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DEVELOPMENT OF FREQUENCY-DOMAIN HAZARD SPECTRA USING PROBABILISTIC SEISMIC HAZARD ANALYSIS FOR ENHANCED EARTHQUAKE RESILIENCE

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ABSTRACT

For the safe and cost-effective design of critical infrastructure such as dams, nuclear power plants, and long-span bridges, it is essential to estimate earthquake ground motions in a site-specific manner accurately. This estimation process involves conducting a seismic hazard analysis tailored to the project site of interest. Seismic hazard assessment is the methodology used to evaluate the seismic design parameters that dictate the ground motion intensity for such structures. Seismic hazard assessment could be approached through two primary methods such as deterministic and probabilistic frame work. However, deterministic method focuses on a specific earthquake scenario as well as designing the structure to withstand a maximum considered earthquake. In contrast, Probabilistic method accounts for the uncertainties in earthquake size, location, and frequency of occurrence, recognizing that the expected lifespan of a structure becomes often much shorter than the recurrence interval of major seismic events. This paper reviews the methodologies involved in seismic hazard assessment, emphasizing developing a Uniform Hazard Spectrum (UHS) in the frequency domain analysis. The UHS serves as a critical tool for deriving seismic design insights, ensuring that structures meet safety standards by accounting for both the severity and the probability of earthquake events.

KEYWORDS: Seismic Hazard Analysis, Peak Ground Acceleration, Response Spectra, Hazard curve

INTRODUCTION

In recent years, earthquakes have inflicted extensive damage on infrastructure across the globe, leading to considerable loss of life and severe economic consequences. Notable seismic events such as the 2023 Turkey earthquake (M_w 7.8), the 2011 Tohoku earthquake in Japan (M_w 9.0), and the 2010 Canterbury earthquake (M_w 7.1) have highlighted the devastating impact that such natural disasters could have on communities and economies. However, India has experienced numerous damaging earthquakes over the past century, reflecting its complex and active tectonic framework governed by the ongoing convergence between the Indian and Eurasian plates. Significant events include the 1934 Bihar-Nepal earthquake (M_w 8.0), which caused widespread devastation across the Indo-Gangetic Plain; the 1941 Andaman Islands earthquake (M_w 8.1); the 1950 Assam earthquake (M_w 8.6), one of the strongest recorded intraplate events globally; the 1967 Koyna earthquake (M_w 6.5), notable for its reservoir-induced seismicity; the 1993 Latur earthquake (M_w 6.2), which occurred in a stable continental region; the 1997 Jabalpur earthquake (M_w 6.0); the 2001 Bhuj (Gujarat) earthquake (M_w 7.7), which resulted in over 20,000 fatalities and extensive infrastructural damages; the 2005 Kashmir earthquake (M_w 7.6), affecting the northwestern Himalayas; and the 2011 Sikkim earthquake (M_w 6.9), which impacted the eastern Himalayan region. These events collectively underscore the widespread seismic hazard present across the Indian subcontinent, ranging from interplate boundary zones in the Himalayas to intraplate regions of peninsular India(Mishra et al., 2024b). Given the profound consequences of these earthquakes, the study of regional seismicity, coupled with the development of effective disaster preparedness strategies, becomes vital for mitigating the impact of future events. Seismic hazard analysis plays a critical role in assessing potential risks by estimating ground shaking intensities and identifying areas most susceptible to damage. In addition to the risk of structural failure caused by ground shaking, earthquakes could also initiate secondary hazards such as landslides, tsunamis, and soil liquefaction, which could significantly exacerbate the overall damage. Accurately predicting

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ground shaking levels becomes, therefore, essential for engineering applications aimed at enhancing earthquake resilience. Reliable seismic hazard assessments inform the design of structures to better withstand earthquakes, ultimately reducing risks to both people and property (Mishra & Sil, 2024);(Mishra et al., 2025).

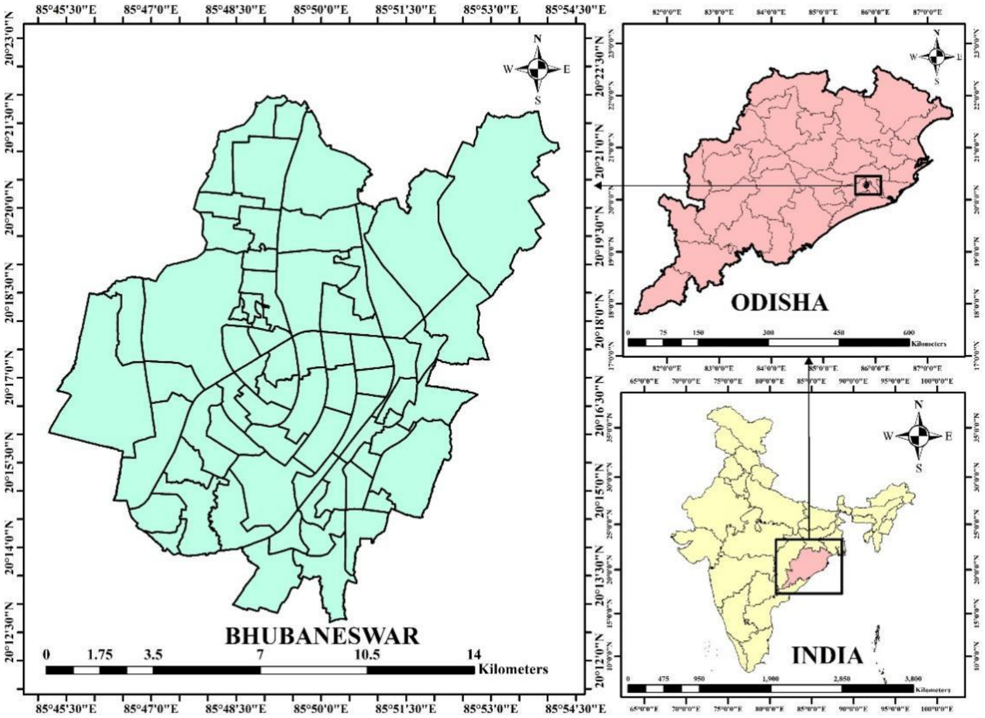

Fig. 1 Study area (Bhubaneswar City)

The occurrence of several catastrophic earthquakes in recent years spurred extensive research focused on seismic hazard assessments (SHA) at both national and regional levels. Researchers utilized both deterministic and probabilistic approaches to evaluate seismic risks across various parts of India (Kumar et al., 2023). To gain a more precise understanding of regional seismicity and enhance the accuracy of risk assessments, site-specific SHA have been carried out for major urban centers, including Mumbai, Delhi, Kolkata, and Chennai respectively.

Historically, Peninsular India (PI), an intra-plate region within the Indian tectonic plate, considered seismically stable. However, significant earthquakes in Koyna, Latur, Jabalpur, and Bhuj have demonstrated the seismic vulnerability of this region. These unexpected events emphasize the need for detailed site-specific hazard studies in PI. The tectonic activity in this region is driven by the Indian plate's collision with the Eurasian plate at a velocity of approximately 50 mm per year, resulting in a flexural bulge in central India that triggers intra-plate earthquakes. This highlights the necessity for comprehensive SHA, even in regions previously thought to be seismically inactive.

In recent years, several researchers have conducted SHAs for various cities in PI, including Patna (Anbazhagan et al., 2019), Amaravati (Satyannarayana & Rajesh, 2023), Dhanbad (Sinha & Sarkar, 2020), Cuttack (Mishra, Sil, et al., 2024a) and Warangal (Singh et al., 2020). However, despite these efforts, the understanding of seismic hazards in PI remains limited, particularly due to the scarcity of detailed site-specific studies of data. This lack of data becomes especially concerning given the region's rapid industrialization, urbanization, and increasing population density, all of which exacerbate the potential risks posed by seismic events.

In this context, the present study focuses on the seismic hazard assessment of Bhubaneswar, a growing city in the state of Odisha, located in the Peninsular India region. Given its developmental trajectory and the seismic potential of the region, a site-specific SHA for Bhubaneswar is crucial for informed urban planning and risk mitigation strategies. The Peak Ground Acceleration (PGA) values for the study area were determined using the Probabilistic Seismic Hazard Analysis (PSHA) method. Slope gradient data were utilized to estimate the V_S30 values, which represent the average shear wave velocity in the upper 30 meters of soil. These values were then used to calculate the surface-level PGA (g). Subsequently, seismic hazard curves and Uniform Hazard Spectra (UHS) developed for the entire city. The results were compared and validated against the seismic design values specified in IS 1893: Part 1 (2016) (BSI, 2016) and the findings of previous studies by other researchers. This comparison ensures that the calculated seismic hazard parameters are consistent with national standards and existing research, enhancing the reliability of the hazard assessment for the region.

SEISMOTECTONIC AND CATALOGUE COMPILATION

Bhubaneswar lies within the Eastern Ghats, a section of the Indian Shield known for its geological complexity and diverse rock formations. The city’s foundation is predominantly composed of granites, gneisses, and migmatites, which are believed to date back to the Archean era, around 2.5 billion years ago. Over time, extensive alluvial deposits accumulated in the region, shaped by erosion and sedimentation processes driven by local rivers, such as the Kuakhai and Bhargavi. According to IS 1893: 2016, Bhubaneswar is situated in Seismic Zone-III, signifying a moderate earthquake risk level. Despite this classification, the city and its surroundings remain vulnerable to seismic activity. Historical seismic events, such as the 1989 earthquake, have caused significant damage to infrastructure, highlighting the region's susceptibility to earthquakes (Mishra & Sil, 2024). To better understand the seismic risk in Bhubaneswar, historical earthquake data spanning the last 285 years (1737-2022) were collected, focusing on a 200 km radius around the state boarder. Several moderate-sized earthquakes have been recorded near Bhubaneswar, including events in the Talcher-Bonaigarh area in 1995, with magnitudes of 5.0 and 4.8, and two earthquakes of magnitude 5.2 in the Rengali region in 1958 and 1962. More recently, in 2014, a magnitude 6.1 earthquake in the Bay of Bengal caused structural damage along the Odisha coastline (Huded & Dash, 2022). The GSI has also detected ongoing tectonic activity in the region. A short-term earthquake monitoring network established in the Talcher-Bonaigarh area recorded low-magnitude seismic events along the Brahmani fault, F1 and the Talcher Basin Fault (TBF), suggesting recent movement along these fault lines. Previous studies in the nearby region have utilized both deterministic and probabilistic seismic hazard assessment (SHA) approaches to estimate PGA, reinforcing the moderate to significant seismic potential of the area. Historical records show that the region has experienced earthquakes exceeding magnitude 6.0 along the Bay of Bengal coastline.

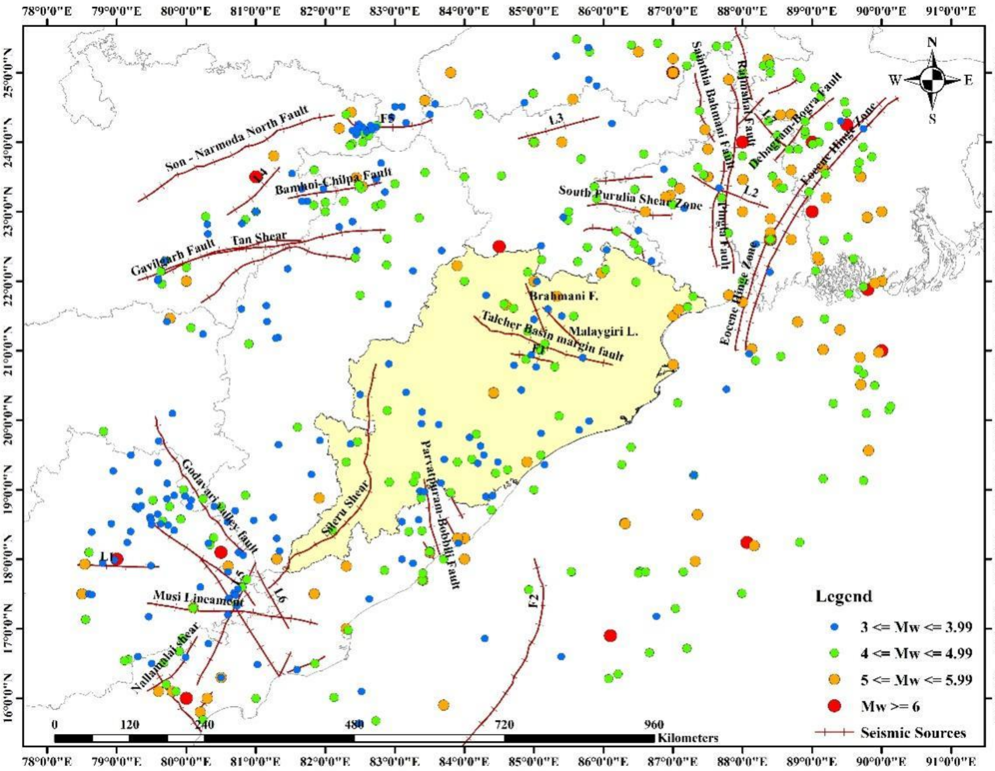

Fig. 2 Seismotectonic map of the study region

It is critical to acknowledge that seismic risk becomes governed by a multitude of factors extending beyond mere proximity to fault lines. The key determinants include subsurface geological conditions, local soil characteristics, and the implementation of current seismic design standards in building codes. Although the eastern region of Peninsular India classified as a moderately active seismic zone, its historical record of recurrent significant earthquakes highlights the imperative for thorough seismic hazard assessments. This further underscores the necessity for the development and application of robust mitigation strategies to enhance structural resilience and minimize earthquake-induced risks. Due to the lack of a detailed and comprehensive seismic event catalogue specific to Odisha, we compiled an earthquake event catalogue covering a 200 km radius around the state, encompassing Odisha and parts of neighboring states. This catalogue integrates both instrumental and historical earthquake data, providing critical information on the date, location, time, and magnitude of seismic events. Data were sourced from reputable seismological agencies, including the International Seismological Centre (ISC), United States Geological Survey (USGS), National Center for Seismology (NCS), and the National Oceanic and Atmospheric Administration (NOAA). By combining instrumental and historical data, ensured a comprehensive and reliable dataset, despite the absence of a dedicated earthquake catalogue for Odisha. To ensure consistency across the dataset, all earthquake magnitudes converted to the moment magnitude scale (M_w) using empirical equations proposed by (Trianni et al., 2014). This conversion is crucial because different magnitude scales—such as local magnitude (M_l), body wave magnitude (m_b), and surface wave magnitude (M_s)—tend to saturate at higher magnitudes, whereas M_w provides a more accurate and unsaturated measure of seismic energy release, particularly for larger events.

Duplicate entries from different data sources were carefully cross-verified and eliminated based on criteria such as magnitude, location, and time of occurrence. This process ensured the integrity and reliability of the final earthquake catalogue, which became crucial for the subsequent seismic hazard analysis. In PSHA, it is assumed that independent earthquake events follow a Poisson distribution, while dependent events- such as foreshocks and aftershocks do not. To isolate the independent mainshock events, the catalogue was declustered using the windowing technique developed by (Gardner & Knopoff, 1974). This technique filtered out dependent events, leaving a refined dataset of 411 main earthquakes with magnitudes of $M_w \geq 3.0$ for the region. Declustering is a critical step in seismic hazard analysis, as it allows for a more accurate assessment of seismic risk by focusing solely on independent seismic events. The earthquake catalogue includes both pre-instrumental historical data and modern instrumental records. Before the advent of seismographs, earthquake intensity was primarily determined through observed damage, using scales such as the MMI scale and the Rossi-Forel scale. With the development of seismographic instruments, earthquakes began to be measured using various magnitude scales, each with its own limitations. Converting all historical and instrumental records to the M_w scale ensures uniformity and comparability across the entire dataset, enhancing the robustness of the seismic hazard assessment. A comprehensive catalogue is essential for accurate seismic hazard analysis. Incomplete or inconsistent data could lead to unsatisfactory results and undermine the reliability of hazard predictions. To ensure the completeness of the earthquake catalogue, the Cumulative Visual Inspection (CUVI) method applied, which helps assess the adequacy of the catalogue over different time periods. This step becomes crucial for identifying periods of potential data gaps and ensuring that the seismic hazard analysis essentially based on the most complete dataset available. In this study, a minimum magnitude threshold of $M_w \geq 3.0$ was adopted for the seismic hazard analysis. This selection guided by two considerations: (i) completeness assessment using the Cumulative Visual Inspection (CUVI) method indicated that the earthquake catalogue for the study region becomes statistically complete for events of $M_w \geq 3.0$ since the 1970s, and (ii) earthquakes with magnitudes lower than 3.0 contribute negligibly to ground motion intensities relevant for engineering design. The adoption of M_w 3.0 as the lower threshold is consistent with standard practices in probabilistic seismic hazard assessments for stable continental regions (Kramer, 1996) (Bajaj & Anbazhagan, 2019).

SEISMIC SOURCE IDENTIFICATION AND FAULT CHARACTERIZATION

By developing a seismotectonic map using this catalogue, we can better understand the seismicity of the region and inform future risk management and mitigation strategies. This detailed and declustered dataset forms the foundation for a reliable seismic hazard analysis, leading to more effective earthquake resilience planning for the study area. Seismic hazard assessment and earthquake prediction becomes fundamentally dependent on accurate seismic zonation and the identification of seismic sources. In this study, seismic sources have been identified using the Seismotectonic Atlas of India (Dasgupta et al., 2000) and previous studies (Mishra & Sil, 2024) (Huded & Dash, 2022). Within Odisha and the surrounding regions, a total of 39 faults have been identified, of which 9 are considered significant for generating potential ground motion. The classification of these faults mainly based on several factors, including the density of seismic events near the faults, key seismicity parameters, and prominent geological and tectonic features. This method of categorization allows us to focus on the faults most likely to produce significant ground shaking in the study area, ensuring a targeted and efficient assessment. Notably, some of the more prominent faults include the Sileru Shear, which extends for 353 km within the study region, and the Eocene Hinge, with a length of 323 km. In contrast, shorter faults such as the Kanada–Kumilt Fault measure only 33.9 km in length. By focusing on the characteristics and potential activity of these specific faults, we can better assess their contribution to the seismic hazard in Odisha and its surroundings. This approach helps prioritize faults based on their potential

SEISMIC SOURCE IDENTIFICATION AND FAULT CHARACTERIZATION

In seismic hazard assessment, it is essential to estimate the recurrence intervals of earthquakes with varying magnitudes for the study region. The seismic activity of a particular area is quantified through seismicity parameters, which becomes crucial for predicting future seismic events. One of the most widely used models for this purpose is the Gutenberg-Richter recurrence law (Gutenberg and Richter, 1944), which relates earthquake magnitude to its frequency of occurrence. This relationship is expressed as:

$$\mathrm{Log10}\ \lambda_M = a - bM \qquad (1)$$

where λ_M is the rate of earthquake occurrence, and ‘a’ and ‘b’ are seismicity parameters representing the activity level and the relative distribution of earthquake magnitudes, respectively. In the present study, a dual approach adopted for seismicity parameter estimation to comprehensively represent the seismic hazard of Bhubaneswar and its surroundings. First, the entire 200 km radius area around Bhubaneswar considered as a single seismic source zone. This was based on the relatively diffuse distribution of intraplate earthquakes, consistent with the tectonic behavior of Peninsular India. The regional Gutenberg-Richter parameters (a and b values) calculated to represent the background seismicity. For the entire region, treated as a single zone, the parameters were found to be a=4.1165 and b=0.8785. Second, to capture the localized effects of major geological structures, seismicity parameters also individually estimated for each significant identified fault, such as the Brahmani Fault, F1 and Eocene Hinge Zone. This dual approach ensures that both regional diffuse seismicity and fault-specific activity incorporated into the PSHA, improving the accuracy and reliability of the hazard estimates. The details of the considered faults, their seismicity parameters and maximum magnitudes are given in Table 1.

For the study area, the seismicity parameters were calculated both for the entire region and for individual faults. A critical aspect of seismic hazard assessment determining the maximum magnitude (M_{max}), which represents the largest possible earthquake that could occur on a given fault in the future. M_{max} is particularly important in engineering applications, as it defines the upper limit of seismic events that structures must be designed to withstand. However, due to the relatively short time span of the earthquake catalogue compared to the recurrence intervals of large earthquakes, there becomes significant uncertainty in estimating M_{max}. Several methods developed to address this uncertainty. For instance (Wells & Coppersmith, 1994) proposed calculating M_{max} based on the fault rupture area and fault type. More recently, (Kijko, 2004) introduced a method that accounts for both the complete and incomplete parts of an earthquake catalogue, using Bayesian methods to estimate the frequency-magnitude distribution and provide a more robust M_{max} value. Given the critical importance of Mmax for predicting higher ground motion during large-magnitude earthquakes, we employed the methods developed by (Kijko, 2004), (Iyengar et al., 2010), and (Anbazhagan et al., 2015) to estimate M_{max} for each identified seismic source in the study area. These estimates then compared with observed historical earthquake magnitudes to ensure accuracy and reliability. The accurate determination of M_{max} becomes essential for understanding the seismic risk posed by faults in the region and for developing effective earthquake resilience strategies in engineering and urban planning.

Table 1: Seismicity parameters and M_{max} for some major faults in the study region

Sl. No.	Name of the Seismic Source	a	b	M_{max} (Obs)	M_{max}, (Kijko)	M_{max}, (NDMA)	M_{max} RLD	M_{max} (Estimated)
1	Sileru Shear	2.45	0.86	5.87	6.4	6.4	6.2	6.4
2	Parvatpuram-Bobbili Fault	2.23	0.7	5.96	6.3	6.5	5.9	6.5
3	F1	1.47	0.64	4.77	5	5.1	5.8	5.8
4	Brahmani Fault	1.79	0.71	6.26	7.2	6.8	5.9	7.2
5	Malayagiri Lineament	2.17	0.89	5.02	5.4	5.6	5.9	5.9
6	Singhbhum Shear Zone	3.04	1.04	5.02	5.3	5.6	5.9	5.9
7	South Purulia Shear Zone	1.82	0.68	5.87	6.4	6.4	5.9	6.4
8	Pingla Fault	1.94	0.68	5.67	6	6.2	6	6.2
9	Eocene Hinge Zone	2.99	0.76	6.86	7.4	7.4	6.2	7.4

GROUND MOTION PREDICTION EQUATIONS (GMPE) AND THEIR ROLE IN SEISMIC HAZARD ASSESSMENT

Ground Motion Prediction Equations (GMPE) establish a relationship between earthquake magnitude, source-to-site distance, source geometry, and local site conditions to estimate ground shaking levels. These equations are typically derived empirically through regression analysis on strong-motion data from specific regions. Selecting an appropriate GMPE is crucial in accurately estimating ground shaking intensity, making it a key component of any seismic hazard assessment (Mishra et al., 2024).

While global GMPEs, such as those developed by (Campbell & Bozorg, 1994) and (Joyner & Boore, 1993), are based on worldwide data, region-specific equations tend to yield more accurate results due to the unique seismic characteristics of different areas. In India, researchers like (Nath & Thingbaijam, 2012), (Raghukanth, 2010), (Sil et al., 2013), and (Baruah et al., 2011) have developed GMPEs tailored to specific regions of the country. In our study, GMPEs from regions with similar seismicity and tectonic features were adopted to address the limitations in strong-motion data specific to the study area. We utilized the predictive equations from (Iyengar et al., 2010), (Toro et al., 1997) for Central and Eastern North America, and (Bajaj & Anbazhagan, 2019) for Peninsular India, as these models are well-suited to regions with similar seismic profiles. After comparing these models with observed data, we assigned weightage factors to the models- BAJAJ-19 (Bajaj & Anbazhagan, 2019), NDMA-10 (Iyengar et al., 2010), and TORO-97 (Toro et al., 1997) to account for variations in distance. For distances less than 200 km, the models were weighted 0.5, 0.3, and 0.2, respectively, while for distances greater than 200 km, the factors shifted to 0.2, 0.5, and 0.3. Two key parameters commonly used to characterize earthquake ground motions are PGA and SA at different periods. PGA measures the maximum ground acceleration during an earthquake, indicating the immediate force experienced by the ground. SA, on the other hand, provides a more detailed view of the acceleration response of structures at different periods, which is crucial for understanding how buildings with varying natural frequencies will react to seismic forces. Utilizing both PGA and SA ensures a comprehensive assessment of seismic hazards and informs the design of earthquake-resistant structures. One of the challenges in this study was the unavailability of a sufficient number of strong-motion data for the region, which hindered the direct development and validation of GMPEs specific to the area. Given these data limitations, we relied on previously developed GMPEs for the region, as well as GMPEs from stable continental regions with similar seismotectonic characteristics. This approach ensures that the seismic hazard assessment remains robust despite the scarcity of local strong-motion data, enabling us to make informed predictions about ground shaking intensity and seismic risk. By integrating both region-specific and globally recognized GMPEs, we can improve the accuracy of ground motion predictions and enhance the reliability of the seismic hazard assessment for the study area.

METHODOLOGY

Seismic hazard analysis is a robust scientific methodology aimed at evaluating and forecasting the potential risks posed by earthquakes in a given region. Its primary objective is to estimate the probability of earthquake occurrence and the associated impacts on infrastructure and human activities. Seismic hazard analysis could be broadly classified into two principal methodologies: Deterministic Seismic Hazard Analysis (DSHA) and Probabilistic Seismic Hazard Analysis (PSHA). DSHA focuses on identifying the Maximum Credible Earthquake (MCE) that could occur on a specific fault or seismic source, estimating the corresponding ground motion at a site without accounting for the likelihood of its occurrence. PSHA, in contrast, offers a more comprehensive framework by incorporating the inherent uncertainties in earthquake size (magnitude), source-to-site distance, recurrence rates, and ground motion variability. It evaluates the probability of exceeding different ground motion levels over a given time period, producing hazard curves, uniform hazard spectra (UHS), and site-specific ground motion estimates for varying design return periods. In the context of this study, PSHA chosen for several reasons. First, Bhubaneswar lies in an intraplate region of Peninsular India, where earthquake recurrence becomes relatively infrequent and characterized by significant uncertainty in fault behavior and historical seismicity. Second, the lack of strong-motion recordings and long-term seismic records in the region makes it impractical to rely solely on deterministic scenarios. PSHA’s ability to integrate multiple sources, varying magnitudes, and multiple Ground Motion Prediction Equations (GMPEs) through logic tree frameworks makes it highly suited to such data-constrained settings.

Furthermore, PSHA aligns with national and international best practices for performance-based seismic design and risk-informed planning. The outputs of PSHA (particularly UHS) are indispensable for designing structures to withstand earthquakes of varying likelihoods over their design life, especially in emerging urban areas such as Bhubaneswar.

The PSHA process entails several critical steps:

1. **Seismic source characterization**, where the potential seismic sources and their behavior are identified.
2. **Magnitude-frequency distribution**, which determines how often earthquakes of different magnitudes occur in the region.
3. **Ground Motion Prediction Equation (GMPE) selection**, which estimates the level of ground shaking based on earthquake magnitude and distance to the site.
4. Incorporating uncertainties in the model parameters.
5. **Hazard calculation** by integrating these factors to evaluate the ground motion probabilities at different levels of intensity.
6. **Result aggregation**, which compiles the data into hazard curves that quantify the probability of exceedance of ground motion thresholds over specified time frames.

This systematic approach ensures a comprehensive and probabilistically sound assessment of seismic hazards, facilitating effective earthquake-resistant design and risk mitigation strategies (Kramer, 1996).

The results of PSHA are typically presented as hazard curves, which shows the probability of exceeding various ground motion levels over a specific time period. These curves reflect the full range of seismic hazard outcomes, accounting for all uncertainties, including spatial, temporal, and magnitude-related factors. By following this procedure, PSHA provides a detailed and robust assessment of seismic hazards, capturing the spectrum of potential earthquake impacts. The seismic hazard curves generated for Bhubaneswar city are shown in Figure 3 and can serve as fundamental inputs for site-specific studies aimed at estimating surface-level hazards, including site effects such as amplification.

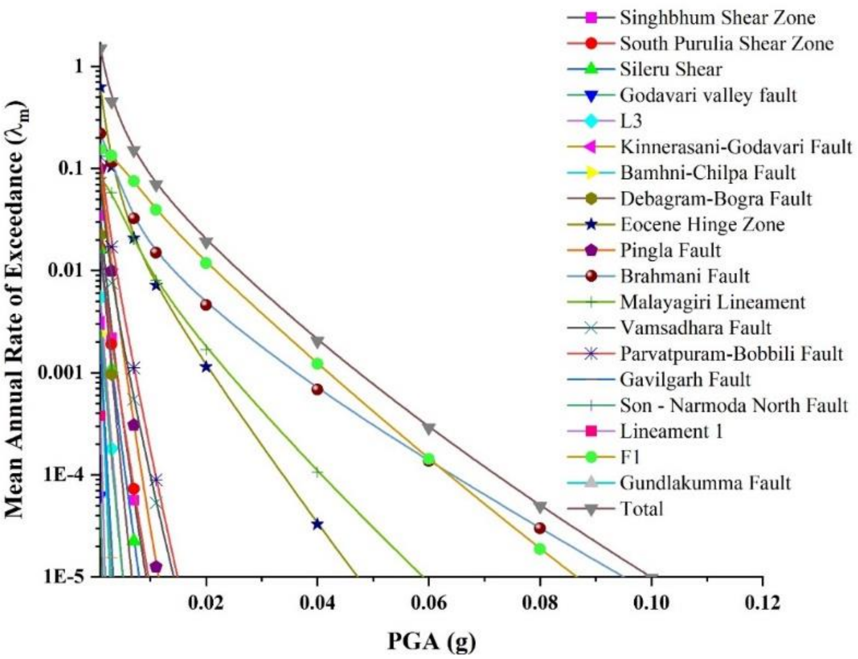

Fig. 3 Hazard curves from different sources for the city

Local soil conditions play a critical role in amplifying ground shaking during an earthquake, thereby increasing the risk of structural damage. For an accurate assessment of ground response and site effects, precise knowledge of the geological, geomorphological, and seismotectonic settings is essential. This highlights the importance of site characterization in seismic microzonation studies (Kirar et al., 2016). Several factors, including the thickness of overburden soil, soil density, type, subsoil geometry, and surface topography, contribute to the amplification of earthquake ground motion. Indirect measurements, such as shear wave velocity and dynamic shear modulus of the subsoil, are commonly used to determine site amplification characteristics. However, obtaining site-specific shear wave velocity profiles through in-situ testing is not always feasible due to site inaccessibility or challenging testing conditions. In such cases, alternative methodologies are adopted to mitigate these limitations (Kolathayar et al., 2012).

In our study, we used topographic slope as a proxy for seismic soil conditions, a widely applicable method that leverages globally available elevation data (Allen & Wald, 2009). We conducted site characterization for the entire state of Odisha using slope maps derived from Digital Elevation Models (DEMs) obtained from the USGS Earth Resources Observation and Science (EROS) Center. To process the data, we employed GIS platform, initially projecting the DEMs from the WGS-1984 geographic coordinate system to the UTM coordinate system, which is recommended for terrain analysis. The DEMs were resampled to a grid size of 1 km × 1 km for enhanced accuracy. Through correlation studies conducted in active tectonic and stable continental regions, (Allen & Wald, 2009) established slope ranges corresponding to each NEHRP site class. In this study, we used these correlations to estimate ground motion at the surface level. For site amplification, we applied the non-linear site amplification technique proposed by (Raghukanth & Iyengar, 2007), which accounts for local soil conditions.

The UHS, which plot spectral acceleration (SA) over different time periods, were generated for specified hazard levels such as 2% and 10% probabilities of exceedance (PE). UHS are crucial in the design of structures, as they are used to calculate the base shear and perform response spectrum analysis, ensuring that structures are adequately designed to withstand seismic forces.

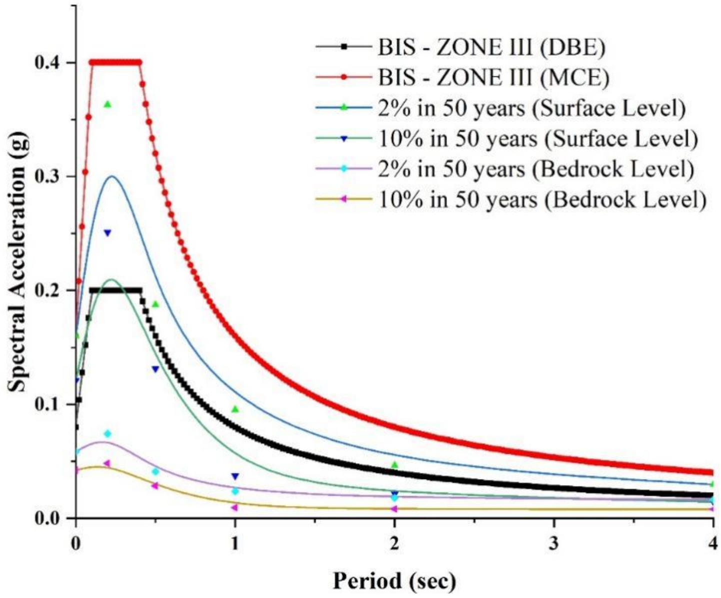

Fig. 4 Comparison of UHS with IS Code

By integrating these methodologies, this study provides a comprehensive assessment of seismic hazards in Bhubaneswar, aiding in the design of earthquake-resistant structures and contributing to enhanced risk mitigation strategies for the region.

RESULTS AND DISCUSSION

From the probabilistic seismic hazard analysis conducted for the region, the PGA values at the bedrock level for a 10% PE in 50 years and a 2% PE in 50 years were found to be 0.038g and 0.055g, respectively. When adjusted for surface-level conditions using the topographic gradient method, the PGA values increase to 0.042g for a 10% PE in 50 years and 0.16g for a 2% PE in 50 years. The UHS indicate that the spectral acceleration reaches its peak at a 0.2-second time period, with the F_1 fault and Brahmani fault identified as the primary contributors to seismic hazard in the Bhubaneswar region. An amplification factor of 2.7 was determined for the region.

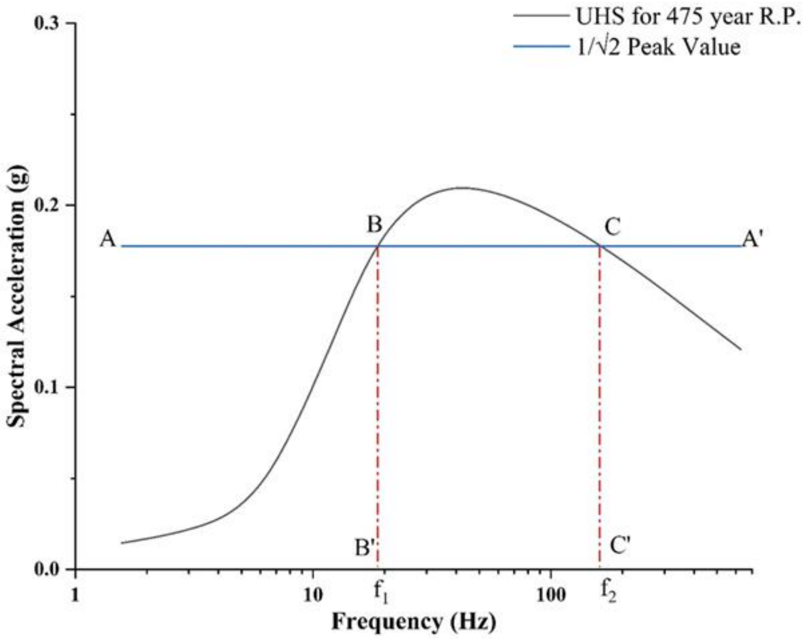

Fig. 5 UHS for 475-year RP of Bhubaneswar with frequency ranges

The UHS for both bedrock and surface levels were compared with the IS Code Zone-III response spectra in Figure 4, revealing a strong correlation between the UHS for a 475-year return period and the IS standard curve. Figure 5 presents a frequency domain-based form of hazard spectra for Bhubaneswar city with 475 return period. This indicates that the seismic design criteria established by Indian standards align well with the probabilistic seismic hazard data for Bhubaneswar. Of particular importance is the frequency-based analysis of the response spectra for Bhubaneswar. The UHS for a 475-year return period was segmented into three distinct zones, identified by the line segment AA' ($1/\sqrt{2}$ times the peak spectral acceleration). These zones include:

1. **Displacement-Controlled Zone (Low-Frequency Zone)**: This region is characterized by low-frequency ground motion, typically affecting tall, flexible structures.
2. **Velocity-Controlled Zone (Intermediate-Frequency Zone)**: The intermediate zone where resonance effects are more pronounced, potentially posing a risk to structures with natural frequencies within this range.
3. **Acceleration-Controlled Zone (High-Frequency Zone)**: High-frequency ground motion, typically impacting shorter, stiffer structures.

Based on the analysis, it is recommended that tall structures in Bhubaneswar have natural frequencies below f_1 (18 Hz) to avoid the intermediate frequency zone, while shorter structures should have natural frequencies exceeding f_2 (160 Hz). Avoiding the intermediate frequency zone is critical to minimizing the risk of resonance, which could lead to amplified structural vibrations and damage during seismic events.

This frequency-based response spectra provides a valuable tool for engineers, enabling them to strategically design buildings that avoid resonance-prone frequencies, thereby enhancing the seismic resilience of structures in Bhubaneswar. By incorporating these insights, engineers can optimize building designs for specific local conditions, ensuring safer, more durable infrastructure.

CONCLUSIONS

This study presents a comprehensive seismic hazard assessment for Bhubaneswar, focusing on the development of frequency-based UHS using PSHA. The analysis yielded key insights into the seismic vulnerability of the region, providing essential data for earthquake-resistant design. The UHS generated for Bhubaneswar effectively captures the seismic characteristics of the area, particularly the spectral acceleration, which peaks at a 0.2-second time period. A notable contribution of this research is the segmentation of the UHS into three distinct frequency zones: the displacement-controlled (low-frequency) zone, velocity-controlled (intermediate-frequency) zone, and acceleration-controlled (high-frequency) zone. The identification of these zones allows for a more nuanced understanding of how different structures may respond to seismic forces, emphasizing the critical role of natural frequency in mitigating the risk of resonance. Specifically, tall structures in Bhubaneswar are advised to have natural frequencies below f_1 (18 Hz), while shorter structures should exceed f_2 (160 Hz) to avoid the resonance-prone intermediate zones. The frequency-based approach to seismic hazard assessment introduced in this study enhances traditional methodologies by providing design engineers with a practical tool to strategically avoid resonance frequencies during the design process. This ensures a higher level of structural resilience, particularly for critical infrastructure in regions like Bhubaneswar, where seismic activity poses a significant threat. By incorporating these insights into building design, engineers could optimize performance, reduce seismic risk, and contribute to the development of safer and more sustainable urban environments. The successful integration of frequency-based UHS into the seismic hazard assessment highlights its value in guiding future research and practical applications in earthquake engineering. This approach not only reinforces the importance of considering frequency effects in seismic design but also sets a precedent for its broader application in other regions with similar seismic profiles.

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