years in the district. At the district headquarter, the PGA is 0.06g for a 2% PE over 50 years and 0.04g for a 10% PE over 50 years.
- From the seismic hazard assessment of the area, the maximum spectral acceleration is obtained at 0.1 second spectral period.

Seismic hazard estimations provided in this study pertain to bed rock level conditions with Vs30 ≥ 1,500 m/s. It is important to note that these values may change when accounting for site-specific soil properties and associated site effects.

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